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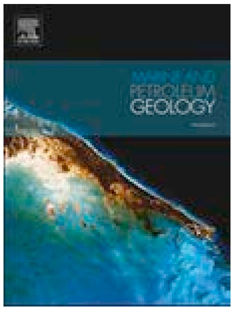

The Black Sea basins structure and history: new model based on new deep penetration regional seismic data. Part 1: Basins structure and fill

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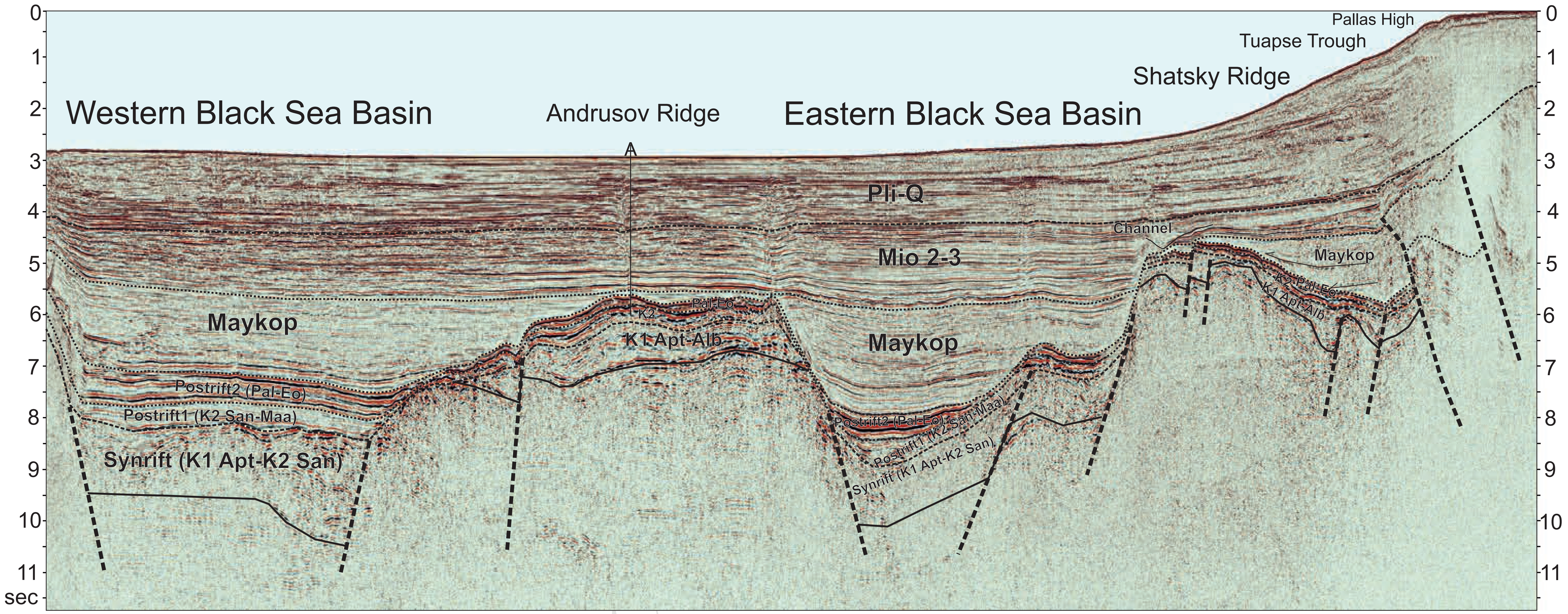

Western Black Sea Basin
Andrusov Ridge
Eastern Black Sea Basin
Shatsky Ridge
Tuapse Trough
Pallas High
Pli-Q
Mio 2-3
Channel
Maykop
Maykop
Maykop
K2
Pal-Eo
K1 Apt-Alb
K2-Pal-Eo
K1 Apt-Alb
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Synrift (K1 Apt-K2 San)
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Synrift (K1 Apt-K2 San)
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The Black Sea basins structure and history: new model based on new deep penetration regional seismic data. Part 1: Basins structure and fill

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Abstract

This work is based upon results of interpretation of about 8,872 km-long regional seismic lines acquired in 2011 within the international project *Geology Without Limits* in the Black Sea. The seismic lines cover nearly the entire Black Sea Basins, including Russia, Turkey, Ukraine, Romania and Bulgaria sectors. A new map of acoustic basement relief and a new tectonic structure scheme are constructed for the Black Sea Basins. The basement of the Black Sea includes areas with oceanic crust and areas with highly rifted continental crust. A chain of buried seamounts, which were interpreted as submarine volcanoes of Late Cretaceous (Santonian to Campanian) age, has been identified to the north of the Turkish coast. On the Shatsky Ridge, probable volcanoes of Albian age have also been recognized. Synorogenic turbidite sequences of Paleocene, Eocene and Oligocene ages have been mapped. In the Cenozoic, numerous compressional and transpressional structures were formed in different parts of the Black Sea Basin. During the

Pleistocene-Quaternary, turbidites, mass-transport deposits and leveed channels were formed in the distal part of the Danube Delta.

Keywords: Black Sea, interpretation of seismic data, volcano, rifting, Messinian event, inversional structure.

Introduction

The geological structure of the Black Sea has been under investigation since the publications of regional seismic lines for the entire area in the 1980's (Tugolesov et al., 1985; Finetti et al., 1988; Belousov et al., 1988, 1989). More recent seismic lines were shot in parts of the Black Sea and were published by Robinson et al. (1996), Dinu et al. (2005), Afanasenkov et al. (2007), Shillington et al. (2008), Rangin et al. (2002), Khriachtchevskaia et al. (2009, 2010), Munteanu et al. (2011), Menlikli et al. (2009), Stovba et al. (2009), Tari et al. (2009), Stuart et al. (2011), Nikishin et al. (2010, 2012), Mityukov et al. (2012), Almendinger et al. (2011), Georgiev (2012), TPAO/BP Eastern Black Sea Project Study Group (1997), Gozhyk et al. (2010), Graham et al. (2013). In recent years, various petroleum companies have acquired a very large amount of 2D and 3D seismic data for individual blocks, though results of these operations are not published.

Presence of oceanic crust has been proposed for the deep-water part of the Black Sea (Neprochnov et al., 1970). Data on structure of the crust in the Black Sea were summarized by Starostenko et al. (2004). Recent research dealing with the crustal structure in the Eastern Black Sea Region is presented in Scott et al. (2009) and Shillington et al. (2008, 2009).

Formation history and dynamics of the Black Sea basins were discussed in many publications. Starting from several classical works (Letouzey et al., 1977; Zonenshain and Le Pichon, 1986; Görür, 1988; Finetti et al., 1988), it is considered that the Western Black

Sea Basin and the Eastern Black Sea Basin were formed as back-arc basins behind the Pontide volcanic arc. This problem was considered by a number of researchers (Okay et al., 1994, 2013; Robinson et al., 1996; Nikishin et al., 2003, 2012; Saintot et al., 2006; Afanasenkov et al., 2007; Shillington et al., 2008, 2009; Stephenson and Schellart, 2010; Meijers et al., 2010; Munteanu et al., 2011). The unresolved issues are the time of formation of back-arc basins and whether the Western Black Sea and the Eastern Black Sea basins were formed synchronously or at different times.

Based on published data and on our recent research presented in this paper, we have compiled a new scheme explaining the tectonic structure of the Black Sea Region (Fig. 1). The major elements of the Black Sea Basin are the two basins – the Western Black Sea Basin and the Eastern Black Sea Basin, each one with oceanic or strongly thinned continental crust. These basins are separated by the Andrusov and Arkhangelsky ridges with continental crust. Other structural elements include the Shatsky Ridge with continental crust and the Tuapse, Sorokin and Gurian foredeep basins. The largest shelf area is the Odessa Shelf. Many other structures are also identified (Fig. 1) and will be discussed in this paper.

This work is based upon results of interpretation of the new regional seismic lines acquired in 2011 within the international project *Geology Without Limits* in whose realization specialists from Russia, Turkey, Ukraine, Romania and Bulgaria took part (Fig. 2). Total length of the acquired seismic lines reaches up to 8,890.5 km. The processing of these seismic data is still underway. In this paper we will only delineate our key findings with respect to structure and formation history of the Black Sea region based on the early processing results of the new seismic data.

2. Results

2.1. Interpretation of 2D Seismic Lines

The seismic survey was conducted from the research vessel «Mezen». The study area within the Program included Exclusive Economic Zones of the Black Sea Countries: Russia, Ukraine, Romania, Bulgaria, Turkey, and Abkhazia. In the final form, the International Project included 27 separate 2D lines with the total length of 8,890.5 line km. An airgun array with total volume of 5,680 cu. in was used as a seismic source, and a 10,200 m long streamer was used as a seismic receiver.

Our geological interpretations of new seismic profiles are presented in Figures 3 to 20. The order of presentation of the seismic profiles is according their geographical location and form part of an atlas of seismic data. This atlas provides the base of this study.

2.2. Acoustic Basement and Major Structures

Fig. 21 shows the new map of acoustic basement of the Black Sea on which the major structural elements are clearly seen. On the whole, our map is similar to the maps published previously (Tugolesov et al., 1985; Finetti et al., 1988; Belousov et al., 1988; TPAO/BP Eastern Black Sea Project Study Group, 1997) but it is based on data acquired using more advanced seismic technologies and is more accurate, at least for the deepest parts of sedimentary basins.

2.3. Rift Origin of the Western and the Eastern Black Sea Basins

We will substantiate our key findings with examples based on individual seismic lines. On Line BS-80 it is seen that the deep basins of the Black Sea are bounded by normal faults and their systems (Fig. 9A) emphasizing their rift origin. However we are still unable to recognize the particular geometry of faults (whether they are planar, listric, etc.). The time of rifting was not tightly defined. Based on correlation with data from the onshore, the phase of extension is Cretaceous ranging from Late Barremian to mid Santonian (Tüysüz et al., 2012; Nikishin et al., 2012).

2.4. On Presence of Oceanic Crust in the Black Sea

A considerable part of top of the acoustic basement in the Western Black Sea Basin is characterized by a hummocky surface with lens-shaped sediment infill. This is distinctly seen, for example, on Lines BS-40 and BS-140 (Figs. 5B, 12B). Such relief is probably caused by extension of the lithosphere and irregular filling of corrugations with volcanic material. We assume that such type of relief, seen within most part of the Western Black Sea Basin, is indicative of the proposed spreading character of its crust. Two different teams reached this conclusion using these seismic data (Nikishin et al., 2013a; Graham et al., 2013). Such crust is locally characteristic of the Eastern Black Sea Basin as well, as it is seen on Line BS-90 (Fig. 9B). Areas probably having oceanic crust with volcanism are shown on Fig. 22. Our seismic data cannot exclude that oceanic crust could be composed of serpentinized upper mantle at least locally close to continental margins. We suggest the presence of strongly extended rifted crust in areas where oceanic crust with volcanism is not observed. These areas often form uplifted terraces relative to areas with oceanic crust, and show half-graben type structures.

2.5. The Moho Surface

On Line BS-90 (Fig. 9B) a reflector is distinctly identified under the Eastern Black Sea Basin at time-depth of about 12 seconds, that most probably corresponds to the Moho interface. This is the first reflected seismic data on which this boundary is distinctly expressed (Nikishin et al., 2013a; Graham et al., 2013). This reflector practically coincides with the Moho interface recently identified in this area by wide-angle seismic data (Minshull et al., 2005). Numerous ‘hummocks’ are seen on the surface of the acoustic basement above the zone with uplifted Moho surface. This is a probable sign of oceanic crust with volcanism. Thus, the thickness of the oceanic crust is evaluated at 8-10 km. Reflection Moho is not uncommonly observed below the oceanic crust in oceans (Mutter and Carton, 2013).

2.6. The Trabzon Basin

In the southern part of the Eastern Black Sea Basin, the Ordu Ridge transversally to the basin's trend (Figs. 13, 14). Seismic lines distinctly show that this is a projection of the basement. At its continuation at the bottom of the Eastern Black Sea Basin, the Ordu-Pitsunda flexure represents a distinct lineament (Ordu is a name of city in Turkey and Pitsunda is a city in Abkhazia). Presence of the transversal Ordu Ridge and the Ordu-Pitsunda Flexure is indicative that the axis of the rifting-spreading could not extend further to the south, beyond the Eastern Black Sea Basin proper. The most probable solution would be that south of the Ordu-Pitsunda line, the axis of spreading was located parallel to this line. It follows from this that it is necessary to identify a separate basin in the southeastern part of the Eastern Black Sea Basin which we refer to as the Trabzon Basin (Figs. 1, 22). In terms time of formation it should be synchronous to the Eastern Black Sea Basin proper because they both have a common postrift cover.

2.7. Volcanic Structures in the Sedimentary Cover of the Black Sea Basin

On some lines (e.g. BS-110, 120, 140, 160, 170, 220, 222, Figs. 10B, 11, 12B, 13, 17), we identify isometric highs 500-2500 msec high and 10-15 km in diameter, of conical shape and without eroded tops. Geographically, these highs are located closer to Turkey. At least some of them show positive seismic velocity anomalies (Fig. 17). We assume that most of these highs (if not all) are submarine volcanoes. Their bases coincide approximately to the stratigraphic level of Cretaceous or Upper Cretaceous deposits. In Turkey the Pontides Cretaceous volcanic arc stretches parallel to the coast (Fig. 1). Maximum volcanic activity is reached in the Santonian-Campanian (or Campanian) (Tüysüz et al., 2012). On that basis, we assume that the age of these hypothetical volcanoes is Santonian-Campanian. Since these volcanoes do not show distinct signs of erosion, we understand that they formed underwater at depths of not less than 2 km. We conclude that by the end of the Cretaceous the Western and the Eastern Black Sea Basins were already deep-water basins. We have recognized nearly 12 buried volcanos on a few seismic lines north of the Cretaceous Pontides volcanic belt in Turkey and we assume that in reality the numerous additional volcanoes could be present in the basin. We propose to name this long volcanic arc located north of the Pontides, the Peri-Pontides volcanic arc. The Upper Cretaceous magmatic rocks in the Pontides consist mainly of pyroclastic deposits derived from the Peri-Pontide arc.

2.8. Albian Volcanism on the Shatsky Ridge

Several volcano-like looking structures are seen in the Albian sequence on the Shatsky Ridge (Line BS-200) (Fig. 16). Albian volcanics are also known in the Adjaro-Trialeti Zone in Georgia and in the area of Balaklava in Crimea (Nikishin et al., 2003, 2012, 2013b). It is suggested that an Albian volcanic belt extended from the area of Balaklava, through the Shatsky and Andrusov Ridges into the Adjaro-Trialeti Zone. This volcanic belt was located above the subduction zone, as it is shown for the Adjaro-Trialeti Zone and for the Balaklava area (Nikishin et al., 2012, 2013b). Thickness of the Albian volcanics and volcanoclastic sediments may reach several hundreds of meters. The Albian volcanics and volcanoclastics are well known from the Karkinit Graben on the Odessa Shelf (Gnidec et al., 2010; Khriachtchevskaia et al., 2010; Nikishin et al., 2012).

2.9. Difference in the Geometric Structure of the Western and Eastern Black Sea Basins

The Eastern Black Sea Basin is an approximately symmetrical rift structure, while the Western Black Sea Basin has a distinct asymmetry: its southern side is steep and narrow while its northern slope is gentler and has a large number of normal faults (see Figs. 5, 9A, 16). There are indications of Albian volcanism on the shoulders of the Eastern Black Sea Basin (the Shatsky and Andrusov ridges). We conclude that the Eastern Black

Sea Basin originated through rifting along the Albian volcanic arc within a weak and hot lithosphere (Nikishin et al., 2003, 2012). For such conditions, symmetrical rifting with normal faults along both sidewalls and a neck-shaped thinning of the lithosphere is typical (Ziegler and Cloetingh, 2004). The Western Black Sea Basin was probably formed at the rift stage according to the Wernicke model (Wernicke, 1981; Ziegler and Cloetingh, 2004) with a single gentle-dipping main detachment fault along the southern sidewall of the basin, while its northern sidewall was bounded by a large number of lesser-amplitude normal faults.

2.10. Thickness of Pre-Maykopian Deposits

Pre-Maykopian (Cretaceous to Eocene) deposits in the Western Black Sea Basin (up to 5-8 km) are two-three times thicker than the ones in the Eastern Black Sea Basin (up to 3-4 km) (Figs. 4, 7, 9), indicating that sedimentation rate in the Western Black Sea Basin was significantly higher during this time. The most probable explanation is that bigger amounts of clastic material were entering into the Western Basin from the Balkans and Turkey, while the Eastern Basin received mainly pelagic deep-water carbonates with only minor turbidites.

2.11. Upper Cretaceous-Eocene on the Shatsky and Andrusov Ridges

Probable Late Cretaceous-Eocene deposits on the Shatsky and Andrusov Ridges appear very similar in the form of a series of subparallel bright reflections (Figs. 9, 13, 14, 16). Judging by the fact that thicknesses and seismofacies are consistent over great distances, we assume that Upper Cretaceous-Eocene is represented mainly by deep-water carbonates, shales and siltstones.

2.12. Carbonate Platform in the Southern Part of the Shatsky Ridge and Carbonate Build-ups in the Northern Part of the Shatsky Ridge

In the southern part of the Shatsky Ridge on Line BS-190 (Fig. 15), a carbonate platform of Late Jurassic to Eocene in age is recognized. Such carbonate deposits are known onshore in Abkhazia and in the Sochi-Adler area in the Russian part of the Great Caucasus (Afanasenkov et al., 2007; Nikishin et al., 2012). In the northern part of the Shatsky Ridge, large possible carbonate build-ups are recognized, which may be Callovian to Barremian in age (Afanasenkov et al., 2007; Nikishin et al., 2012; Guo et al., 2011).

2.13. Maykopian (Oligocene-Lower Miocene) Deposits

Maykopian deposits, up to 3-6 km thick, form a common cover on the basins and ridges of the Black Sea including the Western Black Sea Basin, the Eastern Black Sea Basin, the Andrusov, Arkhangelsky and Shatsky Ridges. However, the Andrusov-Arkhangelsky and Shatsky Ridges are only covered with deposits of the upper part of Maykop sequence. It is likely that during that time the Andrusov-Arkhangelsky, Shatsky and Ordu ridges were continuously submerged based on the lack of evidence for any erosion (Figs. 8, 9, 10, 13, 14, 15, 16). Within the Western and the Eastern Black Sea basins, water depth was not less than 2 km, while the Andrusov-Arkhangelsky Ridge and Shatsky Ridge (in its southwestern part) probably had depths in the order of several hundreds of meters. In these ridges, we see no signs of erosion. The dip of the slope on both sides of the Andrusov Ridge are steep, though much less than the dip of the Cretaceous faults that bounded them from the deep-water basins. It is probable that during deposition of the Maykop sequence, submarine landslide processes were prevalent on the steep slopes of the ridges, with formation of mass-transport deposits at the base of the slope and in the basins.

The Tuapse and Sorokin Troughs are filled with Maykopian deposits. They started forming at the boundary of Eocene and Oligocene as flexure basins and were being filled mainly with synorogenic deep-water turbidites (Afanasenkov et al., 2007: Nikishin et al., 2012; Mityukov et al., 2012). Middle Miocene deposits cover the Tuapse and Sorokin troughs as well as the entire Eastern Black Sea Basin. Hence, by Middle Miocene time these troughs had ceased to exist as separate basins.

It was traditionally assumed that the Maykop sequence of the Black Sea is composed of shales only. Our data demonstrate that the Maykopian deposits comprise various facies. Thick clinoform complexes of turbidites are distinctly recognized in the Tuapse Trough (Fig. 9) and possibly in the Sorokin Trough. Close to the Bulgarian shores, numerous channels are identified on Line BS-020 (Fig. 4). In the Balkans, the Thrace Basin is situated at the onshore continuation of this channel system. During the Oligocene, a strait probably existed between the Thrace Basin and the Black Sea Basin through which large amounts of clastic material were entering into the Black Sea. We call this straight the Paleo-Bosporus. Paleogeographic data of the Thrace Basin in the Oligocene show that the main transport direction of clastic material was toward the Black Sea (d'Atri et al., 2012). On the whole, facies of the Maykop sequence closer to the Western Pontides and Bulgaria are more diversified; numerous horizons of turbidites with sandstones probably exist in this region.

2.14. The Time of Formation of the Gurian Basin

The Gurian Basin in the eastern Turkish waters is not similar to the Tuapse Trough in its structure as the new seismic lines did not show an increased thicknesses of the Maykop sequence in the trough (Fig. 14). Here, the thickness of Middle and Late Miocene deposits is relatively large. We conclude that the main phase of subsidence of the Gurian Trough was in Middle-Late Miocene.

2.15. Late Eocene Flysch Basin North of the Western Pontides

Along the continental slope of the Western Pontides a triangular-shaped fan is mapped in the Late Eocene (Figs. 4, 5, 12B). We assume that it corresponds to a turbidite basin that was formed as a result of collisional deformation and ensuing uplift in Western Turkey, as was proposed by Menlikli et al., (2009) and Nikishin et al., (2012). In the Western Pontides the time of collision is considered as Late Eocene; Late Eocene and Oligocene sediments are absent in onshore sections in the Pontides (Okay et al, 2001; Sunal and Tüysüz, 2002). Apatite fission-track thermochronology of the Western Pontides shows that the main uplift of the Pontides occurred during the interval 43.5–32.3 Ma (Late Lutetian–Early Rupelian) (Cavazza et al., 2012). We conclude that the flysch trough is most likely of Late Eocene age.

Apatite fission-track data show that structural inversion of the Central Pontides fold-and-thrust belt started at ca. 55 Ma (Espurt et al., 2014). This would imply the presence of Early Eocene turbidite fans in the Western Black Sea Basin.

2.16. Regional Late Eocene and Oligocene Compressional Deformations

Late Eocene and Oligocene gentle-folding and thrust-fault deformations are of considerable importance in the Shatsky Ridge, the Western Black Sea Basin, shelves of Romania, Bulgaria, Ukraine and Turkey (Figs. 5A, 6) (Sunal and Tüysüz, 2002; Dinu et al., 2005; Afanasenkov et al., 2007; Khriachtchevskaia et al., 2010; Nikishin et al., 2012; Munteanu et al., 2011). The Tuapse and Sorokin troughs have clearly experienced flexural syncompressional subsidence at the boundary of Eocene and Oligocene (base of the Maykop sequence) (Figs. 8, 9, 10). On the Romanian shelf and continental slope in the area of the Histria Basin, a large number of inversion folds and reverse faults are recognized, which were formed in the Late Eocene-Oligocene (Fig. 19).

2.17. Middle Miocene to Pliocene Compressional Deformations

During Middle Miocene to Pliocene time, sediments of the Tuapse, Sorokin, and Gurian foredeep basins suffered strong compressional deformations (see Figs. 8, 9, 10, 14, 15; Afanasenkov et al., 2007; Nikishin et al., 2009; Stovba et al., 2009; Almendinger, 2011). Some deep-water anticline folds have been formed, for example the Sevastopol Swell (Figs. 7, 20), and within the Romania shelf (Bega and Ionescu, 2009).

2.18. The Kamchia-Marine Foredeep Basin

Located at the continuation of the Kamchia Foredeep Basin onshore, the Kamchia-Marine Foredeep Basin of Late Paleocene-Middle Eocene age (Fig. 18), extends in the Bulgarian part of the Black Sea. The foredeep consists of a prism of sediments with bottom onlap indicative of its dominantly turbiditic infill. This trough outcrops onshore; it was formed in Late Paleocene-Middle Eocene as a foreland basin facing a collisional deformation front (Tari et al., 2009; Stuart et al., 2011; Georgiev, 2012).

2.19. Differences between the Andrusov and Arkhangelsky Ridges

As seen on seismic lines, the Andrusov Ridge definitely has a sedimentary cover of Cretaceous-Cenozoic age with possible volcanic rocks in the Cretaceous. Seismic data over the Arkhangelsky Ridge show no clear evidence for the presence of a thick Mesozoic cover (for example, Line BS-200, Fig. 16); hence its hydrocarbon potential is judged as much lower.

2.20. The Messinian Event in the Black Sea

The Messinian event in the Black Sea, i.e. a sudden sea level drop followed by a fast rise, has been well documented (Hsü and Giovanoli, 1979; Gillet et al., 2007). Here, we provide additional data on the scale of this event. On Line BS-10 (Fig. 3), an erosional boundary is distinctly seen approximately at the level of the Neogene-Quaternary boundary which may represent the Messinian (Intra-Pontian) erosional boundary. The exact correlation of Messinian stratigraphy and events in the Mediterranean and the Black seas remains problematic.

2.21. Deep-water Channel Systems

Recent deep canyon incisions are known in the deep-water Danube fan as leveed channel systems (Lericolais et al., 2010, 2013; Munteanu et al., 2012). Buried leveed channels can be seen on lines BS-40, BS-50, BS-150, BS-230 (Figs. 5B, 6, 12A, 18), indicating that such depositional systems have formed continuously during a considerable span of time corresponding to the entire the Pliocene-Quaternary interval, during which time the Danube Delta was actively outbuilding.

3. Conclusions

1. A map of the acoustic basement relief of the Black Sea showing some new structures was constructed using the new 2D seismic data.

2. According to seismic reflection data the Western and Eastern Black Sea basins have an oceanic and highly extended continental crust.

3. A chain of buried submarine volcanoes of Late Cretaceous (Santonian-Campanian) age was recognized in the Black Sea; it extends parallel to the Late Cretaceous Pontides volcanic arc in northern Turkey and is here referred to as the Peri-Pontides volcanic arc. A possible Early Cretaceous (Albian-?) volcanic arc is suggested along the Shatsky Ridge.

4. The Eastern Black Sea Basin is more symmetric than the Western Black Sea Basin. We interpret the Eastern Black Sea Basin have originated through rifting along an Early Cretaceous volcanic arc with heated the lithosphere making it more ductile.

5. The Andrusov and Shatsky continental highs started a phase of thermal subsidence in the Late Santonian. Late Santonian to Eocene deposits are presented by condensed sediments of the deep shelf.

6. New Paleocene and Eocene turbidite basins were recognized along southern and southwestern parts of the Western Black Sea Basin. Turbidite basins originated due compression, thrusting and uplifting events in orogenic belts of Turkey and the Balkans.

7. Rapid sedimentation persisted since the Oligocene, when the Black Sea deep-water basins were infilled predominantly by shales. Channelized systems were documented in the area of the recent Bosporus strait.

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FIGURE CAPTIONS

Figure 1. Tectonic map of the Black Sea region. The map is compiled by using both new data presented in this paper and published data (Tugolesov et al., 1985; Okay et al., 1994, 2013; Robinson et al., 1996; Afanasenkov et al., 2007; Khriachtchevskaia et al., 2010; Munteanu et al., 2011; Nikishin et al., 2012; Georgiev, 2012). Eo – Eocene, T-K – Triassic to Cretaceous. 1 - Polshkov Ridge, 2 - Tindala-Midia Ridge, 3 - Tomis Ridge, 4 - Lebada Ridge, 5 - Sf. Georg Ridge, 6 - Sevastopol Swell, 7 - Lomonosov Massif, 8 -Tetyaev Ridge, 9 -Anapa Swell, 10 - North Black Sea High, 11 - South-Doobskaya High, 12 - Gudauta High, 13 -Ochamchira High, 14 - Ordu-Pitsunda Flexure, 15 -Rezovo-Limankoy Folds, 16 - Kamchia Basin, 17 - East-Moesian Trough, 18 - Babadag Bassin, 19 - Küre Basin.

Figure 2. Location of the seismic lines presented in this paper. The seismic lines were acquired in 2011 within the framework of "Geology Without Limits" project.

Figure 3. Geological interpretation of seismic line BS-10. Two erosional surfaces are easily identifiable in this profile. We interpret the upper one as the Messinian erosion surface, which originated due to a rapid see level fall (Suc et al., 2011; Munteanu et al., 2011, 2012; Barche et al., 2012); the deeper erosional surface corresponds to the intra-Eocene unconformity. Pont – Pontian, Eo – Eocene, K – Cretaceous. For location of this and other lines see Figure 2.

Figure 4. **A**. Geological interpretation of seismic line BS-20. The Messinian erosion surface is well expressed. The Maykopian seismocomplex is characterized by a number of channel features. We suggest that transport of clastic material was from the Thrace Basin in the Balkans. Turbidite fans are interpreted at the uppermost part of the Eocene sequence, which originated possibly from an uplift of the Western Pontides (Istanbul Terrane) and Balkanides. Half-graben like structures are likely present at the base of the sedimentary

sequence. A rift-related origin of the basin is most probable (Finetti et al., 1988; Robinson et al., 1996; Nikishin et al., 2003, 2012). Pli – Pliocene, Q – Quaternary, Mio – Miocene, Apt – Aptian, San – Santonian, Maa – Maastrichtian. **B**. Un-interpreted window of the seismic section.

Figure 5. **A**. Geological interpretation of seismic line BS-30. The Romanian Shelf is characterized by a thick Oligocene to Recent sedimentary sequence. Late Eocene to Oligocene inversion structures (Dinu et al., 2005; Munteanu et al., 2011) are clearly recognizable. The Polshkov Ridge is bounded to the northwest by possible normal or transtensional faults of Oligocene age. A large Upper Eocene turbidite unit was possibly fed by the uplift of the Western Pontides (Istanbul Terrane). The Western Black Sea Basin has a general asymmetric geometry; the southern slope is very steep while the northern slope is gentler and have some internal steps. **B**. Geological interpretation of seismic line BS-40. The leveed channel complex of the distal Danube fan-delta (Lericolais et al., 2010; Munteanu et al., 2012) is well recognizable. The Histria Basin in the Romanian Shelf has a complicated structure including gravity-driven thrusting and folding. A large turbidite unit is seen at the Upper Eocene level, possibly related with the Late Eocene uplift of the Western Pontides (Istanbul Terrane). A considerable part of the top of the acoustic basement in the basin has a characteristic hummocky surface with lense-shaped sediment infill. Such relief is probably caused by extension of the lithosphere and irregular filling of linear zones with volcanic material. The general asymmetry of the basin is well expressed: the southern slope is steep and the northern slope is much gentler.

Figure 6. Geological interpretation of seismic line BS-50. The leveed channel complex of the distal Danube fan system is distinctly recognizable. The Late Pontian unit is interpreted as a sequence deposited immediately after the Messinian erosion event. The Karkinit Basin is a rifted basin partly inverted during the Late Eocene to Oligocene time.

Figure 7. Geological interpretation of seismic line BS-60. The Lomonosov Slope consisting of Albian, Middle Jurassic and possible Paleozoic and older rocks (Shnyukov et al., 1997) is a basement for the Black Sea sedimentary cover. Middle Jurassic (Bajocian) age (168±1.7 Ma) of volcanics was recently obtained using zircon dating (Shnyukova, 2013). Based on this seismic line, we identify the Sevastopol Swell as a Neogene structure possibly originating from transpressional movements along the former rifted passive margin.

Figure 8. Geological interpretation of seismic line BS-70. The Andrusov-Tetyaev Ridge is a continental block. The Sorokin Trough is the Maykopian flexural foredeep basin for the South Crimea Orogen. The Andrusov-Tetyaev Ridge it tilted toward the Sorokin Trough as a peripheral bulge. The Sorokin Trough was folded during Neogene times. The fold structure is bounded by detachment surfaces at the bottom of the Maykop sequence.

Figure 9. **A**. Geological interpretation of seismic line BS-80. The main features of the Black Sea Basins are well recognizable on this line. The Eastern Black Sea is a rifted Cretaceous basin. Details of the synrift geometry are not seen clearly on this line. The postrift sequence could be subdivided into a few units. The Western Black Sea Basin is similar to the Eastern basin, but here also the synrift structures are not seen in details. The Andrusov Ridge is a typical continental terrane with a sedimentary cover consisting of synrift and postrift sequences. The Andrusov and Shatsky ridges are very similar with respect to the basement and pre-Maykopian deposits. The Shatsky Ridge was tilted during the Oligocene as a peripheral bulge for the Maykopian Tuapse flexural foredeep basin. Post-Maykopian deposits commonly cover all the Black Sea Basins. The Shatsky and Andrusov ridges experienced marine sedimentation during Maykopian times, without any evidence of erosion. **B**. Geological interpretation of seismic line BS-90. A seismic reflector, possibly corresponding to the Moho is identified on this line. Seismic thickness

of the oceanic crust is about 3-4 seconds. Rifted structure with Early Cretaceous normal faults is typical for the Shatsky and Andrusov ridges. The Tuapse Trough looks like a classical Maykopian flexural foredeep basin.

Figure 10. **A**. Geological interpretation of seismic line BS-100. The Eastern Black Sea looks like a nearly symmetric rift basin. **B**. Geological interpretation of seismic line BS-110. Top of the crustal basement in the central part of the Eastern Black Sea Basin has a hummocky structure, possibly indicating the presence of volcanic bodies or tilted fault blocks. We interpret this surface as marking the top of the oceanic crust. A large mountain-like buried structure is located close to the Arkhangelsky Ridge, which is also recognized perpendicularly on seismic line BS-170 (Fig. 13). On both lines the geometry of the structure is a cone-like buried mountain, leading us to interpret it as a Late Cretaceous volcano, with its base resting within postrift deposits. The volcano shows no signs of erosion features at its top, and it is buried by sediments of possible Eocene age. We conclude that the volcano originated in a deep-water Late Cretaceous basin, where water depth could be in excess of 2-3km (1.5 seconds seismic time). The volcano is located slightly to the north of the Pontides Cretaceous volcanic belt in Turkey.

Figure 11. Geological interpretation of seismic line BS-120. Two possible Late Cretaceous volcanoes could be interpreted in this line; they are located in the Trabzon Basin not far from the Pontide Cretaceous volcanic belt.

Figure 12. **A**. Geological interpretation of seismic line BS-150. The Western Black Sea is an asymmetric rift basin. The Romanian Shelf has a thick sedimentary sequence. Late Eocene to Oligocene inversion structures are typical for this shelf. A buried possible Cretaceous volcano and a Neogene to Recent leveed channel complex are also distinguishable on this line. **B**. Geological interpretation of seismic line BS-140. This line crosses the East-Moesian Trough and the Polshkov Ridge in the Bulgarian sector of the

Black Sea. A deeply buried Cretaceous volcano is mapped on the rifted continental crust of the Turkish sector. A turbidite fan fed by the Western Pontides is tentatively interpreted at the upper part of the Eocene sequence. The Western Pontides were folded and thrusted toward the Black Sea during Late Eocene to Early Oligocene times (Okay et al., 2001; Sunal and Tüysüz, 2002; Cavazza et al., 2011). This fold and thrust belt is separated by a detachment surface at the bottom (Sunal and Tüysüz, 2002). We cannot see this fold and thrust structure on our seismic lines but the Maykopian deposits cover this fold and thrust belt and the proposed detachment surface.

Figure 13. Geological interpretation of seismic line BS-170. The Andrusov Ridge is made up of a large continental block. Early Cretaceous half-grabens and normal faults are clearly identifiable. In our interpretation, the postrift cover consists of Upper Cretaceous sediments. The Ordu High is a continental block with no identifiable Mesozoic sedimentary cover.

Figure 14. Geological interpretation of seismic line BS-180. This line follows the axis of the Eastern Black Sea Basin. The North Black Sea High, one of the highest uplifts of the Shatsky Ridge, was a tilted block during Maykopian times and acted as a peripheral bulge simultaneously for the Sorokin and Tuapse foredeep flexural basins. The Ordu-Pitsunda Flexure separates the Eastern Black Sea and the Trabzon basins. The Gurian Trough has no anomalously thick Maykopian deposits as compared with the Tuapse and Sorokin troughs. The Gurian Trough is possibly Miocene in age and it is not analogous to the Tuapse and Sorokin troughs.

Figure 15. Geological interpretation of seismic line BS-190. The profile follows the axis of the Shatsky Ridge. The northern part of the Shatsky ridge is different from its southern part. The large South Adler platform characterizes its southern part; it is likely composed of Upper Jurassic to Eocene shallow marine carbonates. Large Late Jurassic carbonate

build-ups are recognized on the northern part of the Shatsky Ridge (Afanasenkov et al., 2007; Nikishin et al., 2012). J3 – Upper Jurassic.

Figure 16. Geological interpretation of seismic line BS-200. The profile originates in the Tuapse Trough, crosses the Shatsky Ridge and the Eastern Black Sea Basin, the Andrusov and Archangelsky ridges and terminates in the Sinop Graben of the Western Black Sea Basin. The Shatsky Ridge has Early Cretaceous graben-like structures. One of these structures is characterized by hummocky seismic facies (see zoomed-in fragment of the profile within the inset). Height of some hummocks is up to 0.2-0.4 sec. The corresponding regional stratigraphic level of this hummocky facies is approximately Albian. We therefore propose that these are volcanic edifices of Albian age. Albian aged volcanoes are known from the Karkinit Graben in the Odessa Shelf and southern Crimea (Nikishin et al., 2012, 2013). The Arkhangelsky Ridge and the Andrusov Ridge are separated by Early Cretaceous half-graben. The Andrusov Ridge has a thick Mesozoic sedimentary cover but the Arkhangelsky Ridge is devoid of it. The Arkhangelsky Ridge possibly has Cretaceous volcanics similar to the Pontides volcanic arc in Turkey.

Figure 17. Geological interpretation of seismic line BS-222 (above) and seismic velocities along the same line (below). A sizeable mountain-like feature can be recognized at bottom of the layered sedimentary sequence. This structure has a positive seismic velocity anomaly indicating dense rock origin of the structure; we interpret this feature as a likely Cretaceous volcano. The volcano was not eroded and its height is up to 2.5 seconds, indicating a Late Cretaceous water depth in excess of 2-3 km. The volcano was buried by sediments later, during the Eocene. This hypothetical volcano is not mud volcano as was proposed by Graham et al. (2013).

Figure 18. Geological interpretation of seismic line BS-230. Some graben-like structures are seen below the post-rift regional cover. A large sedimentary wedge of approximately

Paleocene-Eocene age (pre-Maykopian) is seen close to the Bulgarian Shelf; it is interpreted as a flexural foredeep basin. This basin is probably the offshore continuation of the Kamchia Foredeep Basin of Late Paleocene-Middle Eocene age, well described in Bulgaria (Tari et al., 2009; Stuart et al., 2011; Georgiev, 2012). Large leveed channel complexes are seen between the Bulgarian and the Crimea continental slopes. The base of this complex lies close to Miocene/Pliocene boundary; according to the interpretation of this seismic line, the origin of the Danube Delta is close to the Messinian erosion event.

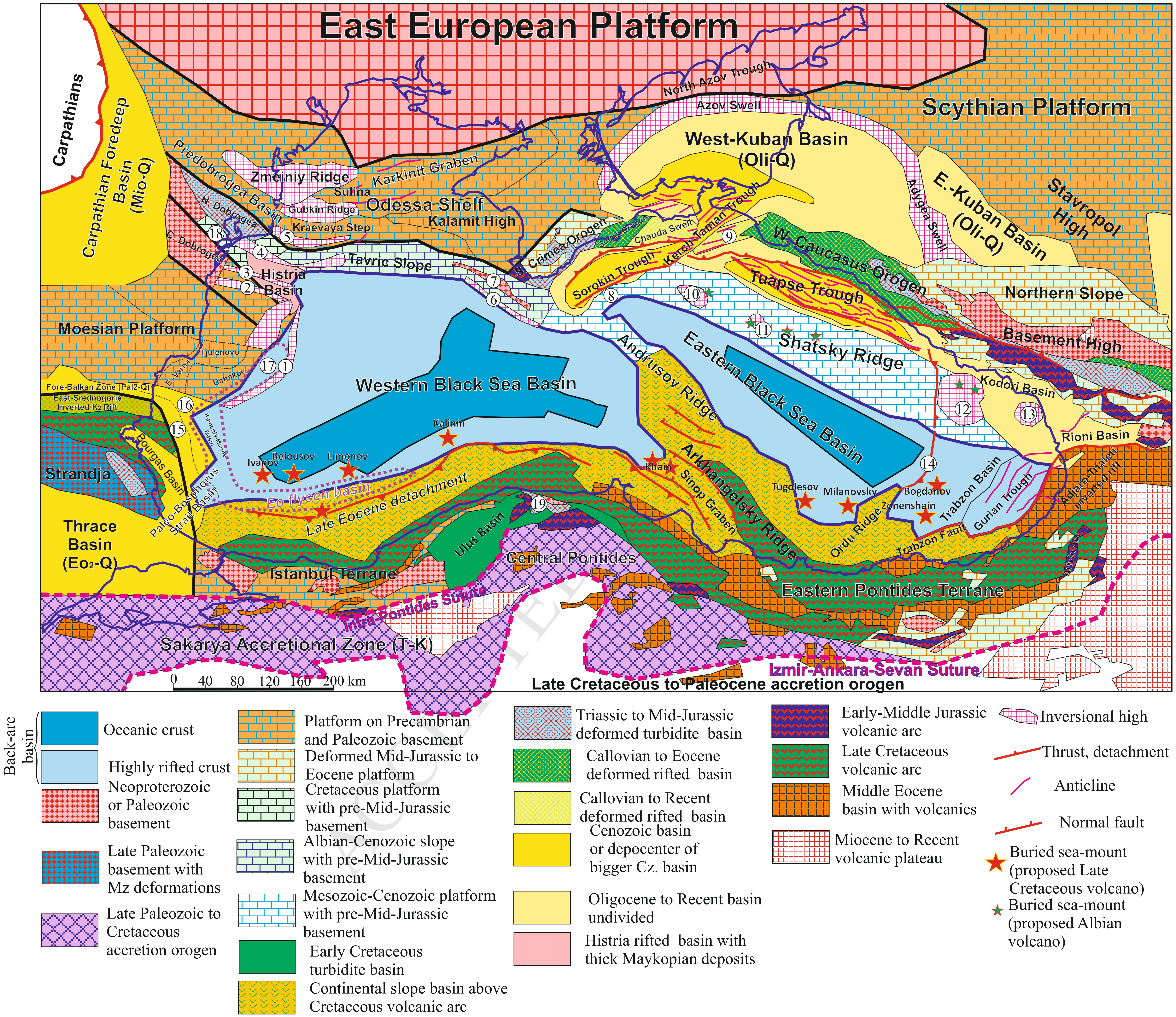
Figure 19. Geological interpretation of seismic line BS-240. This line shows the structure of the Histria Basin, which was effected by inversion tectonics during the Late Eocene to Oligocene. It was rapidly filled by Maykopian to Recent deposits.

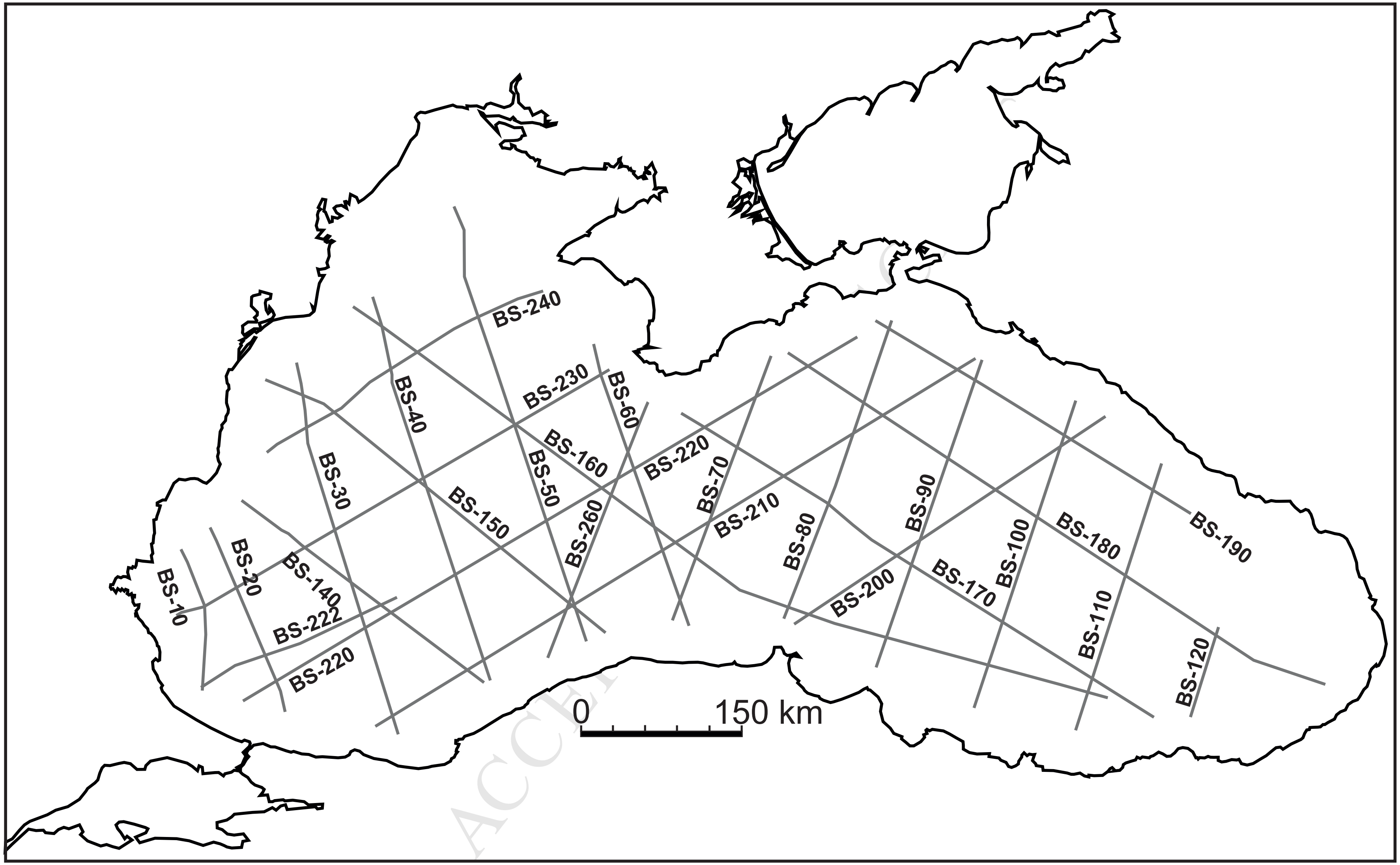
Figure 20. Geological interpretation of seismic line BS-260. This line shows some structure of the Western Black Sea Basin. The Sevastopol Swell possibly corresponds to a transpressional structure. A recent, active mud volcano is recognized as a positive structure on the sea bed; at depth, a buried mud volcano system is seen, with roots in the Maykopian stratigraphic level.

Figure 21. Basement topography of the Black Sea Basin. This map is based mainly on data from the new seismic lines.

Figure 22. Areas of the Black Sea with different crustal types. The map is based on the interpretation of basement topography features discussed in this paper.

Tectonic Scheme of Black Sea Region




BS-240
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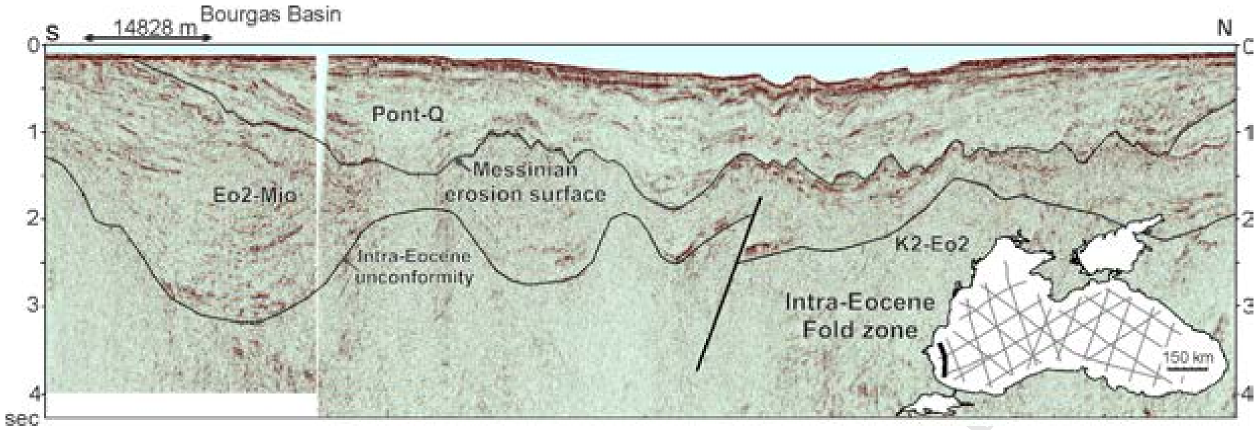
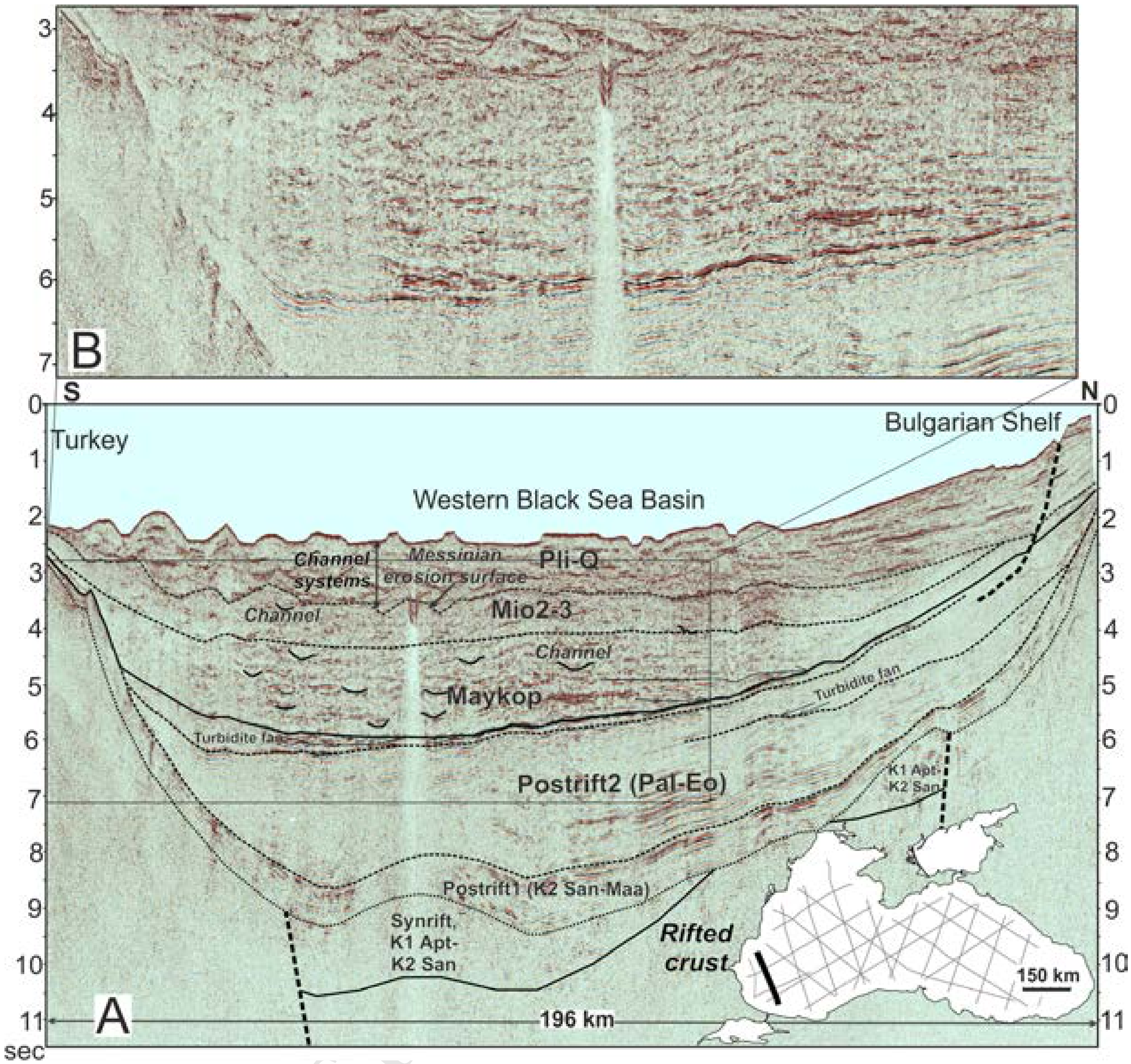
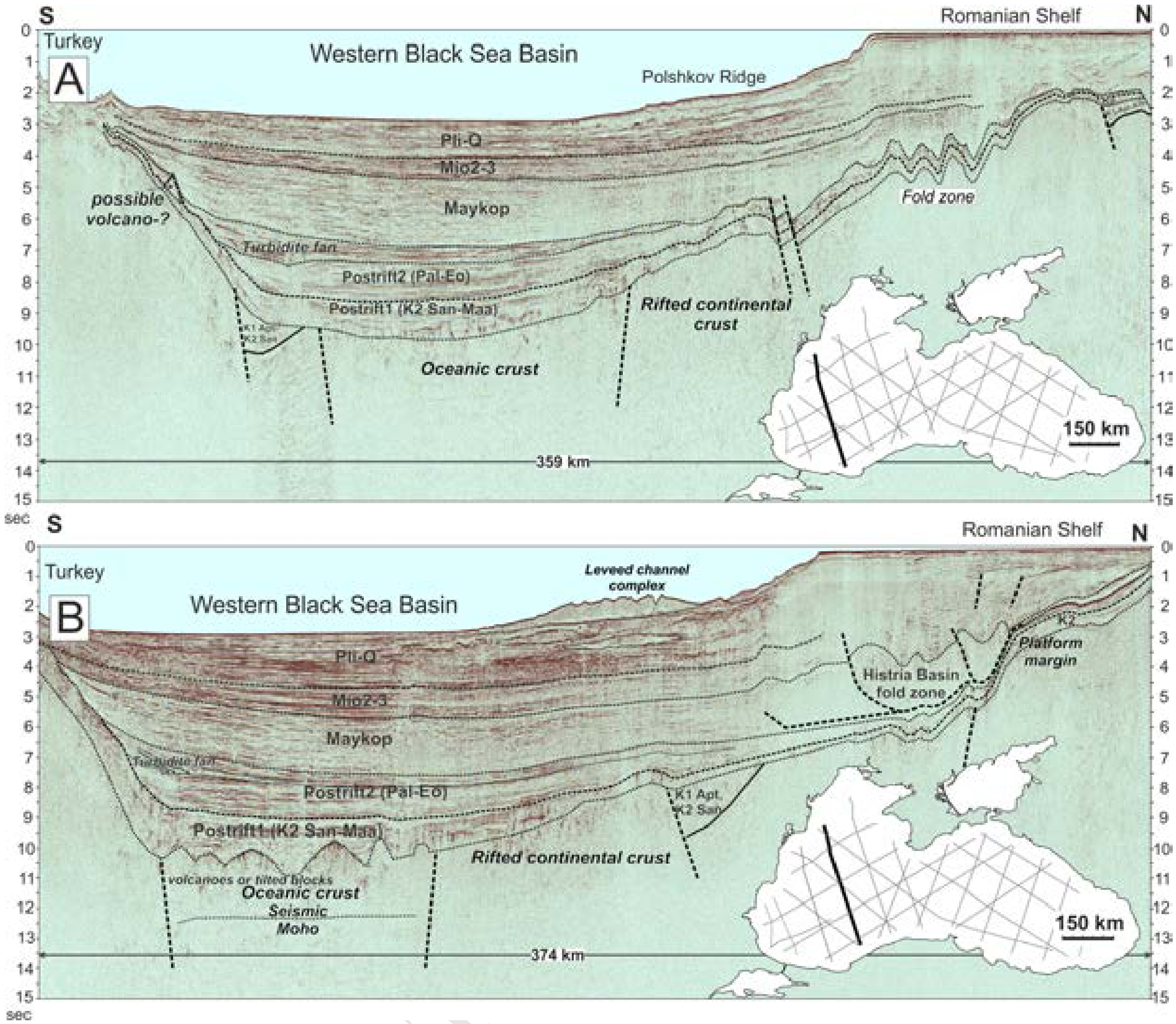
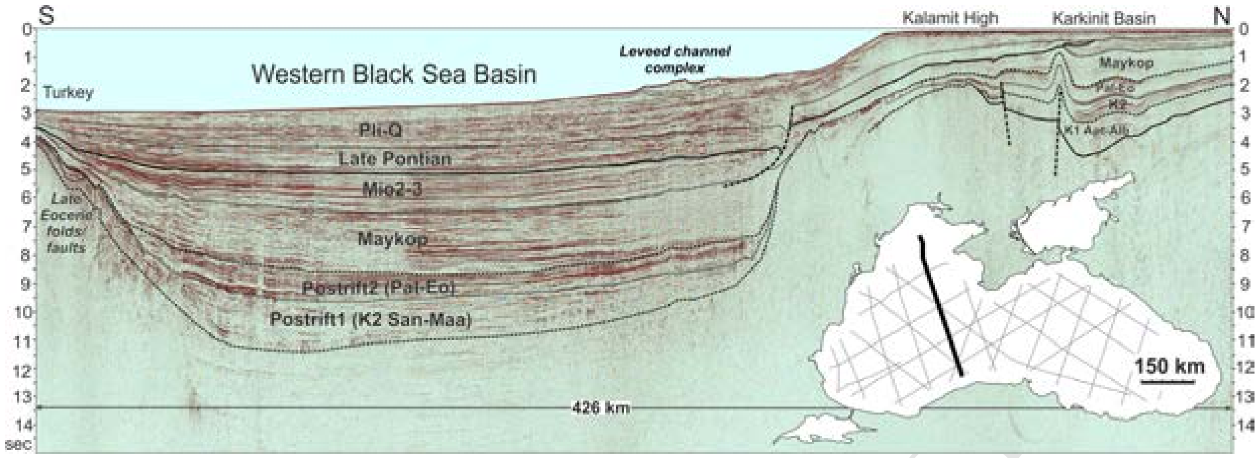
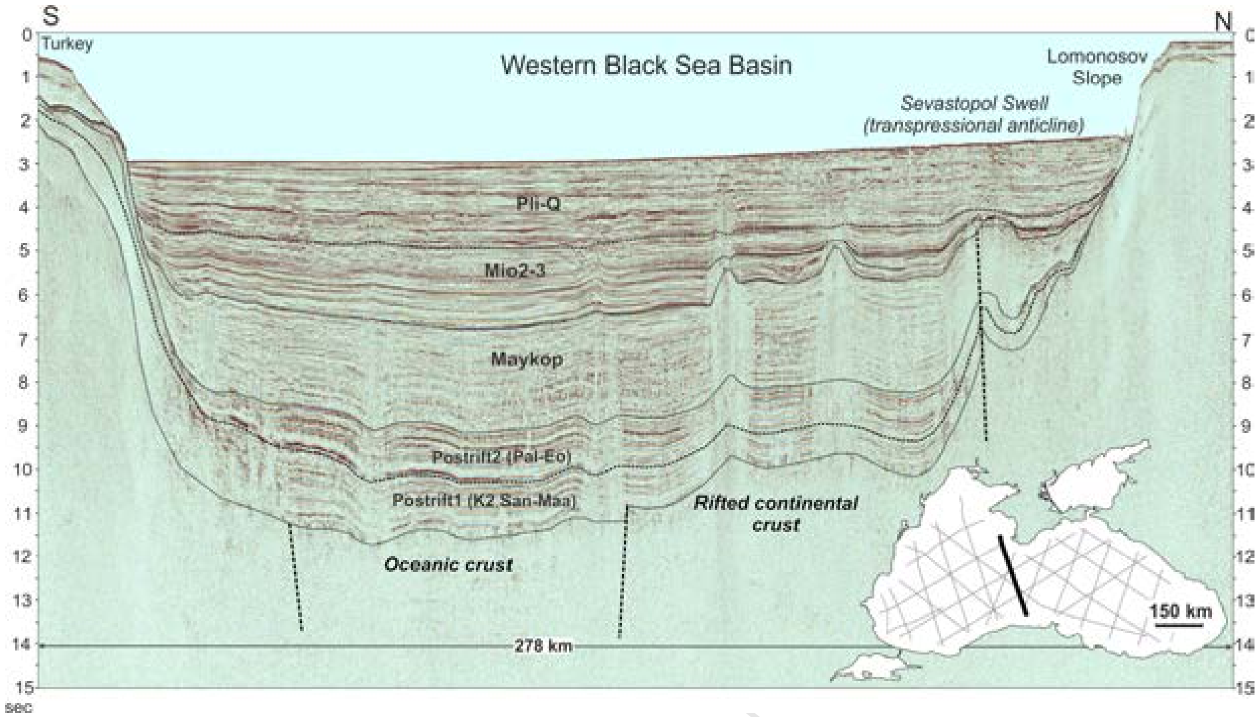
BS-150
BS-210
BS-260
BS-90
BS-80
BS-180
BS-190
BS-100
BS-10
BS-20
BS-140
BS-200
BS-170
BS-222
BS-110
BS-220
BS-120
0
150 km

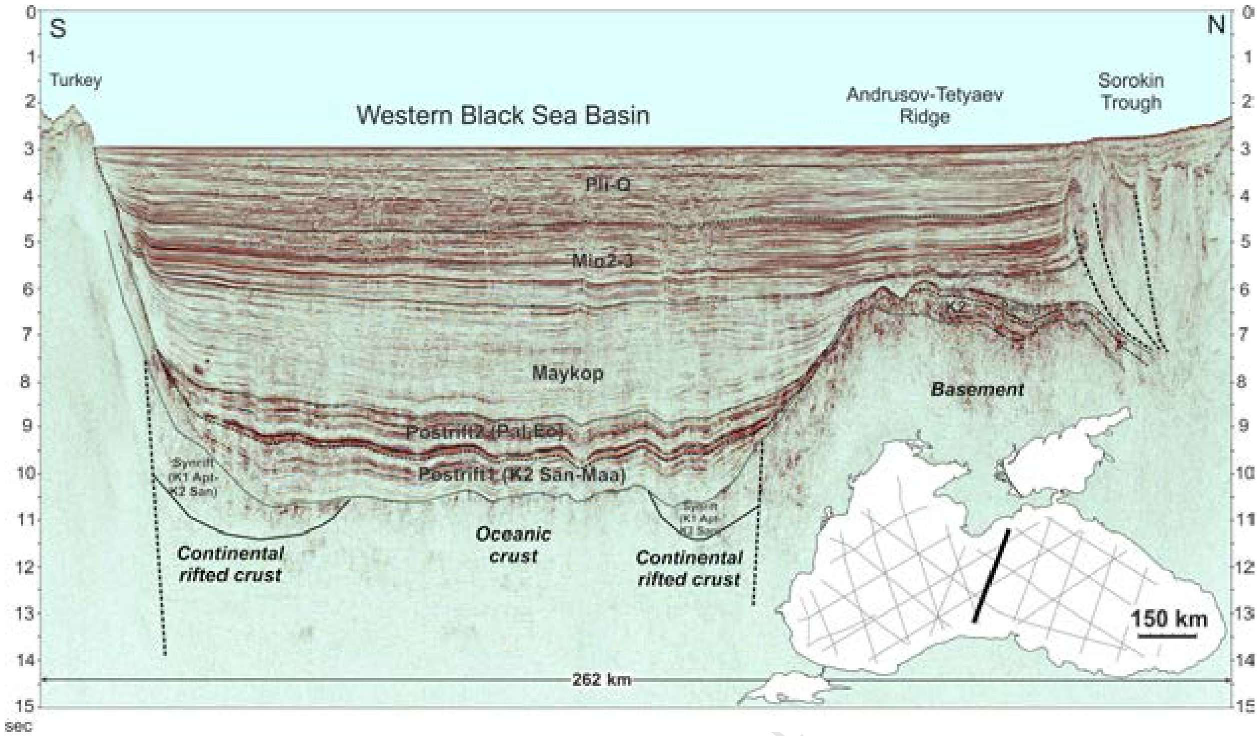

S
N
14828 m
Bourgas Basin
0
1
2
3
4
sec
Pont-Q
Eo2-Mio
Messinian
erosion surface
Intra-Eocene
unconformity
K2-Eo2
Intra-Eocene
Fold zone
150 km

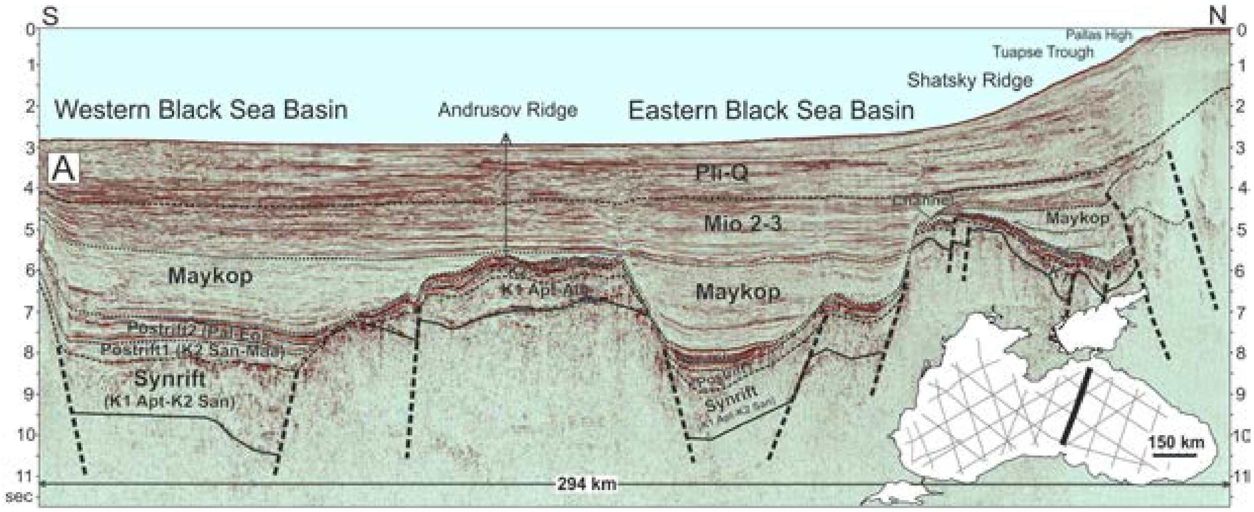

B
S
N
Turkey
Bulgarian Shelf
Western Black Sea Basin
Channel systems
Messinian erosion surface
Pli-Q
Mio2-3
Channel
Channel
Maykop
Turbidite fan
Turbidite fan
Postrift2 (Pal-Eo)
K1 Apt-K2 San
Postrift1 (K2 San-Maa)
Synrift, K1 Apt-K2 San
Rifted crust
150 km
A
196 km
sec

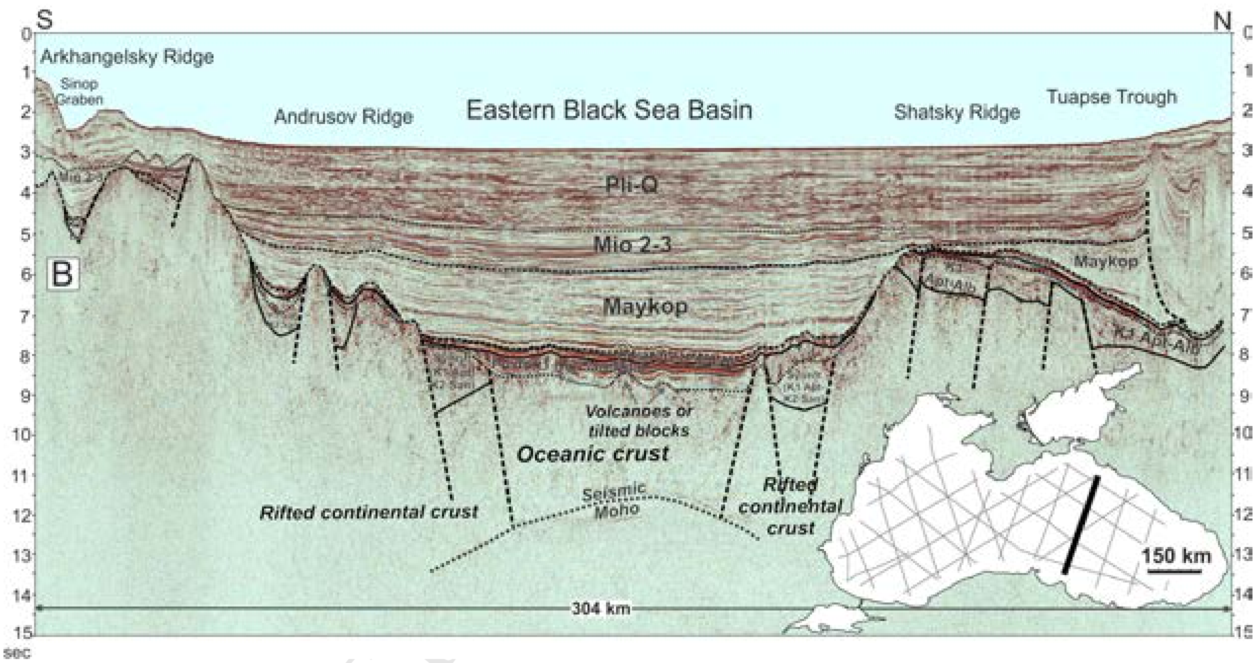

S
N
Romanian Shelf
Turkey
A
Western Black Sea Basin
Polshkov Ridge
Pli-Q
Mio2-3
possible
volcano-?
Maykop
Fold zone
Turbidite fan
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Rifted continental
crust
Oceanic crust
150 km
359 km
sec
B
Leveed channel
complex
Platform
margin
Histria Basin
fold zone
K1 Apt,
K2 San
Rifted continental crust
volcanoes or tilted blocks
Oceanic crust
Seismic
Moho
374 km

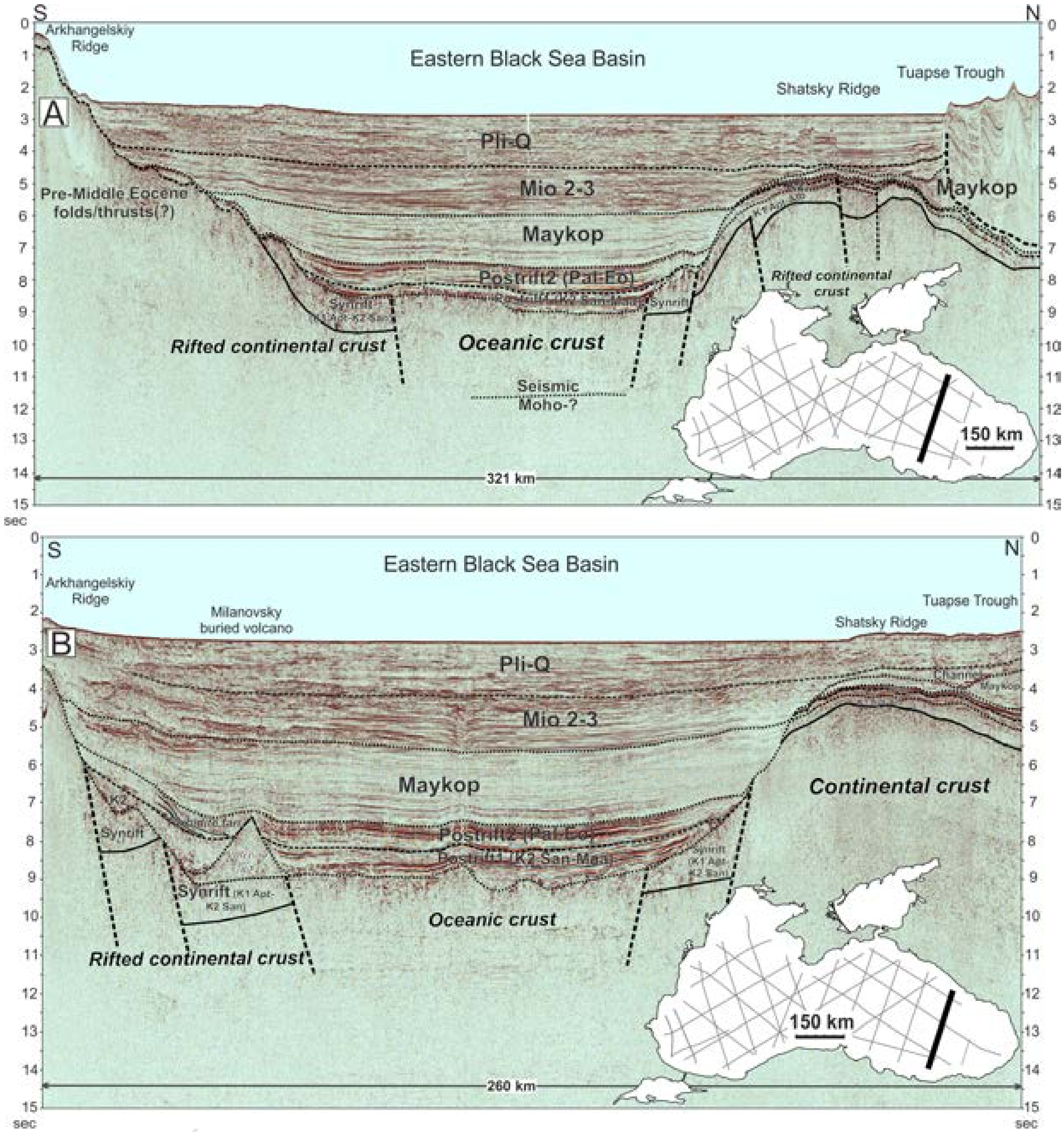

S
N
Western Black Sea Basin
Turkey
Leveed channel complex
Kalamit High
Karkinit Basin
Pli-Q
Late Pontian
Mio2-3
Maykop
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Late Eocene folds/ faults
Maykop
Pal-Eo
K2
K1 Apt-Alb
426 km
150 km
sec


S
N
Turkey
Western Black Sea Basin
Lomonosov Slope
Sevastopol Swell (transpressional anticline)
Pli-Q
Mio2-3
Maykop
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Rifted continental crust
Oceanic crust
278 km
150 km
sec

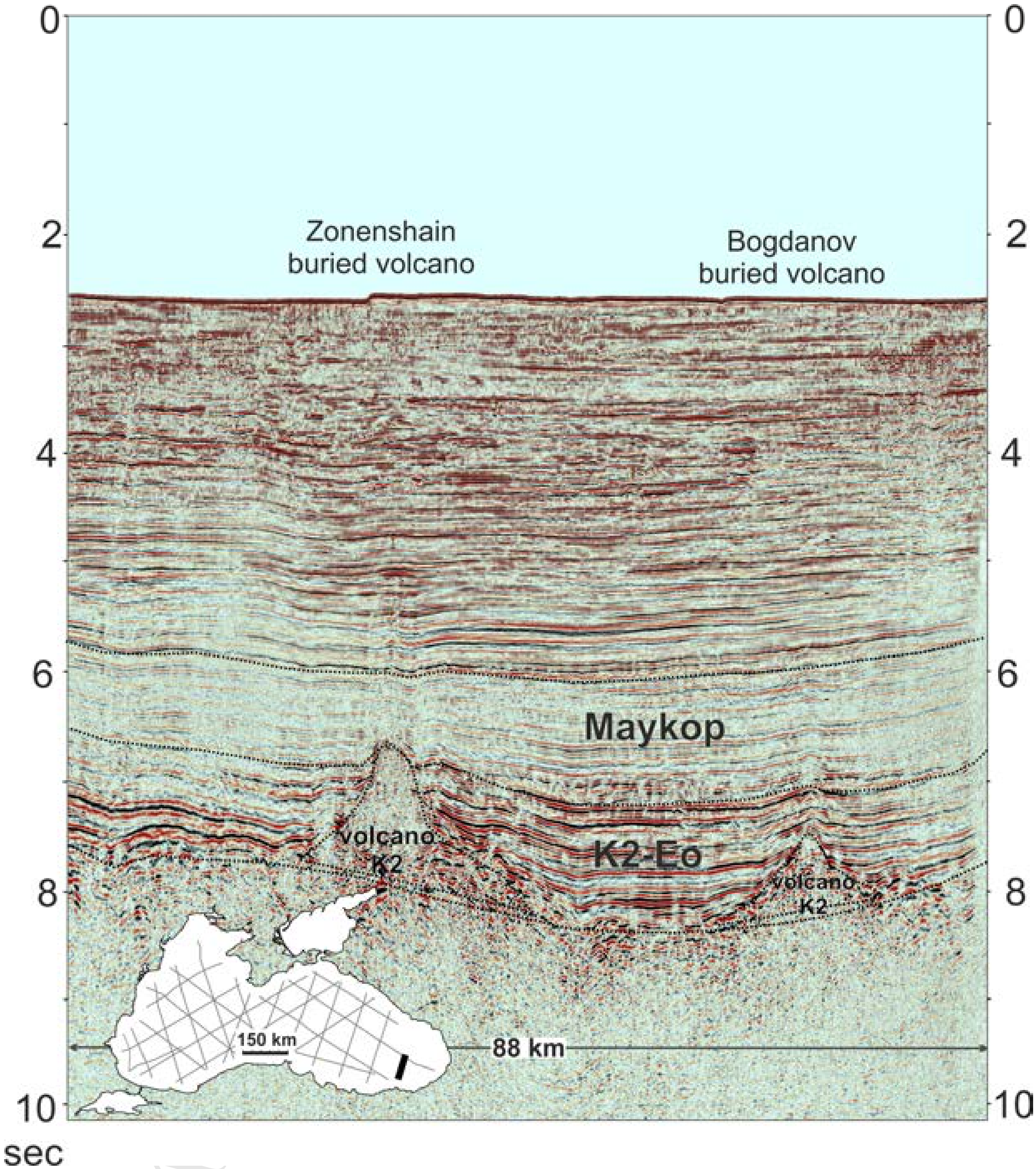

S
N
Turkey
Western Black Sea Basin
Andrusov-Tetyaev
Ridge
Sorokin
Trough
Pli-Q
Mio2-3
K2
Maykop
Basement
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Synrift
(K1 Apt-
K2 San)
Continental
rifted crust
Oceanic
crust
Continental
rifted crust
150 km
262 km
sec


S
N
Western Black Sea Basin
Andrusov Ridge
Eastern Black Sea Basin
Shatsky Ridge
Tuapse Trough
Pallas High
A
Pli-Q
Mio 2-3
Maykop
Channel
K1 Apt-Alb
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Synrift
(K1 Apt-K2 San)
150 km
294 km
sec

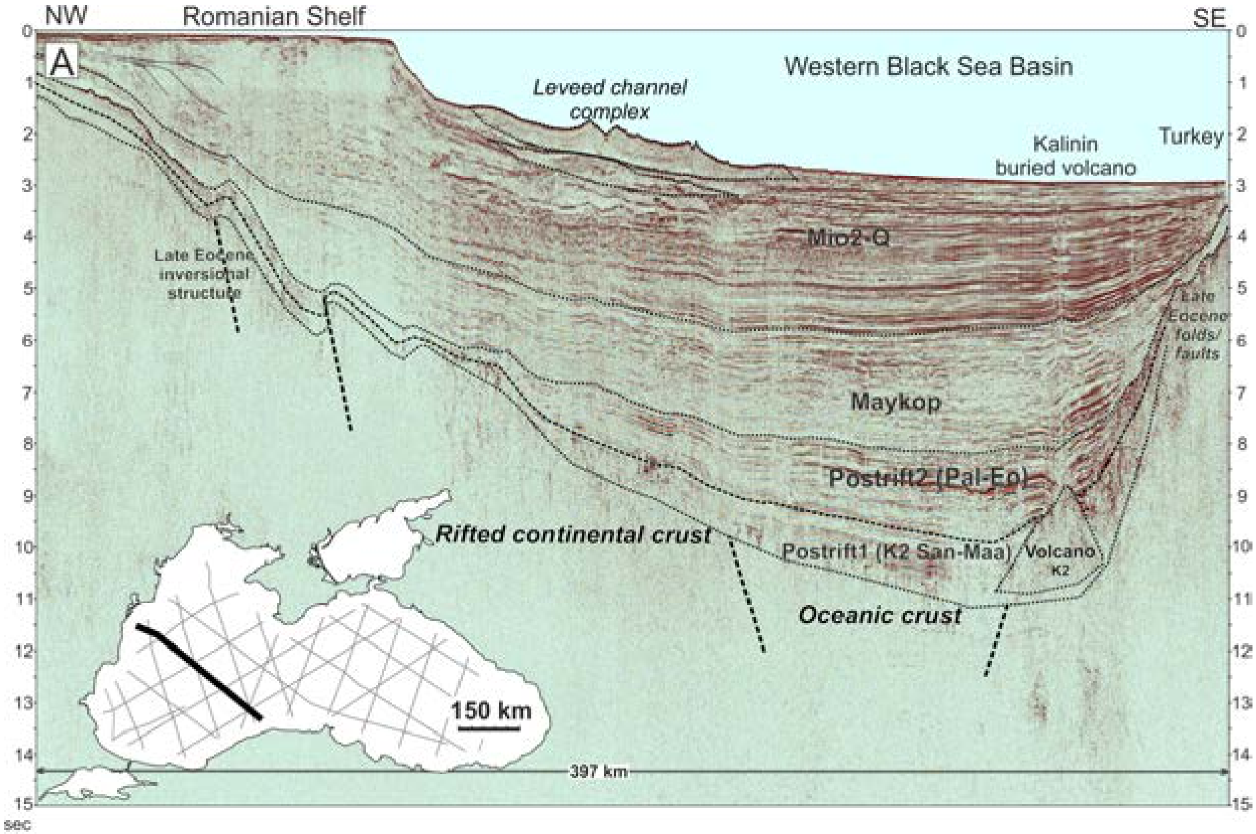

S
N
Arkhangelsky Ridge
Sinop Graben
Andrusov Ridge
Eastern Black Sea Basin
Shatsky Ridge
Tuapse Trough
B
Pli-Q
Mio 2-3
Maykop
K1 Apt-Alb
Volcanoes or tilted blocks
Oceanic crust
Rifted continental crust
Seismic Moho
Rifted continental crust
150 km
304 km
sec



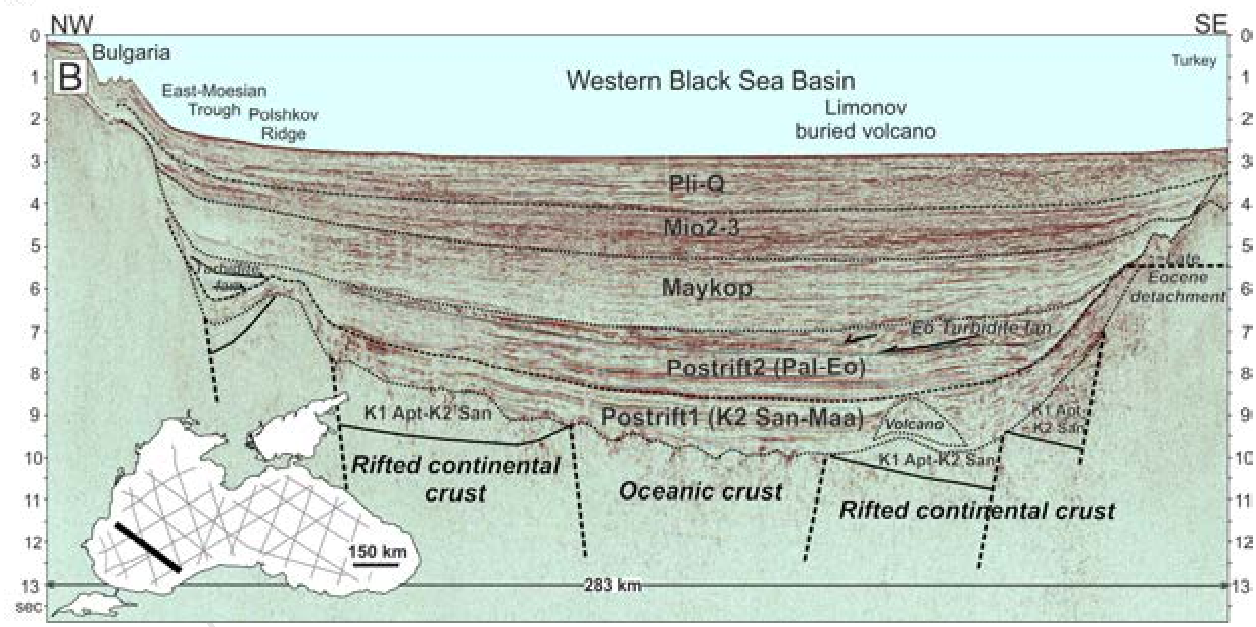
S
N
A
Eastern Black Sea Basin
Arkhangelskiy Ridge
Shatsky Ridge
Tuapse Trough
Pli-Q
Mio 2-3
Maykop
Pre-Middle Eocene folds/thrusts(?)
Postrift2 (Pal-Eo)
Synrift
Rifted continental crust
Oceanic crust
Seismic Moho-?
150 km
321 km
sec
B
Eastern Black Sea Basin
Arkhangelskiy Ridge
Milanovsky buried volcano
Shatsky Ridge
Tuapse Trough
Pli-Q
Mio 2-3
Maykop
Channel
K2
Synrift
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
Synrift (K1 Apt-K2 San)
Continental crust
Oceanic crust
Rifted continental crust
150 km
260 km
sec



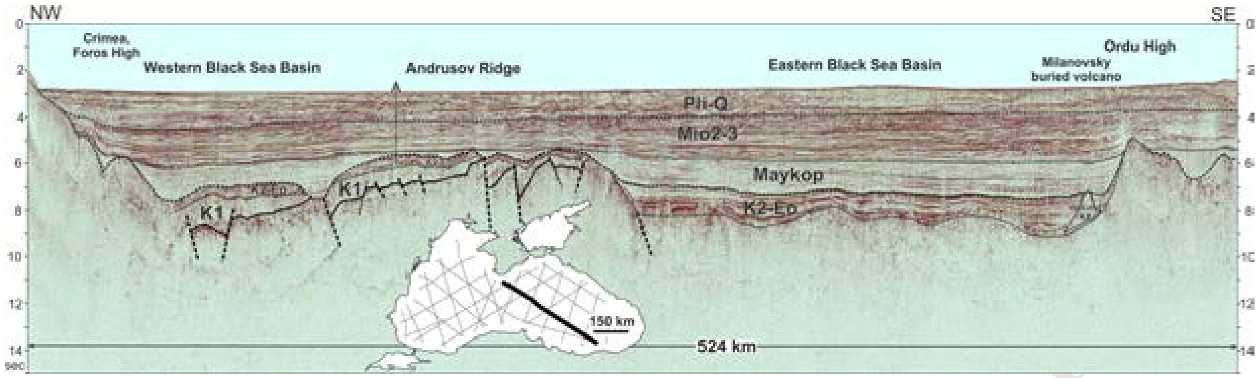
0
2
4
6
8
10
sec
Zonenshain
buried volcano
Bogdanov
buried volcano
Maykop
volcano
K2
K2-Eo
volcano
K2
150 km
88 km

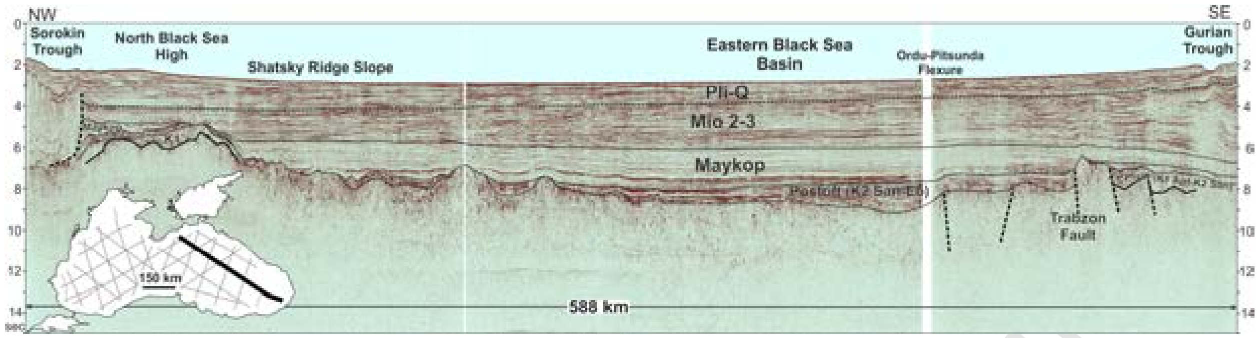


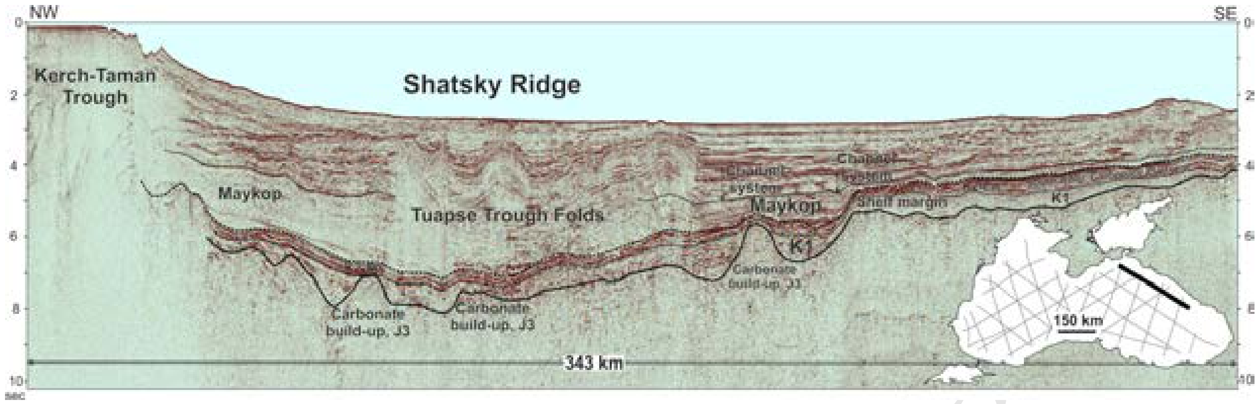
NW
Romanian Shelf
SE
A
Western Black Sea Basin
Leveed channel complex
Kalinin buried volcano
Turkey
Late Eocene inversional structure
Mio2-Q
Late Eocene folds/ faults
Maykop
Postrift2 (Pal-Eo)
Rifted continental crust
Postrift1 (K2 San-Maa)
Volcano K2
Oceanic crust
150 km
397 km
sec



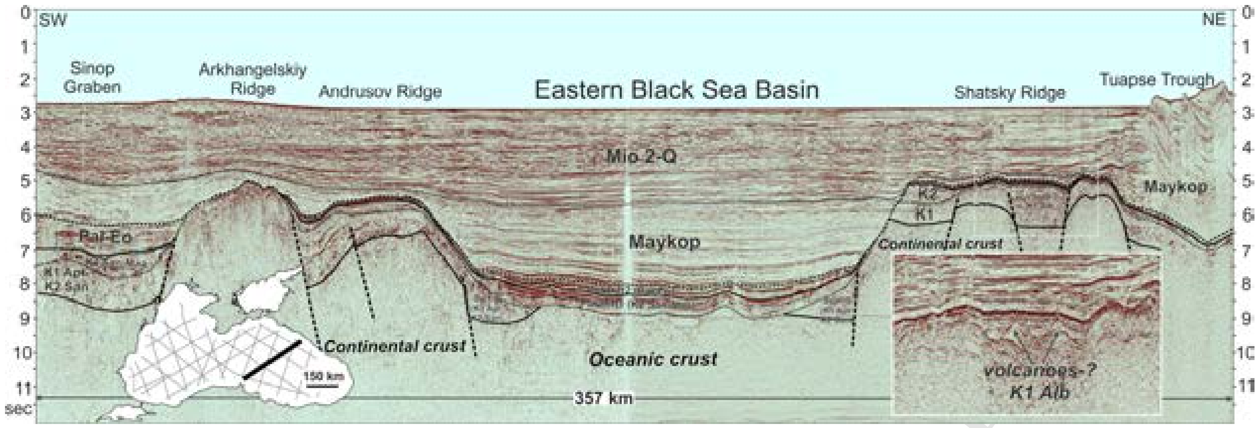
NW
SE
Bulgaria
B
Turkey
Western Black Sea Basin
East-Moesian Trough
Polshkov Ridge
Limonov buried volcano
Pli-Q
Mio2-3
Maykop
Eocene detachment
Eo Turbidite fan
Postrift2 (Pal-Eo)
K1 Apt-K2 San
Postrift1 (K2 San-Maa)
Volcano
K1 Apt-K2 San
Rifted continental crust
Oceanic crust
Rifted continental crust
150 km
283 km
sec


NW
SE
Crimea, Foros High
Western Black Sea Basin
Andrusov Ridge
Eastern Black Sea Basin
Milanovsky buried volcano
Ordu High
Pli-Q
Mio2-3
Maykop
K2-Eo
K1
150 km
524 km
sec

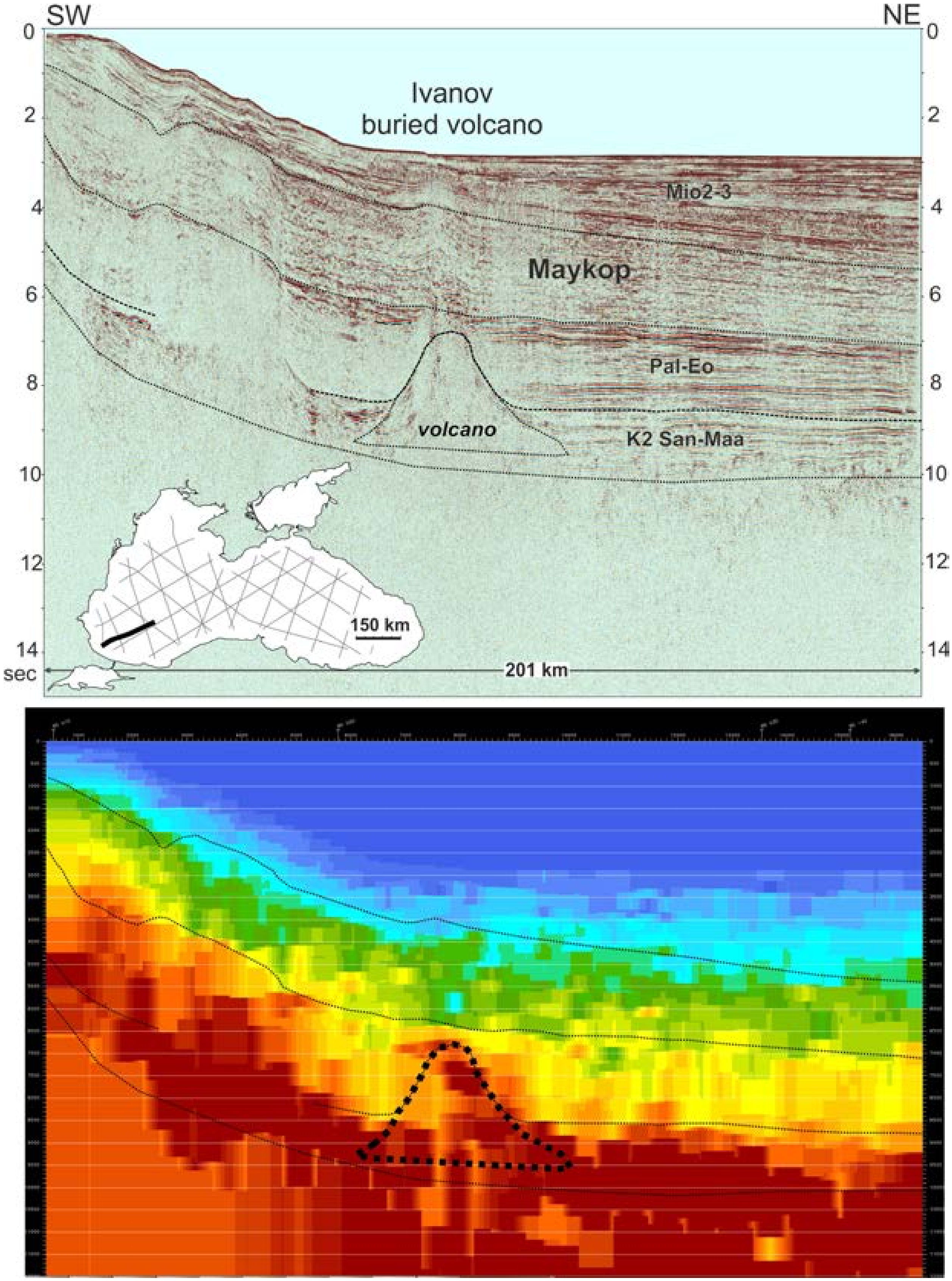

NW
SE
Sorokin Trough
North Black Sea High
Shatsky Ridge Slope
Eastern Black Sea Basin
Ordu-Pitsunda Flexure
Gurian Trough
Pli-Q
Mio 2-3
Maykop
Trabzon Fault
150 km
588 km
0
2
4
6
8
10
12
14

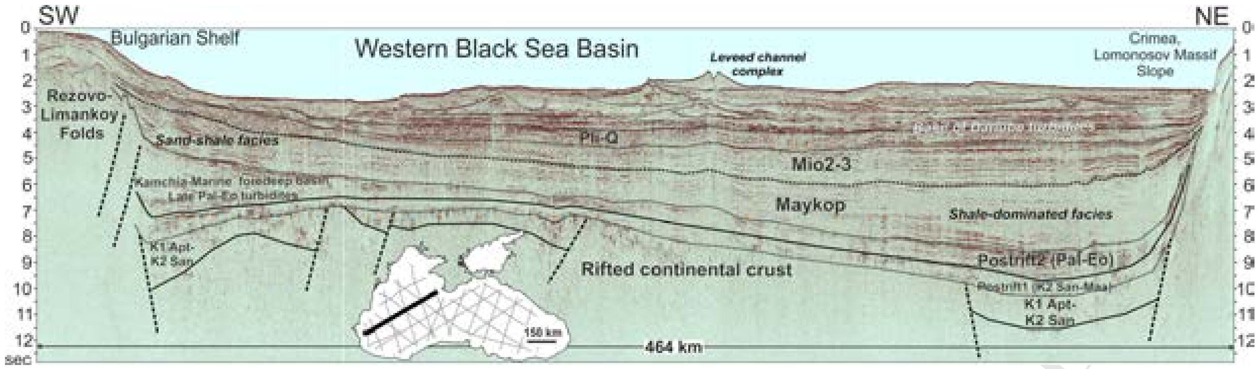


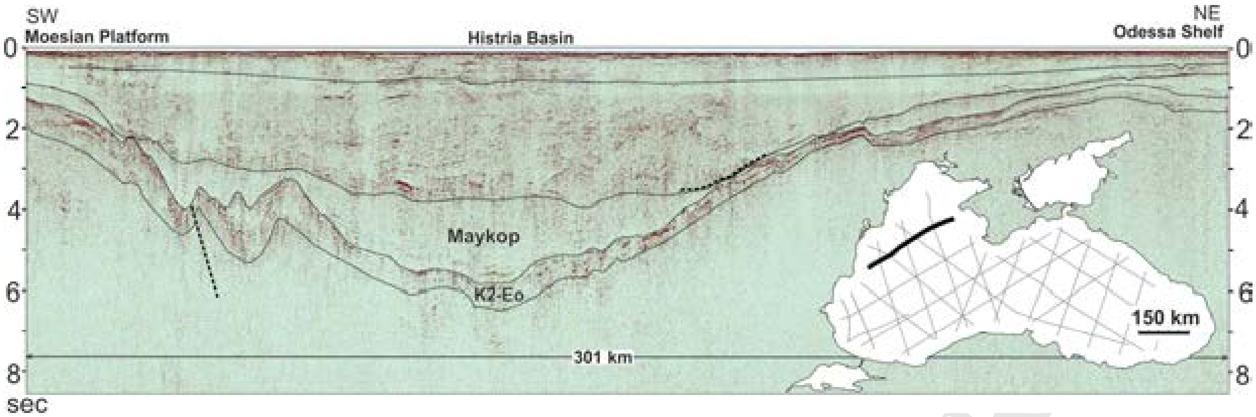
NW
SE
Kerch-Taman Trough
Shatsky Ridge
Maykop
Tuapse Trough Folds
Channel system
Channel system
Maykop
Shelf margin
K1
K1
Carbonate build-up, J3
Carbonate build-up, J3
Carbonate build-up, J3
150 km
343 km
sec

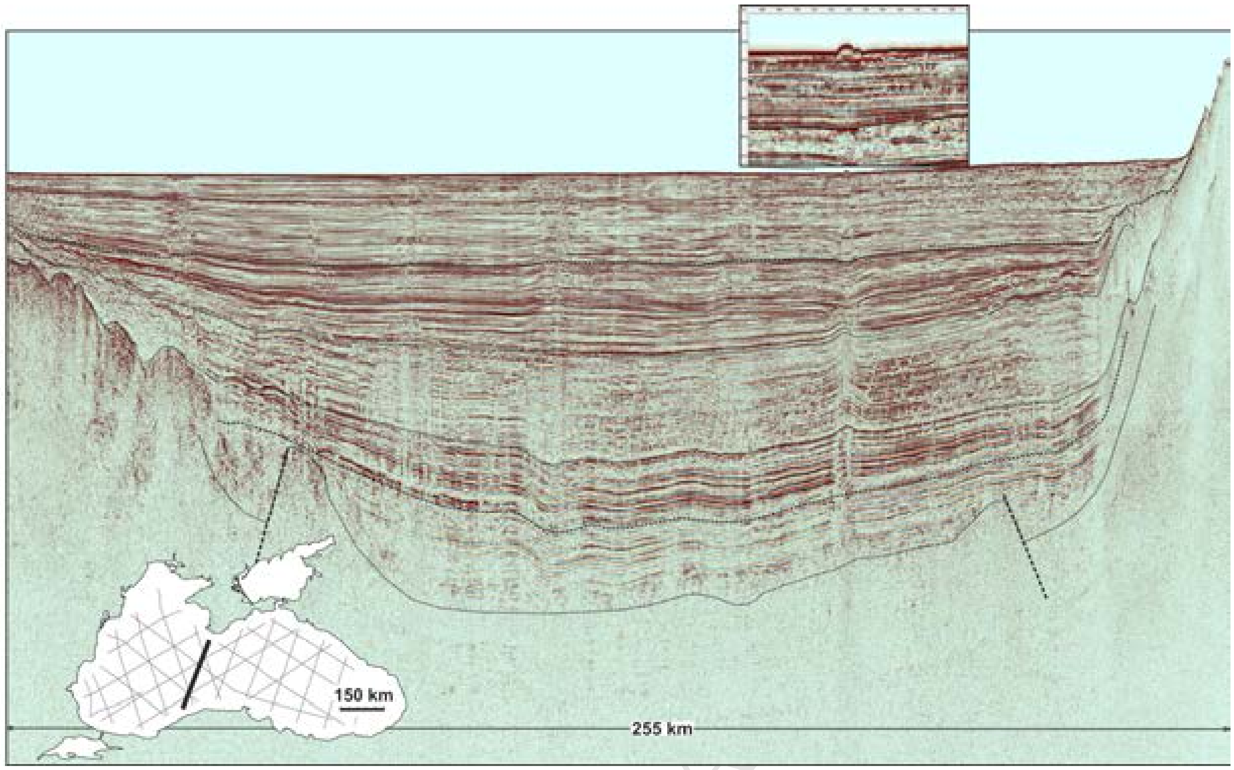


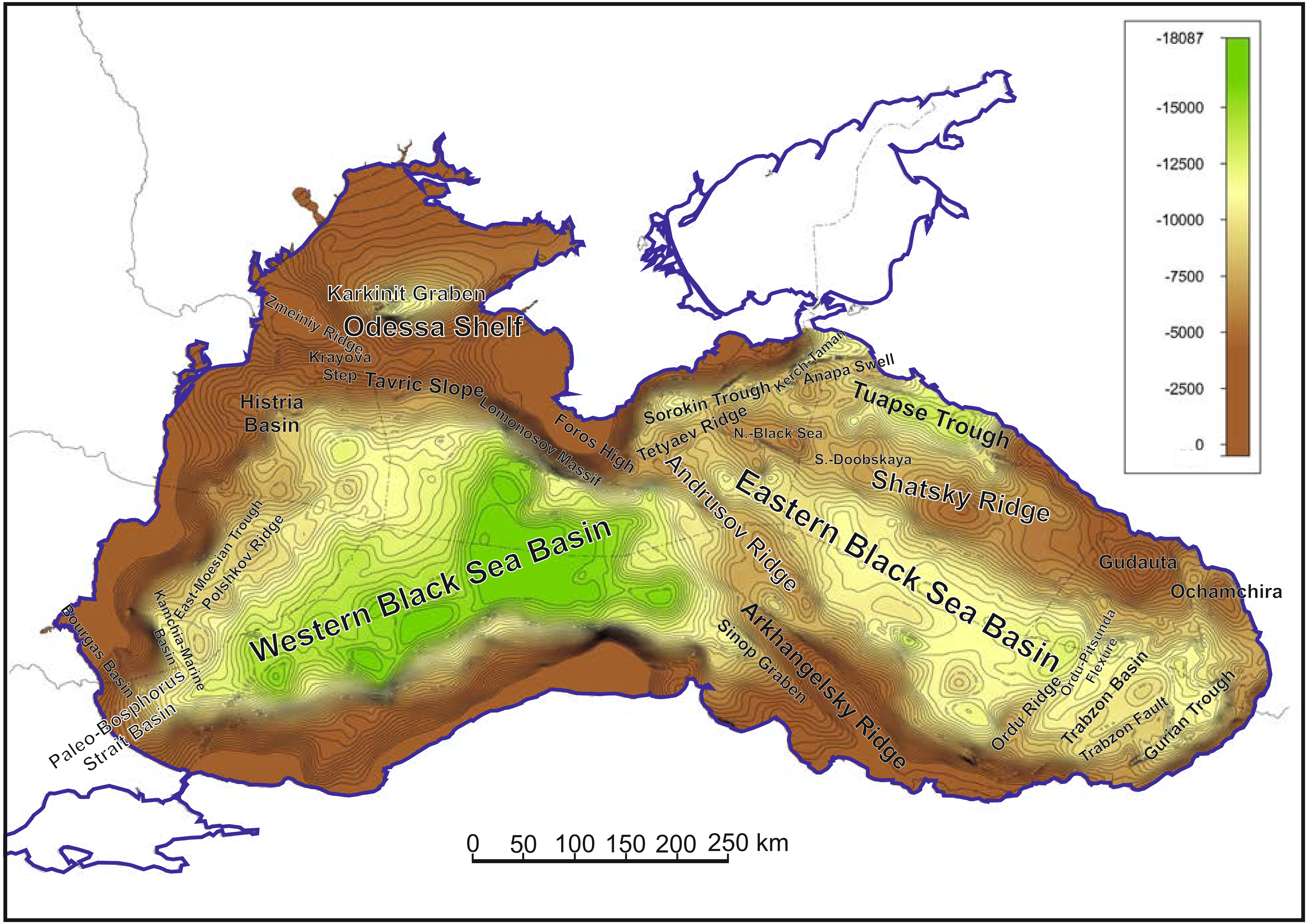
SW
NE
Sinop Graben
Arkhangelskiy Ridge
Andrusov Ridge
Eastern Black Sea Basin
Shatsky Ridge
Tuapse Trough
Mio 2-Q
Maykop
Pal-Eo
K1 Apt
K2 San
K2
K1
Continental crust
Oceanic crust
volcanoes-?
K1 Alb
150 km
357 km
sec

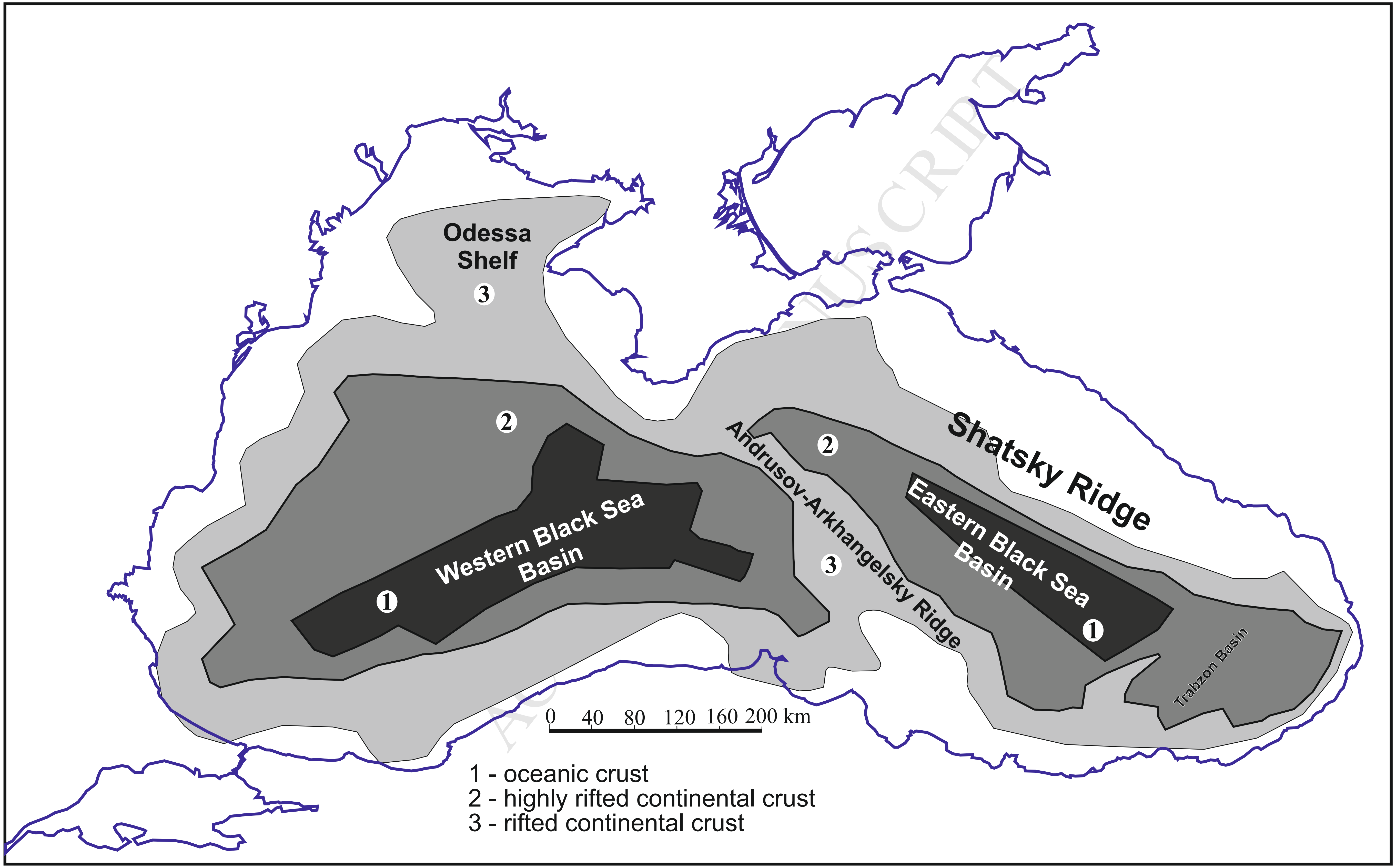

SW
NE
0
2
4
6
8
10
12
14
sec
Ivanov
buried volcano
Mio2-3
Maykop
Pal-Eo
volcano
K2 San-Maa
150 km
201 km


SW
NE
Bulgarian Shelf
Western Black Sea Basin
Leveed channel complex
Crimea, Lomonosov Massif Slope
Rezovo-Limankoy Folds
Sand-shale facies
Pli-Q
Mio2-3
Maykop
Shale-dominated facies
Kamchia-Marine foredeep basin
Late Pal-Eo turbidites
K1 Apt-K2 San
Rifted continental crust
Postrift2 (Pal-Eo)
Postrift1 (K2 San-Maa)
K1 Apt-K2 San
150 km
464 km
0
1
2
3
4
5
6
7
8
9
10
11
12
sec


SW
Moesian Platform
Histria Basin
NE
Odessa Shelf
Maykop
K2-Eo
301 km
150 km
sec
0
2
4
6
8


150 km
255 km


-18087
-15000
-12500
-10000
-7500
-5000
-2500
0
Karkinit Graben
Odessa Shelf
Zmeiniy Ridge
Krayova
Step
Tavric Slope
Lomonosov Massif
Foros High
Histria
Basin
Sorokin Trough
Kerch-Taman
Anapa Swell
Tuapse Trough
Tetyaev Ridge
N.-Black Sea
S.-Doobskaya
Shatsky Ridge
Andrusov Ridge
Eastern Black Sea Basin
Western Black Sea Basin
East-Moesian Trough
Polshkov Ridge
Kamchia-Marine
Basin
Bourgas Basin
Paleo-Bosphorus
Strait Basin
Sinop Graben
Arkhangelsky Ridge
Gudauta
Ochamchira
Ordu-Pitsunda
Flexure
Ordu Ridge
Trabzon Basin
Trabzon Fault
Gurian Trough
0 50 100 150 200 250 km


Odessa
Shelf
3
2
Western Black Sea
Basin
1
Andrusov-Arkhangelsky Ridge
3
2
Shatsky Ridge
Eastern Black Sea
Basin
1
Trabzon Basin
0 40 80 120 160 200 km
1 - oceanic crust
2 - highly rifted continental crust
3 - rifted continental crust

Highlights

- Late Cretaceous buried Peri-Pontides volcanic arc
- Albian buried volcanic belt
- Eocene synorogenic turbidite fans
- Oligocene channelized system