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Deep structure of the Mid Black Sea High (offshore Turkey) imaged by multi-channel seismic survey (BLACKSIS cruise)[1,2]

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Abstract

The Black Sea is considered to be a Mesozoic–Early Cenozoic marginal basin related to the north-dipping subduction of Tethys beneath Europe. However deformation of this basin during the successive Eocene to Neogene collisions of African-derived continental fragments (Kirshehir and Arabian micro plates) remains poorly understood. A multi-channel seismic survey conducted in the central part of the Black Sea has shed light on the superimposed tectonic fabrics of the Central Ridge (the Mid Black Sea High, MBSH) in response to these successive collisions. The MBSH is formed by a series of large NW–SE trending anticlines and synclines, and possible northeast-verging thrusts were identified at the boundary with the deep East Black Sea Basin northeast of the ridge. These buried folds and thrusts, blanketed by 3 to 8 s TWT of undeformed sediments, are interpreted as the offshore extension of the Early Cenozoic tectonic belt resulting from the collision between the Pontides in the north and the Kirshehir block to the south. The offshore part of the belt forming the ridge could have then collapsed when collision ended. Neogene structures also affect the MBSH. A recent graben (the Sinop Trough) extends between this central high and mainland Turkey. This graben could have been formed during the late Miocene incipient dextral strike slip motion of the North Anatolian Fault that was initiated during extrusion of the Anatolian microplate. Active tectonic inversion of deep-seated normal faults present along the Pontides passive margin was also observed along the northeastern flank of the Eastern Pontides. This deformation is the westernmost extension of the Lesser Caucasus front that outlines the suturing of the Eastern Black Sea Basin in easternmost Turkey and in Georgia.

Keywords: Black Sea; tectonics; North Anatolia Fault; collision; multi-channel seismics

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1. Introduction

Collision and amalgamation of continental fragments along the southern margin of the Pontides in North Anatolia occurred from the Eocene to the present time (Şengör, 1979). These collisions post-date the opening of the Black Sea Basin, which was probably opened in a back-arc position from the Early Cretaceous–Paleocene Pontides volcanic arc (Zonenshain et al., 1986; Okay et al., 1994; Robinson et al., 1996).

The Pontides, extending south of these basins in northern Turkey, were intensively shortened and affected by strike-slip faulting during the successive docking and collision episodes of African-derived continental fragments (Kirshehir block and Arabia) with the European active margin. However, the Black Sea Basin remained apparently undeformed and is considered to be the rigid buttress for these successive collisions.

The deformation of this area is here discussed on the basis of new deep multi-channel seismic data collected in the South Central part of the Black Sea Basin, and particularly on the Mid Black Sea High (MBSH) and its transitions to the deep basins. We will show that part of the Early Cenozoic deformation related to the Kirshehir/Pontides collision was partly absorbed in the MBSH. In the current study we also discuss the recent and active deformation related to the Arabia/Europe collision, such as the westward extension of the Lesser Caucasus tectonic front along the MBSH, and the origin of the Sinop Trough, a large graben recently developed along the southwestern flank of the MBSH, and interpreted as the initial stage of tectonic escape of Anatolia along the North Anatolian Fault during the Late Miocene.

2. Active geodynamic setting of the Black Sea

The Black Sea is located on the western flank of the active collision of Arabia with Eurasia (Fig. 1) and north of the North Anatolian Fault (NAF) that permits the tectonic escape of Anatolia (Le Pichon et al., 1995). The Arabia/Eurasia collision of the plate was probably initiated during the middle Miocene (McKenzie, 1970; Şengör et al., 1985; Yılmaz et al., 1993; Jestin et al., 1994), and induced in Anatolia intense shortening from 13 to 6 Ma, along a wide zone extending from Zagros to Eastern Turkey. After this period of intraplate deformation, this block moved westward along the E–W propagating North Anatolian Fault (Şengör et al., 1985). Recent GPS observations (McClusky et al., 2000) illustrate the present rigid anti-clockwise rotation of Anatolia with respect to Eurasia. According to these data, only the easternmost part of the Black Sea is affected by the active N–S shortening related to the Arabia collision (Fig. 1). This deformation decreases rapidly along the Lesser Caucasus tectonic front towards the west along the Eastern Turkey Black Sea shore line. In the collision zone itself, total convergence is estimated by McClusky et al. (2000) to be over 1 cm/yr. The partitioning of shortening between the Lesser Caucasus and the Great Caucasus located on both sides of this collision zone has been estimated by McClusky et al. (2000) to be between 5 and 6 mm/yr along the Great Caucasus front, and between 4 and 5 mm/yr in the Lesser Caucasus southwards.

What are the implications of the present GPS velocity field for the recent geologic evolution of this area? Can we extrapolate these instantaneous shortening rates to the last millions of years. If it is the case, significant deformation could be evidenced along the Black Sea shore line or within the Eastern Basin. How far to the west can this recent and active shortening be evidenced? Is the Black Sea central ridge affected by this deformation?

Concerning the NAF, present detailed geological and seismological descriptions, including estimation of slip rates, age of the current fault, configuration and total fault offsets, have been discussed by Şengör (1979), Barka et al. (1992) and Armijo et al. (1999). The age of the NAF as observed today is constrained to be Early Pliocene (4–5 Ma) with total offsets in the range of 80 to 100 km. According to McClusky et al. (2000) this gives an average geological slip rate of 16 to 25 mm/yr, in good agreement with the GPS upper bound at 24 mm/yr. These authors conclude that the NAF is Pliocene in age, and slip rates along

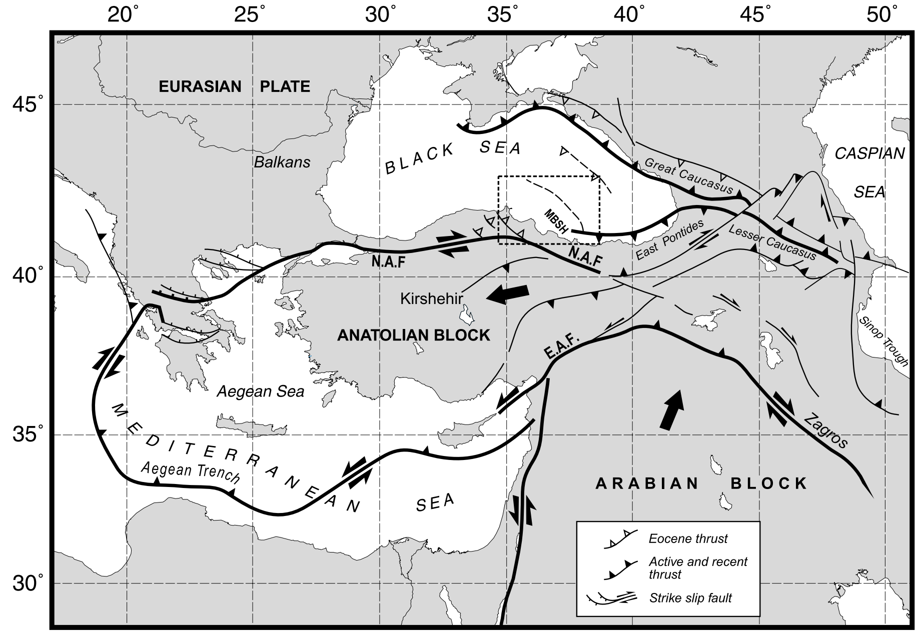

Fig. 1. Tectonic sketch of the Arabia/Eurasia collision zone. Eastern Black Sea Basin is located directly north of the tectonic escape of Anatolia. Dotted frame indicates the surveyed area. MBSH: Mid Black Sea High, NAF: North Anatolian Fault, EAF: East Anatolian Fault. Thick black arrows indicate motion of main crustal blocks with respect to Eurasia.

the fault have not changed substantially since its initiation.

The trace of the NAF follows pre-existing basins developed within the Pontides, the magmatic belt extending along the southern coast of the Black Sea. These basins are filled by the Pontus formation of Pliocene age (Över, 1996; Över et al., 1997). These basins, well developed immediately south of our survey area close to Sinop, could represent the initial stage of dextral motion along the NAF. The stress regime determined by inversion of slip vectors measured on fault planes in the Pontus basins (Bellier et al., 1997), reveals a change in the strike-slip regime from transpression to transtension during the Quaternary. Traces of such fluctuations in the stress regime along NAF has been evidenced offshore in our survey area as described below.

According to these previous studies it appears that during the last 4 to 5 Ma most of the Black Sea remained protected from the Arabian collision by the rigid tectonic escape of Anatolia, with most of the deformation being accommodated along the NAF. Only the easternmost part of this basin was, and still is, considerably affected by significant inversion of the Black Sea continental margins.

In the present study we will try to image the recent deformation induced by the NAF and also try to estimate the amount of active inversion along the Black Sea margin.

3. Closure of the Tethys ocean and the Early Cenozoic collision along the southern margin of the Black Sea

Up to the Paleocene–Eocene, collision and amalgamation of continental fragments (mainly the Kirshehir continental block) occurred in North Anatolia along the southern margin of the Pontide volcanic arc, and induced major deformation in Turkey. This collision was followed during most of the Paleogene by intraplate deformation that predates the rigid escape of the Anatolian block, probably initiated during the early Pliocene.

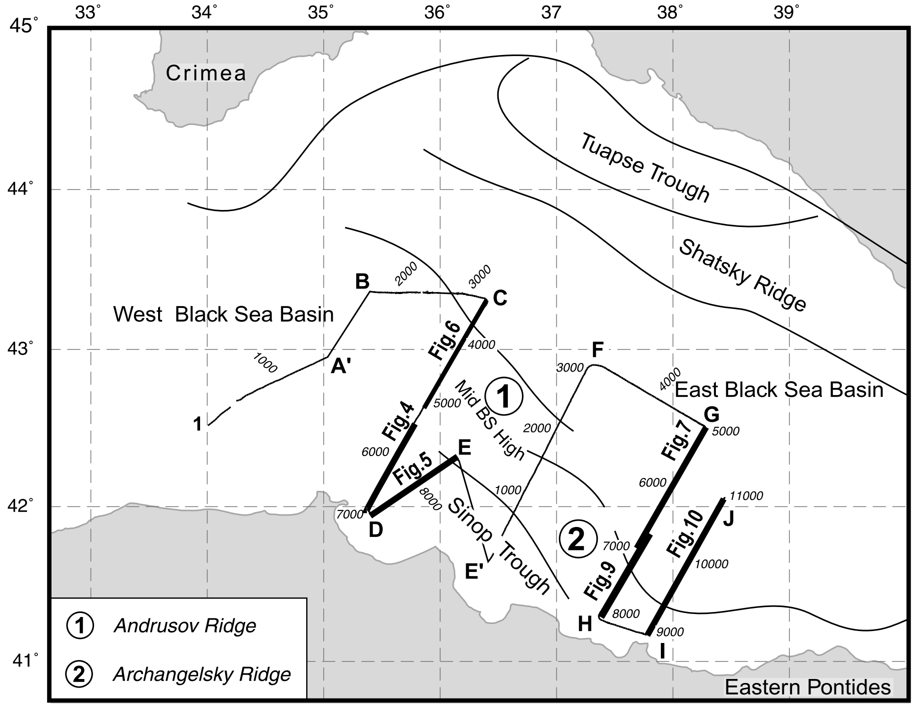

Fig. 2. Location of seismic lines of the BLACKSIS cruise in the central part of the Black Sea. Segments of lines shown in this paper are highlighted and correspond to indicated figure number.

Intraplate deformation in Eastern and Central Turkey induced thickening of the Anatolian crust as shown by the 2-km height of the Eastern Anatolian plateau. The whole area from the Black Sea coast to the Arabian indenter is the locus of this penetrative and complex deformation observable south of the present central segment of the NAF, in the Anatolian plateau (Bitlis thrust-and-fold belt).

This deformation extends also north of the present NAF, in the Central Pontides but we have no evidence for its extension northwards in the Black Sea and particularly in the Mid Black Sea High. Evidence of deformation directly related to this collision is particularly well exposed in the Central Pontides north of NAF, in the Sinop area (Görür and Tüysüz, 1997) immediately south of the Archangelsky Ridge. Here the Pontide volcanic arc and sedimentary sequences (Late Cretaceous to Eocene) are folded and tectonically imbricated with Mesozoic platform carbonates and its metamorphic basement. Thrusts and folds follow the general curvature of the Pontide belt with NW–SE, E–W and NE–SW trends from east to west. Scarce Neogene sediments are disconformably deposited on this Eocene belt and the NAF located southwards shows the same global trend (Fig. 1).

In their offshore petroleum study of the Black Sea, Robinson et al. (1996) interpret most of the MBSH tectonics as the trace of extension related to the opening of the Eastern Black Sea Basin. For instance folding imaged along the northeastern slope of the Archangelsky ridge is interpreted as roll-over structures related to a deep detachment at the ocean–continental crust boundary during the Paleocene, and is then relatively coeval with the collision. In this scenario no trace of shortening related to the Kirshehir–Pontides collision largely observed on land could be found offshore.

If such extensional structures are present at the

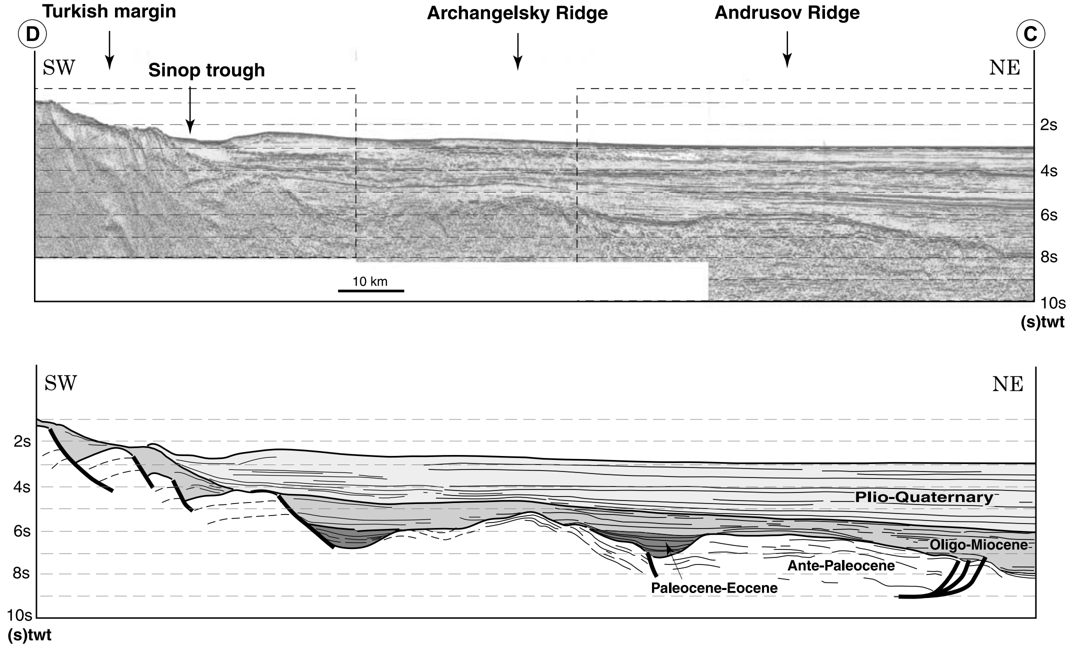

Fig. 3. BLACKSIS profile CD with main seismic sequences shown with different grey tones (see explanation in text). Main inactive faults are also shown. Dotted boxes help to locate Figs. 4 and 6 from SW to NE respectively.

base of the Central Ridge as stated by Robinson et al. (1996), we should prefer to interpret them as detachments, coeval, or following shortly the collision. The collapse of part of this belt could easily explain the vertical offset between the roof of the MBSH and the Pontide belt onshore. If it is not the case, a major discontinuity (strike-slip fault?) has to be found in the Sinop Trough that separates the MBSH from onshore Turkey.

4. Tectonic zoning of the Black Sea

The Black Sea is characterised by two distinct basins (Fig. 2) separated by en-echelon NW–SE trending central highs, the Archangelsky and Andrusov ridges constituting the Mid Black Sea High (MBSH).

4.1. Western Black Sea Basin

Timing of the rifting of the Black Sea is still a matter of debate. The most recent interpretations based on stratigraphic evidences from the northern margin, favours a mid-Cretaceous age for the opening of the Western Basin (Robinson et al., 1996), and confirms the Mesozoic age earlier proposed by Zonenshain et al. (1986). No mid-ocean ridge was identified in this basin and the location and nature of its margins is in several areas problematical. According to the most recent interpretations, this basin opened by southward drifting of the Pontides, the motion being guided by two major strike-slip (transfer) fault zones. These lie close to the Black Sea western coast (presently mostly obscured by the Balkanides Thrust Belt), and along the southwestern margin of the MBSH.

4.2. Eastern Black Sea Basin

The Eastern Basin is smaller and shallower, and may not have a fully oceanic basement. The opening age is contentious, but there are several lines of evidence supporting a Paleogene date (Robinson et al., 1996). The geometry of the basin is unclear mainly in the south and east, where the deep basin margin is overridden by the Pontides

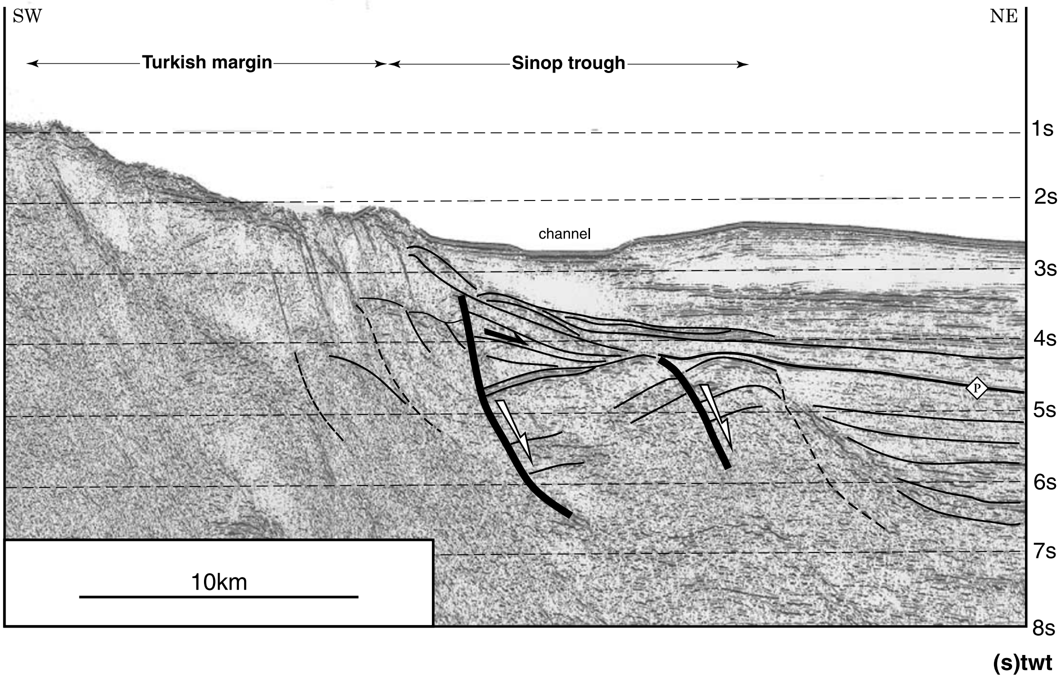

Fig. 4. Extract of the line CD, located on the Turkish margin at the northwest termination of the Sinop Trough. P: base of the Pliocene. White and black arrows indicate normal faulting and overlapping sediments respectively.

(Fig. 2). The northeastern and southwestern conjugate margins are significantly different, suggesting highly asymmetric rifting. The opening history of this basin remains speculative, but is probably linked with oblique compressive deformation in the Caucasus.

The Eastern Basin is filled by between 8 and 12 km of so-called post-rift sediments, so the critical structures of the margins remain poorly known on classical multi-channel seismic profiles. The origin of the basin is still a matter of debate. This basin can be interpreted as a coeval fragment of the Western Black Sea (Zonenshain et al., 1986). An alternative hypothesis considers rifting of this basin as coeval with the Paleocene Kirshehir/Pontides collision (Robinson et al., 1996). Rifting is thus counterbalanced by shortening in the Caucasus, and a certain amount of extension linked to the Kirshehir block collision with Eurasia could also have contributed to opening up this basin.

4.3. *Mid Black Sea High*

MBSH is composed of two main ridges. In the south the Archangelsky Ridge starts at the Turkish shoreline and plunges northward. It is relayed to the northwest by the Andrusov Ridge (Fig. 2). These two ridges separate the Western and the Eastern Basins. Southwestwards, the Sinop Trough is a narrow depression parallel to the MBSH, located between the MBSH and the Turkish coast.

5. Description of new seismic data collected in the central part of the Black Sea

In February 1997 we collected 900 km of multichannel seismic across the Mid Black Sea High (Fig. 2). We used a single bubble source with 14 guns totalling 3060 cubic inches and a streamer 2400 m long with 96 hydrophone groups. Five

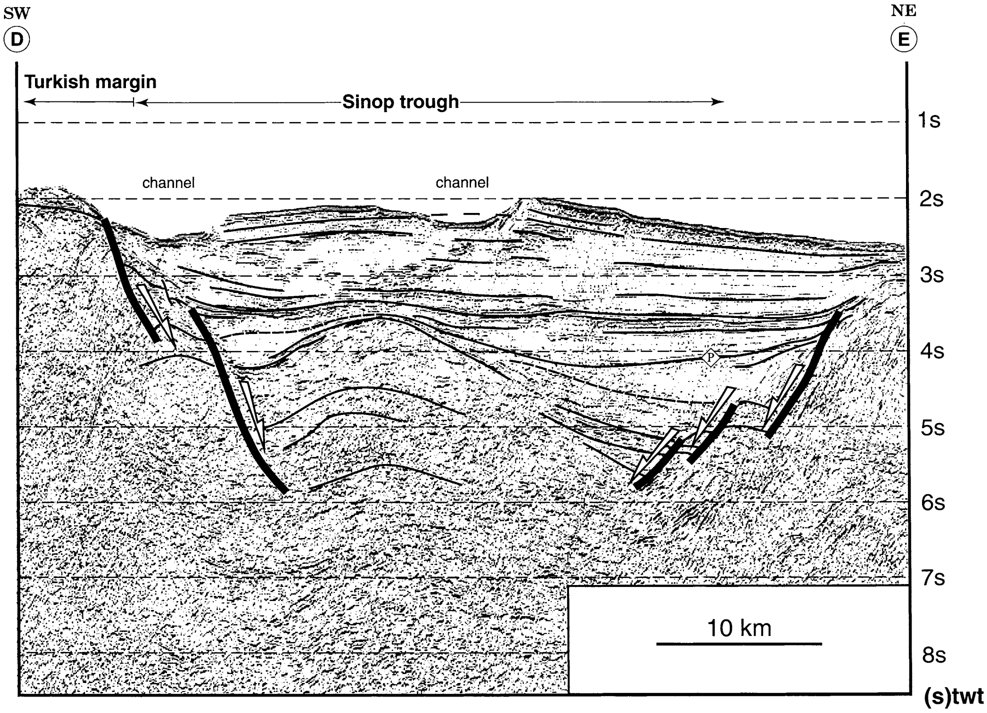

Fig. 5. Extract of the line DE across the Sinop Trough. P: base of the Pliocene.

main lines were recorded (CD, DE, E′F, GH, and IJ) with an acquisition gap in the line E′F.

In order to identify the seismic sequences, we used the crossing composite British Petroleum and Turkish Petroleum lines shot along the high (Robinson et al., 1996).

On line CD (Fig. 3) three main seismic sequences were identified deposited above an acoustic basement with scarce internal reflectors. The Pliocene–Quaternary sequence (light grey on Fig. 3) is over 3 s TWT thick in the central part of the Eastern Basin and thins towards the ridge where it was deposited with an onlap on the underlying 2 s TWT thick Oligocene–Lower Miocene Maykop sequence (medium grey on Fig. 3). Local isolated tilted basins (dark grey on Fig. 3) are identified in some part of the section, and are probably filled by less than 1 s TWT thick Paleocene–Eocene sediments (Robinson et al., 1996).

The lowermost seismic sequence, reveals two distinct tectonic fabrics: reflectors tilted towards northeast were identified along the Turkish margin and are observable on the southeastern part of line CD (Fig. 3). The Central High to the northeast shows large anticlines moderately affected by normal faults. These faults control the NW trend of the Sinop Trough separating the Turkish margin from the Central High. We will describe first the structure present along the Sinop Trough, then we will focus our study on the ridge itself and its transition to the Eastern Black Sea abyssal plain. Finally we will discuss the active inversion of old normal faults present offshore the E–W trending Eastern Pontides.

5.1. Sinop Trough

This trough, filled by recent sediments, is a discrete furrow separating the Archangelsky Ridge from the coast of Turkey. This trough connects northwestwards with the deep Western Black Sea Basin.

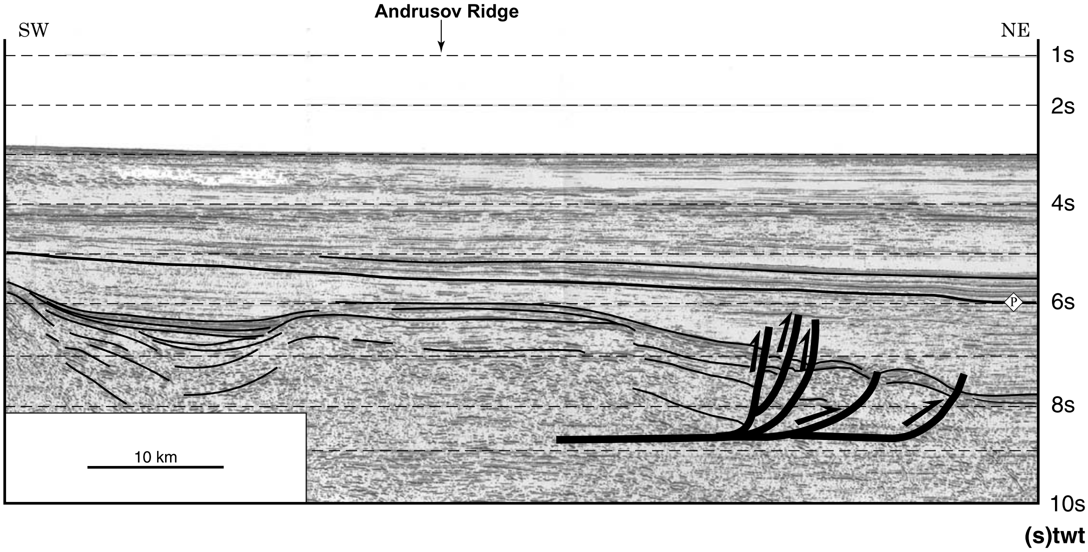

Fig. 6. Extract of the line CD across the Andrusov Ridge and within the Eastern Black Sea Basin. Thrusts are indicated by thick lines and black arrows.

In the deeper part of the trough (Fig. 4), Pliocene and Quaternary sediments are apparently conformable with the underlying sedimentary section. The base of the Pliocene sequence (*P* on Fig. 4) onlaps the crest of the northeast-facing tilted blocks, meanwhile the underlying post-rift section is prograding down slope on the block's shoulder. This indicates that the extension is probably as young as the Late Miocene.

The following section to the southeast (Fig. 5)

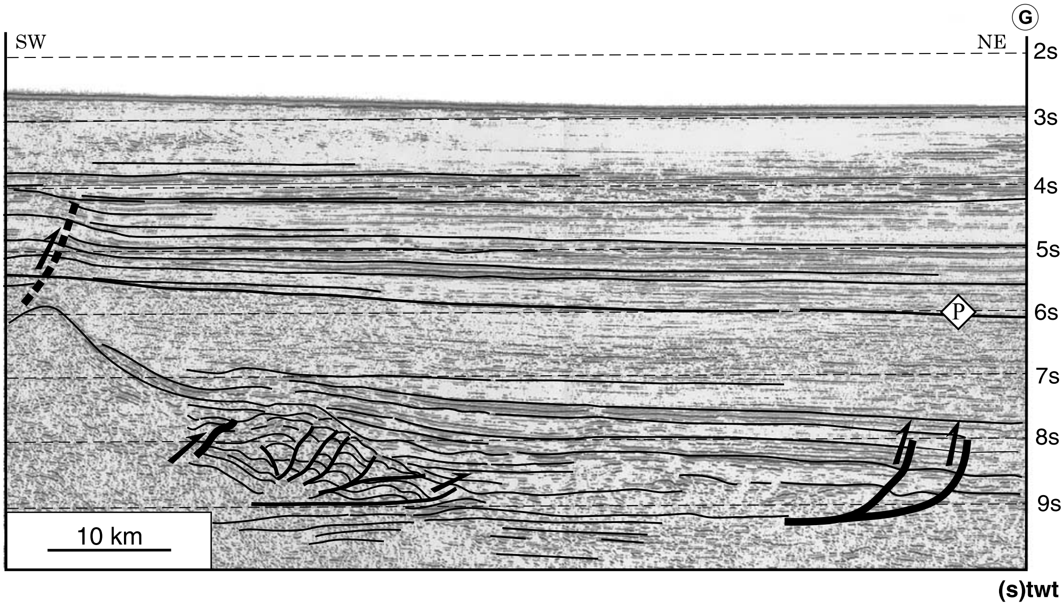

Fig. 7. Northeastern extract of the line GH showing buried thrusting and duplex along the northeastern flank of the Andrusov Ridge. Recently inverted normal fault is indicated by dashed line (see Fig. 9).

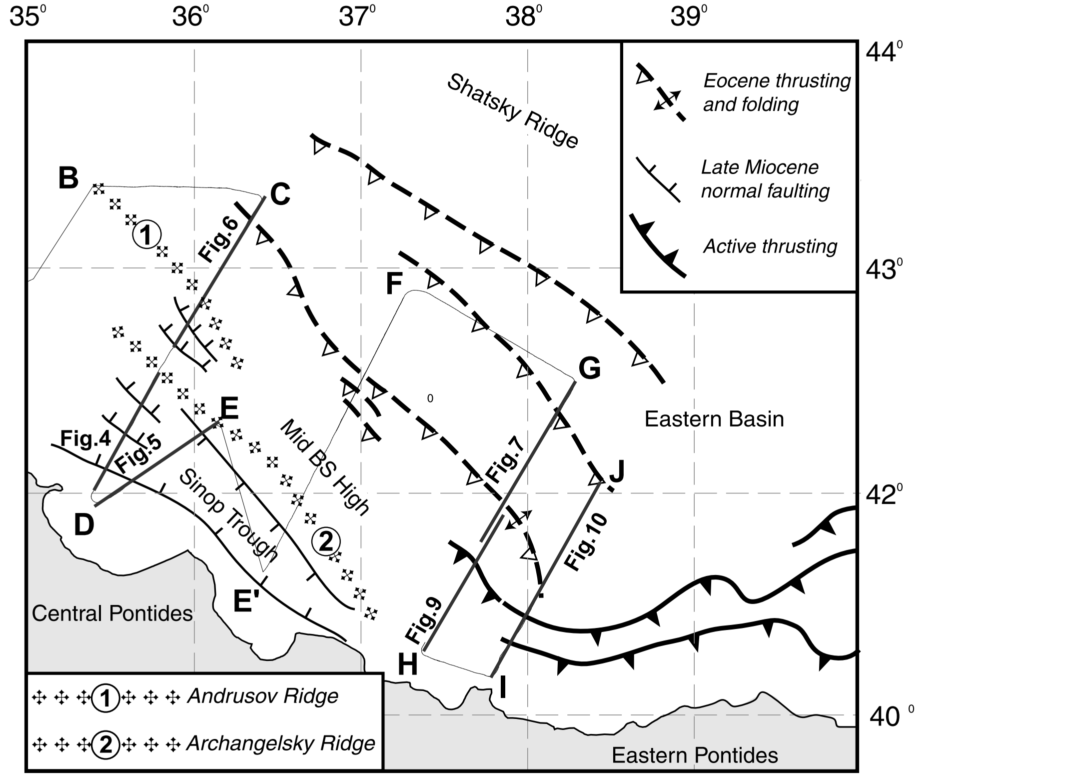

Fig. 8. Structural map based on the interpretation of the BLACKSIS profiles, illustrating the three distinct tectonic events identified in the studied area.

reveals that the Sinop Trough is controlled by normal faults developed both along the Turkish margin and along the Archangelsky Ridge. The identified Miocene–Pliocene Boundary (P in Fig. 5) does not appear to be affected by this rifting phase, confirming its Late Miocene age. A large roll-over structure is present in the syn-rift sediments and confirms the pre-Pliocene normal faulting along the Turkish margin. Syn-rift fanning sediments are also observed to the northeast along the flank of the MBSH.

The post-rift sediments are subsequently domed as shown by the curvature of the mud line- and youngest sediments and an active channel is observable at the top of this anticline. We interpret this geometry as compactional, or as moderate rejuvenation of pre-Pliocene roll-over induced by the normal faults that flank the trough. On the basis of the second hypothesis, the opening of the Sinop Trough could be interpreted as a side effect of the incipient motion along the NAF as discussed later in this paper.

5.2. Deformation of the Mid Black Sea High

Along the northeastern part of line CD (Fig. 3), the MBSH appears as two successive domed structures that could be interpreted as large open folds. This is better imaged on the Andrusov Ridge (Fig. 6). The rare reflectors identified within this lowermost seismic sequence, indicate this ridge is a flat topped anticline. Its northeastern flank is folded and affected by reverse faults, branching at depth on a flat decollement surface that could correspond to a major thrust. This deformation does not affect the Oligocene–Lower Miocene Maykop sequence.

This thrust front was also imaged on line GH (Fig. 7).The contrast between the undeformed sediments and the underlying sequence observed

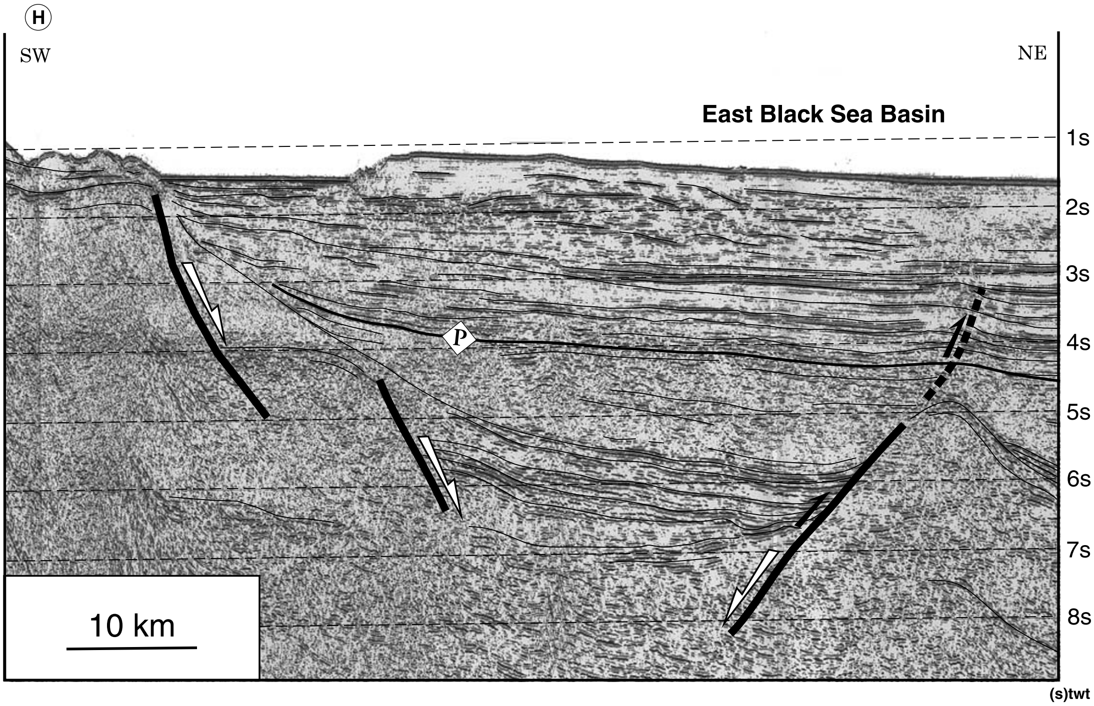

Fig. 9. Southeastern extract of the line GH, located on the eastern flank of the MBSH and East Black Sea Basin. Normal faults (white arrows) locally inverted normal faults (black arrows and dashed lines) are shown.

below 7.5 s TWT is evident. The deformed sediments show internal flats and ramp structures. At the limit of the penetration of our seismic line, below 9 s TWT, flat-lying reflectors has been identified under the frontal ramp and could be interpreted as the emergence of the major thrust below the ridge. At the northeastern end of the profile (Fig. 7), small reverse faults affect the lowermost sediments of the Eastern Basin, and could connect to a decollement.

The flat detachment fault identified by Robinson et al. (1996) at the foot of the ridge corresponds to our duplex and was interpreted on the basis of the presence there of a roll-over structure. We favour the interpretation of a buried pre-Oligocene thrust, on the basis of the observed imbricated structures (Fig. 7), but also the parallel folding that affects the Central Ridge (Figs. 3 and 6).

5.3. Deformation along the Eastern Pontides

The structures described above are all with a NW–SE trend. Approaching the coast of the Eastern Pontides (Figs. 1 and 8), structures swing abruptly northeastward before merging onshore in Georgia (Banks and Robinson, 1997).

Line GH (Fig. 9) shows the southernmost extension of the ridge slope at the transition with the Eastern Black Sea Basin abyssal plain. In the central part of the line and in a small graben presents along the ridge, inversion is observable (Fig. 9). The fan-shaped sediments originally deposited along the southwestern flank of the graben are tilted towards the northeast. Some of the inverted normal faults affect most of the Pliocene section indicating that this inversion is recent.

More eastwards, on line IJ (Fig. 10) reverse faults affect all the section up to the mud line, indicating that there is active deformation here. The recent sediments are folded, but the shortening remains modest, because the former tilted block of the Eastern Black Sea Basin passive margin are preserved.

Using both our seismic data interpretations and

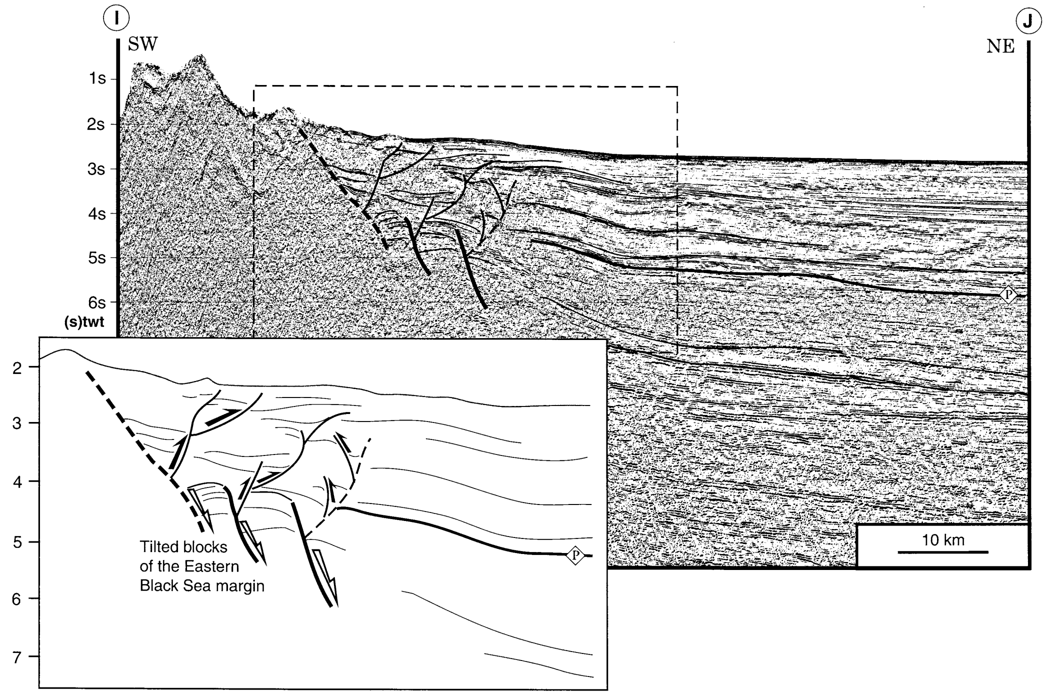

Fig. 10. Line IJ showing inversion of the East Black Sea Basin margin. Ancient normal faults (white arrows) and inverted normal faults (black arrows) are shown.

the contouring of the free air gravity anomalies combined with the total sediment thickness map published by Robinson et al. (1996), we have traced a structural sketch map of the Central Black Sea area (Fig. 8). This map illustrates the tectonic relationships existing between the buried and active structures. The active thrusts present along the eastern Pontides extend offshore with a NE–SW trend, and swing to EW on profile IJ, and to a NW trend on profile GH. However, no direct connection can be evidenced with the similar NW trend of the buried thrusts present at the base of the MBSH (Fig. 7). We think both kinds of structures are unrelated. The active thrusts are directly linked to the seismically active north verging Lesser Caucasus tectonic front, meanwhile the others are buried and considerably older.

6. Discussion and conclusions

The analysis of the deep penetration seismic profiles presented in this paper illustrate the polyphased deformation of the Mid Black Sea High. Three distinct tectonic episodes of deformation corresponding to three distinct structural styles are present around this high.

The most recent tectonic episode is the active deformation linked to the north-verging Lesser Caucasus tectonic front in Georgia. This deformation is concentrated at the southeastern termination of the Eastern Black Sea Basin in response to the collision of the Arabian block with Eurasia (Fig. 11). According to the GPS data of McClusky et al. (2000), less than 0.5 cm/yr shortening is absorbed in front of the Arabia–Eurasia collision zone. Extrapolated to the last 5 Ma, a maximum of 250 km is expected along the Lesser Caucasus front in Georgia. This is qualitatively confirmed by the equilibrated cross section of Banks and Robinson (1997). Considering the active amount of shortening decreases drastically between Georgia and the MBSH, we can expect, for the last 5 Ma, the same westward decrease in the finite

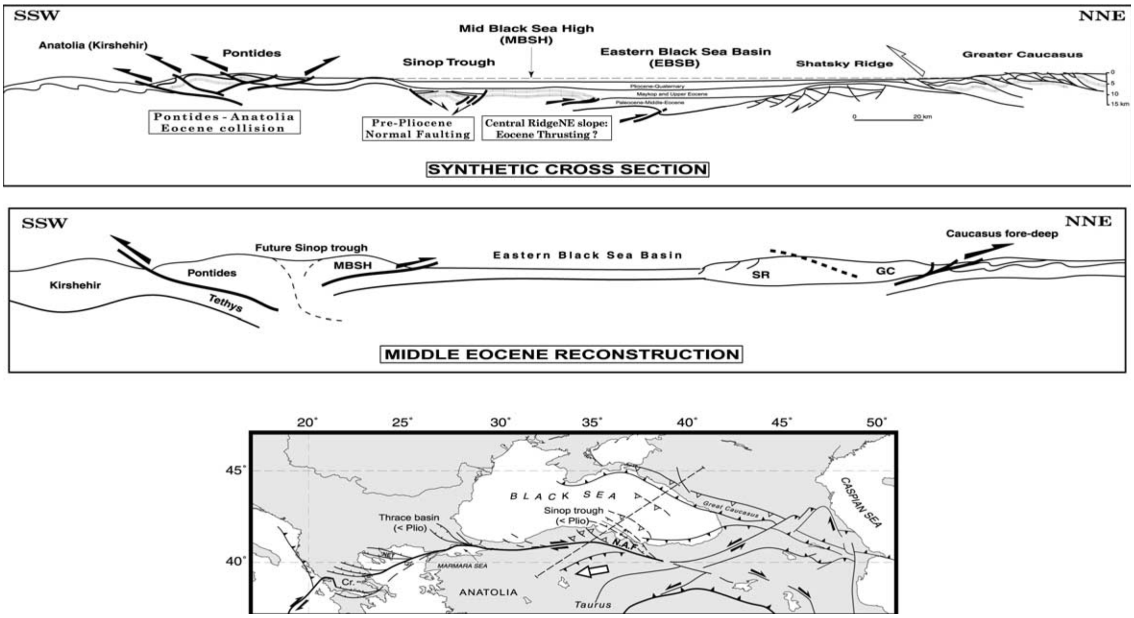

Fig. 11. Synthetic cross section (top) located on map inset. Middle Eocene reconstruction of this section is shown just below. Age ranges of the distinct tectonic episodes are also indicated on top section. On the Middle Eocene reconstructed section, thrusting located along the northeastern flank of the Central High is interpreted as a back thrust of the main Pontides thrust. The Caucasus foredeep can also be coeval. For inset, same legend as Fig. 1. Escape of Anatolia towards the west is indicated by a large white arrow. NET: North Aegean Trough, Cr: Gulf of Corinth.

deformation. Consequently the discrete normal fault inversion observed along profile IJ would be coeval with the Lesser Caucasus front in Georgia.

The second tectonic episode concerns deformation into the Sinop Trough. This deformation is concentrated along both flanks of this narrow furrow. The observed normal faults are mainly active before the Pliocene. Similar NW trending grabens are reported by Bellier et al. (1997) along the central segment of the North Anatolian Fault. These troughs, filled by Early Pontian sediments can be interpreted as en-echelon grabens branching on the North Anatolian Fault. They could correspond to the initial stage of dextral strike-slip along this major fault during the latest Miocene. A similar abandoned lateral branch was described by Barka et al. (2000) south of Sinop, and by Perinçek (1991) in the Thrace Basin immediately north of the Sea of Marmara (Fig. 11). The North Aegean Trough is presently a suite of active en-echelon grabens located at the western tip of the propagating NAF (Fig. 11). We interpret the Sinop Trough as the easternmost and oldest of these structures that we can relate to the incipient right lateral motion along the NAF.

The third and older deformation episode registered along the MBSH could have induced northeast-verging thrusting along the eastern slope of the Central Ridge, in the location of the possible continental oceanic boundary between the Central Ridge and the Eastern Black Sea Basin. This thrust does not affect the Miocene and is probably Oligocene or older in age. It is parallel to the Middle-Eocene thrusts that affect the Pontides onshore, in the Sinop area (Görür, 1997). We propose that these thrusts observed along the MBSH northeastern flank are coeval with the Sinop southwest-verging structures. Both could form a large pop-up affecting the whole central Pontides and most of the MBSH as sketched on the Middle-Eocene reconstruction in Fig. 11. We then interpret the MBSH as part of the Pontides that could have collapsed right away after cessation of the Kirshehir–Pontides collision. This collapse could have occurred along the northeast-facing normal faults observed on profile CD (Fig. 3) present along the Turkish coast, subsequently reactivated in the late Miocene by the opening of the Sinop Trough. The effects of this collision during the Eocene could have been recorded in the Great Caucasus and mainly in the deformation of the Caucasus foredeep to the northeast (Fig. 11).

We do not know the tectonic behaviour of the Eastern Black Sea oceanic crust during this collision. Considering the proposed Paleocene age for the opening of this basin (Robinson et al., 1996), the oceanic crust was less than 15 Ma old when Anatolia collided with the Pontides. A similar situation has been studied in the southeastern Pacific region in the Sulu and Proto South China Sea basins where young oceanic crust is involved in regional shortening (Bader et al., 1999). These previous studies lead us to conclude some slivering and thrusting have to be expected within the Eastern Black Sea oceanic crust. The positive free air gravity high centred on the Eastern Black Sea Basin could be the trace of an intra-oceanic crust splinter. The fact the Cenozoic sediments are not involved in the deformation would suggest that this deformation was induced shortly after rifting of the basin during the Paleocene.

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References

Armijo, R., Meyer, B., Hubert, A., Barka, A., 1999. Westward propagation of the North Anatolian Fault into the northern Aegean; timing and kinematics. Geology (Boulder) 27, 267–270.

Bader, A.G., Pubellier, M., Rangin, C., Deplus, C., Louat, R., 1999. Active slivering of oceanic crust along the Molucca ridge (Indonesia–Philippines). Geodynamic implication. Tectonics 18, 606–620.

Banks, C.J., Robinson, A.G., 1997. Mesozoic strike-slip back-arc basins of the western Black Sea region. In: Robinson, A.G. (Ed.), Regional and Petroleum Geology of the Black Sea and Surrounding Region. AAPG Memoir, pp. 53–61.

Barka, A., Akyüz, H.S., Cohen, H.A., Watchorn, F., 2000. Tectonic evolution of the Niksar and Tasova–Erbaa pull apart basins, North Anatolian Fault Zone: their significance for the motion of the Anatolian block. Tectonophysics 322, 243–264.

Barka, A.A., Buckman, R.C., Hancock, P.L., 1992. The North Anatolian fault zone Major active faults of the world; results of IGCP Project 206. Final meeting of IGCP Project 206, 'A worldwide comparison of the characteristics of major active faults', 6, Suppl., pp. 164–195.

Bellier, O., Över, S., Poisson, A., Andrieux, J., 1997. Recent temporal change in the stress state and modern stress field along the North Anatolian fault zone (Turkey). Geophys. J. Int. 131, 61–86.

Görür, N., 1997. Cretaceous syn- to postrift sedimentation on the southern continental margin of the western Black Sea basin. In: Robinson, A.G. (Ed.), Regional and petroleum geology of the Black Sea and surrounding region. AAPG Memoir, pp. 227–240.

Görür, N., Tüysüz, O., 1997. Petroleum geology of the southern continental margin of the Black Sea. In: Robinson, A.G. (Ed.), Regional and petroleum geology of the Black Sea and surrounding region. AAPG Memoir, pp. 241–254.

Jestin, F., Huchon, P., Gaulier, J.M., 1994. The Somalia Plate and the East African rift system; present-day kinematics. Geophys. J. Int. 116, 637–654.

Le Pichon, X., Chamot-Rooke, N., Lallemant, S., Noomen, R., Veis, G., 1995. Geodetic determination of the kinematics of central Greece with respect to Europe; implications for eastern Mediterranean tectonics. J. Geophys. Res. B, Solid Earth Planets 100, 12675–12690.

McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gürkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, A., Veis, G., 2000. Global positioning system constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J. Geophys. Res. B, Solid Earth Planets 105, 5695–5719.

McKenzie, D.P., 1970. The development of the Red Sea and Gulf of Aden in relation to plate tectonics [abstr., with discussion]. A discussion on the structure and evolution of the Red Sea and the nature of the Red Sea, Gulf of Aden and Ethiopia rift junction. Phil. Trans. R. Soc. London A Math. Phys. Sci. 267, 393–395.

Okay, A.I., Şengör, A.M.C., Görür, N., 1994. Kinematic history of the opening of the Black Sea and its effect on the surrounding regions. Geology (Boulder) 22, 267–270.

Över, S., 1996. Analyse tectonique et états de contraintes cénozoïques dans la zone centrale de la faille Nord Anatolienne. Thèse de doctorat, Université Paris Sud-Orsay, 260 pp.

Över, S., Bellier, O., Poisson, A., Andrieux, J., 1997. Late Cenozoic stress change along the central North Anatolian fault zone (Turkey). Ann. Tecton. 11, 75–101.

Perinçek, D., 1991. Possible strand of the North Anatolian Fault in the Thrace Basin, Turkey: An interpretation. Am. Assoc. Pet. Geol. Bull. 75, 241–257.

Robinson, A.G., Rudat, J.H., Banks, C.J., Wiles, R.L.F., 1996. Petroleum geology of the Black Sea. Mar. Pet. Geol. 13, 195–223.

Şengör, A.M.C., 1979. The North Anatolian transform fault; its age, offset and tectonic significance. J. Geol. Soc. London 136, 269–282.

Şengör, A.M.C., Görür, N., Şaroğlu, F., Biddle, K.T., Christie-Blick, N., 1985. Strike-slip faulting and related basin formation in zones of tectonic escape; Turkey as a case study. Strike-slip deformation, basin formation, and sedimentation. Soc. Econ. Paleontol. Mineral. Spec. Publ. 37, 227–264.

Yılmaz, P.O., Leary, D.A., Norton, I.O., Chuchla, R.J., Anonymous, 1993. Tectonic evolution and paleogeography of Europe. AAPG international conference and exhibition, 77, p. 1677.

Zonenshain, L.P., Le Pichon, X., Aubouin, J.E., Le Pichon, X., Monin, A.S., 1986. Deep basins on the Black Sea and Caspian Sea as remnants of Mesozoic back-arc basins. Evolution of the Tethys. Tectonophysics 123, 181–211.