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Stratigraphic and Structural Features of The Sinop Basin Close to The Mid Black Sea Ridge Using Multi-Channel Seismic and Multi-Beam Bathymetric Data

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ABSTRACT

Focal mechanism solutions of the earthquakes that occurred in the Black Sea in the last 100 years show that thrust and strike-slip faults are predominantly active in the region. One of these clusters is developing off the coast of Samsun where the submarine Sinop basin is located. In order to investigate the seismic sources of earthquakes in this area, high-resolution multi-channel seismic sections and multi-beam bathymetric data were processed and evaluated. The oldest seismic stratigrafic units (U4) is referred to as acoustic basement with wavy reflectors, while its top is marked by high amplitude reflection indicating an unconformity. This uniconformity is overlain by parallel or less parallel Unit 3 deposits. Upper surface of Unit 2 is marked by an erosional surface which is overlain by the parallel reflector of Unit 1. Unit 1 is the youngest sediments and truncated by Yeşilırmak canyon. Three fault types of different ages were determined. The oldest fault could reach only top of unit 4 has been interpreted as inactive fault. Faults that border the Sinop basin and reach the sea floor by cutting all seismic units are considered in the active fault class. However, the faults that remain within Unit 1 and do not reach the seafloor are considered as faults that are coeval with sedimentation. According to these data, faulting in the Central/Eastern Pontide structural block should be reconsidered in the context of the seismic activity of the region and re-evaluated as an earthquake hazard that will pose a risk in the future.

Keywords: Black Sea, Sinop Basin, Multi-Channel Seismic, Multi-Beam Bathymetric Data, Active Faults

Çok Kanallı Sismik ve Çok Işınlı Batimetrik Veriler Kullanılarak Orta Karadeniz Sırtı'na Yakın Sinop Havzası'nın Stratigrafik ve Yapısal özellikleri

ÖZ

Karadeniz'de son 100 yılda meydana gelen depremlerin odak mekanizması çözümleri, bölgede ağırlıklı olarak bindirme ve doğrultu atımlı fayların aktif olduğunu göstermektedir. Bu kümelerden biri de Sinop denizaltı havzasının bulunduğu Samsun açıklarında gelişiyor. Bu bölgedeki depremlerin sismik kaynaklarının araştırılması amacıyla yüksek çözünürlüklü çok kanallı sismik kesitler ve çok ışınlı batimetrik veriler işlenerek değerlendirilmiştir. En yaşlı sismik stratigrafik birimler (U4), dalgalı reflektörlü akustik temel olarak anılırken, üst kısmı uyumsuzluğu işaret eden yüksek genlikli yansımayla işaretlenmiştir. Bu tekdüzelik paralel veya daha az paralel olan birim 3 çökelleri tarafından örtülmektedir. Birim 2'nin üst yüzeyi, Birim 1'in paralel reflektörü tarafından örtülen aşınma yüzeyi ile işaretlenmiştir. Birim 1 en genç çökellerdir ve Yeşilırmak kanyonu tarafından kesilmektedir. Farklı yaşlarda üç fay belirlendi. Birim 4'ün sadece üst dokanağına ulaşabilen en eski fay, aktif olmayan fay olarak yorumlanmıştır. Sinop havzasını sınırlayan ve tüm sismik birimleri keserek deniz tabanına ulaşan faylar aktif fay sınıfında değerlendirilmektedir. Ancak Birim 1 içerisinde kalan ve deniz tabanına ulaşmayan faylar sedimantasyonla eş zamanlı faylar olarak değerlendirilmektedir. Bu verilere göre Orta/Doğu Pontid yapı bloğundaki faylanmaların bölgenin sismik aktivitesi bağlamında yeniden ele alınması ve gelecekte risk oluşturacak bir deprem tehlikesi olarak yeniden değerlendirilmesi gerekmektedir.

Anahtar Kelimeler: Karadeniz, Sinop Havzası, Çok Kanallı Sismik, Çok Işınlı Batimetrik Veriler, Diri Fay

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1. Introduction

The Mid Black Sea ridge (MBSR), which is buried under the waters of the Black Sea today, was a barrier until the Oligocene-Early Miocene between two extensional submarine basins: the Eastern Black Sea Basin (EBSB) and the Western Black Sea Basin (WBSB). The ridge is surrounded on both sides by an antithetical fault system that limits the Andrussov Ridge to the north and Archangelsky Ridge to the south creating a significant topographic elevation on the Turkish coast (Figure 1, Zonenshain and Pichon, 1986; Finetti et al., 1988; Okay et al., 1994; Robinson et al., 1996) Bouguer gravity data suggets that the depth to the sedimentary basement of Cretaceous age in the Sinop basin and on the Archangelsky Ridge approximately reaches 4 km and 1.6 km, respectively (Elmas and Karslı, 2021). However, there are different opinions regarding basin type and basin boundary faults. It is explained as a young foreland basin that has formed as a flexural response to crustal thickening (Meredith and Egan, 2002), or a graben developed between the central Black Sea ridge and the Turkish coast (Rangin et al., 2002). Dondurur (2008), claimed that either the faults border the Sinop basin are inactive and can not generated surface rupture on the sea floor. In order to slove these problems, seismic stratigraphic and structural features of the Sinop basin were examined using high resolution multi seismic data and multi beam bathmetric data.

In this article, firstly, brief information about the Black Sea will be given, then the submarine bathymetry characteristics of the Yeşilırmak Canyon and its immediate surroundings will be presented. In the following section, the basin sequence and its structural features will be interpreted with the help of seismic sections and multi-beam bathymetric data. In the last section, the seismic activity of the region and the active faults that cause this activity will be discussed in the light of the available literature and results obtained from the present study.

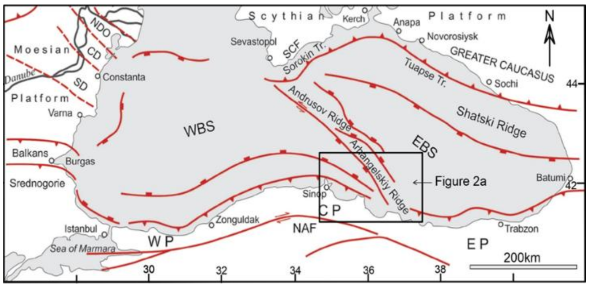

Figure 1. Location map of the study area showing the major tectonic units of the Black Sea. (modified after Robinson et al., 1996 and Oaie et.al. 2016). Abbreviations: PDD, Pre-Dobrogea Depression; NDO, North Dobrogea Orogen; CD, Central Dobrogea, SD, South Dobrogea; SCF, South Crimea Fold Belt; V, Vrancea zone; WP, West Pontides; CP, Central Pontides; EP, East Pontides; NAF, North Anatolian Fault; EBS, Eastern Black Sea basin; WBS, Western Black Sea basin.

1.1 The Black Sea: Regional Geology And Tectonic Setting

The Black Sea is considered to be a marginal basin formed in the back-arc tectonic environment associated with the subduction of the Tethys to the north under Eurasia and behind the Pontide volcanic arc during the Mesozoic-Early Cenozoic period (Finetti et al., 1988; Belousov et al. 1988; Robinson, 1997; Meisner and Tugolesov, 2003; Nikishin et al., 2015). As shown in Figure 2, it is divided into two extensional submarine basins (Western Black Sea and Eastern Black Sea Basins) by the Mid Black Sea Ridge (MBSR), which extends in a NW-SE direction from the coast of Samsun to the coast of Ukraine (Finetti et al., 1988; Okay et al., 1994; Robinson et al., 1995). The two basins coalesced late in their post-rift phases in the Pliocene, forming the present single basin structure (Robinson et al., 1996; Meredith and Egan, 2002).

1.2 Submarine geomorphology of the study area

According to the geomorphological classification made along the Black Sea, the study area where Yeşilırmak Canyon developed on the continental slope between shelf edge and basin apron (Figure 2) as many canyons incise the Black Sea continental slope (Panin et al., 1997; Harris et al., 2014).

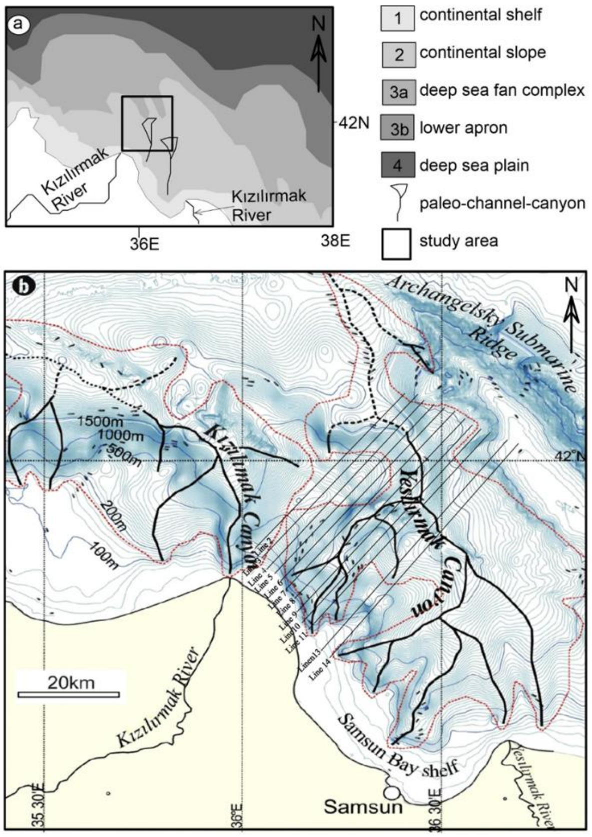

Figure 2. a) Geomorphologic zoning and b) bathymetry map of the study area (Ross et al., 1974; Panin et al., 1997; Harris et al., 2014). Yeşilırmak and Kızılırmak submarine valley systems on the EMODnet Bathymetry chart. Location of seismic lines presented in this study is indicated. Note the southern part of the seismic lines located across Yeşilırmak Canyon, and the northern part on the Archangelsky Ridge. Batimetric map from Jipa et al., 2020. Dotted black lines Show fan valley. Dotted red lines show drainage basins of Yeşilırmak/Kızılırmak River.

Jipa et al., (2020) classified the submarine canyons of the Black Sea basin into two distinct categories: passive canyons (associated with a wide shelf located mainly in the north-western part of the sea) and active canyons (associated with a narrow shelf in the eastern and southern part of the Black Sea basin). Canyons located on the large continental shelf (northern and northwestern shelves of the Black Sea) are (currently) inactive at high elevations and discharge their sedimentary loads into lagoons separated from the sea by beach barriers. Based on this information, canyons off the coast of Romania are currently classified as passive canyons (Popescu et al., 2015; Jipa and Panin, 2020), while Caucasian canyons (Chorokhi Canyon, Sipahioğlu et al., 2013) and Anatolian Black Sea Canyons (Sakarya Canyon), Yeşilırmak Canyon, are classified as active canyons (Algan et al., 2002; Dondurur and Çiftçi, 2007).

The Yeşilırmak Canyon is given to the 26 km shelf incising submarine channel located in the Samsun offshore area, close to the Archangelsky Ridge as shown in Figure 2. The tributary length of the Yeşilırmak submarine valley systems is exceeds 100 km. The surface of its drainage basin is 3,600 sq. km (Jipa et al., 2020). It appears in the milder slope areas, and has a higher dendritic trend, showing a system with a main channel thalweg and several limbs. The study of Dondurur and Çifci (2007), Dondurur et al., (2013) conducted in the south-eastern upstream area of the Yeşilırmak System and on the south-west slope of the Archangelsky Ridge has been able to accurately trace the canyons. According to the authors, the length of the Yeşilırmak submarine system is over 120 km, the dendritic part representing approximately 60 km.

1.3 Methodology, Data acquisition and processing

Seismic stratigraphic and structural features of the Sinop basin were examined using high-resolution multi-channel seismic data and multi-beam bathymetric data. The data within the scope of the study were evaluated with the R/V Koca Piri Reis ship affiliated to Dokuz Eylül University Marine Sciences and Technology Institute with the support from the AlerT (Anatolian pLateau climatE and Tectonic Hazards) Project (Project Code: 607996), which is the 7th Framework project of the European Union. This Project aimed to examine the uplift of the Anatolian Plate, the basin formations and the tectonic conditions affecting them. The project was carried out in partnership with 11 academic institutions and 5 private companies in terrestrial areas. It is processed using Landmark Graphics' ProMAX software and analyzed using Seismic Micro Tech's Kingdom Suite software at the SEISLAB of Dokuz Eylül University as the sole project partner in the marine field. High resolution multi-channel seismic reflection and multibeam bathymetry data acquisition were done by Dokuz Eylül University, Institute of Marine Sciences and Technology post-graduate students and crew onboard of R/V Koca Piri Reis at Kızılırmak Delta/Bafra offshores, Black Sea shelf. A total of, approximately 1300 km long seismic data collected on 17 lines (13 SW-NE and 4 NW-SE directional). 216 channel seismic recorder with 1350m long digital streamer was used in this study. We used GI gun with 45+105 inch3 volumes as seismic source. Shot interval was 25 m, sample rate was 1 ms and record length was 6000 ms. The following data processing stages were carried out: Raw Data Input, Geometry Load, Band-pass Filter (12-200 Hz), F-K Filter, CDP sort, Velocity Analysis, NMO correction, 12-24 Fold Stack, Kirchhoff Time Migration, Automatic Gain Control and SEG-Y Out.

In this study, faults are considered to be active if they show one of these characteristics: 1) seafloor expression on Multi-Beam Bathymetric Data ; 2) Deformation and/or displacement of the sea floor and the most recent sediments on resolution seismic sections; 3) prominent fault scarps showing displacement on or uncovered by recent sediments (Somoza et al. 2021).

Following these criteria, we mapped the main active/inactive submarine faults in and around the Sinop basin. Finally, based on our map, we present a synthetic cross-section of distribution of the active submarine faults linked to seismicity between North Anatolian Fault and Archangelsky Ridge.

2. Seismic Stratigraphy and Structural Features

Four main seismic units can be distinguished from the multi-channel seismic sections (Figure 3). The oldest one (Unit 4) constitutes acoustic basement. During this stage, a thick sequence of volcaniclastic turbidites and subordinate pelagic limestones are accumulated. This accumulation was interrupted at the end of the Early Eocene by compressional tectonics, which resulted from the closure of the Neotethys (Görür, 1988; Robinson et al., 1996; Görür et al., 1997). For that reason, the internal structure of unit 4 is wavy, folded and sometimes chaotic, and its contact with the overlying units reveals itself with a strong reflection level. While this contact forms an anticline on the Archengelsky ridge, it forms a syncline structure under the Sinop basin. This folded contact, which corresponds to the main unconformity plane in seismic sections, is cut by several faults in many places. Unit 3, symbolized by sub-horizontal reflections on the unconformity plane, presents a very thin geometry on the ridge and thickens from the edge of the basin to the middle. This unit may correspond to deposition relates to the initial isolation of Paratethys at the end of the Eocene and the beginning of the Oligocene is characterized by Maykop Suite a distinctive, often fine-grained organic-rich sediments and sandstone packages (Simmons et al., 2018).

Some faults that cut the acoustic basement continue upward to cut this unit as well. No significant difference is observed between unit 3 and the overlying unit 2, on a scale corresponding to unconformity (Figure 4). The contact between unit 2 and unit 1 is clearly erosional. The upper surface of unit 1 corresponds to the seafloor topography. However, it appears as a fragmented plane due to both the erosions caused by the Yeşilırmak canyon on the sea floor and the presence of faults cutting the seafloor topography (see Figure 2).

The local scale studies conducted close to the study area (Ocakoğlu et al., 2022), the seismic units defined in the sections may correspond to the following stratigraphic units: The Plio-Quaternary sequence is over 2 s two way time (TWT) thick in the central part of the basin and thins towards the ridge where it was deposited with an onlap on the underlying 0.5 s TWT thick Oligo-Miocene Maykop sequence. Local folded sequence is identified in some part of the section, represented by approximately 0.3 s TWT thick Eocene sediments. And the oldest one is corresponded to the acoustic basement of Palaeocene-Upper Cretaceous stratigraphic unit.

Three different fault groups stand out in the seismic section in Figure 3. The first group ends at the upper contact of the acoustic basement and does not cut the upper units. These can be considered as faults that lost their activity at the beginning of the Tertiary. The second type of faults are faults that remain within unit 1 and do not cut the sea floor as seen in Figure 4. These faults are considered as faults that are coeval with sedimentation. The third type of faults are observed along the southwestern and northeastern borders of the Sinop basin. Among these faults, the ones in the northeast form the border of the central Black Sea ridge and the Sinop basin, while the ones in the southwest are located in the region close to the shelf break. These faults on both sides of the Sinop basin are inclined to face each other and the whole resembles a negative flower structure as shown in Figure 3, 4 and 5. With these features, third group faults can be considered as active faults. According to these data, the Sinop basin is a young depression limited by NW-SE stiking active faults.

In addition, while normal drag fold is observed in the sediments in front of the faulting in the northeastern part, there are compressional folds in the sediments between the faults on the southwestern edge. It can be said that the ridge in the northwestern part is symbolized by two different elevations, these elevations are separated from each other by step faults, and towards the coast of Turkey, the ridge continues as a single elevation (see Figure 3).

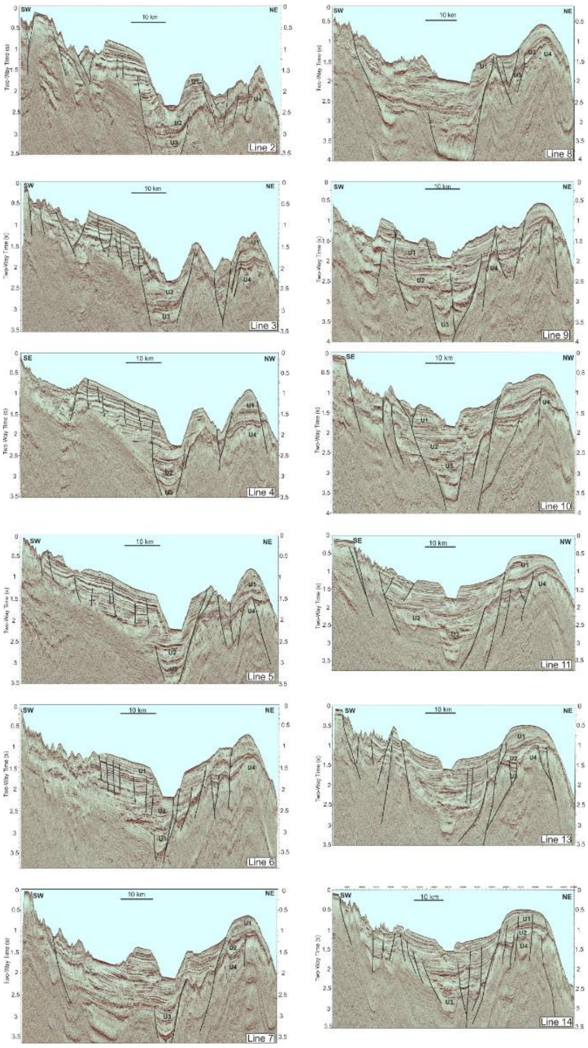

Figure 3. Interpreded seismic lines presented in this study. Black lines show the faults. U1: Plio-Quaternary unit, U2: Oligo- Miocene unit, U3: Eocene unit, U4 Acoustic basement. See Figure 2 for location of the seismic sections.

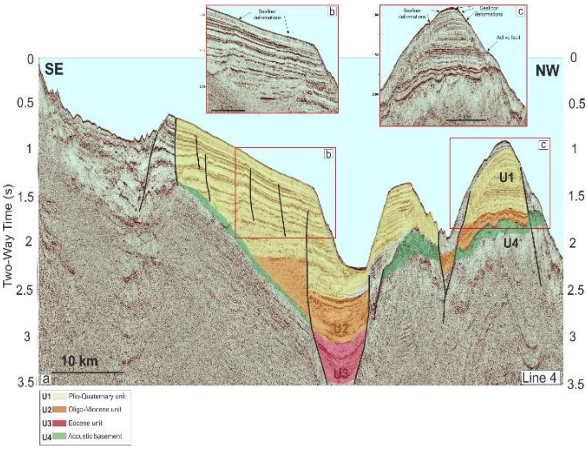

Figure 4. Showing stratigraphic and structural relationships between seismic units.

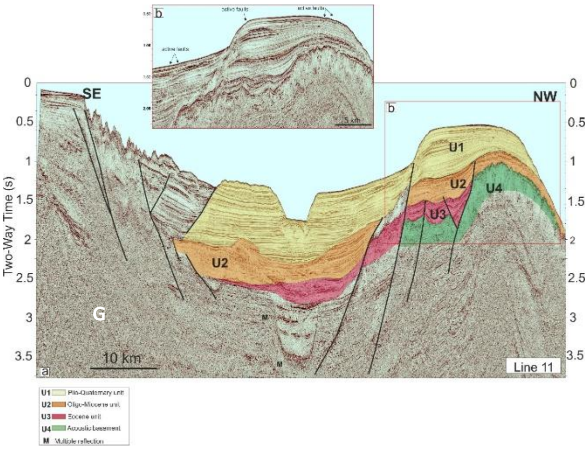

Figure 5. Showing stratigraphic and structural features of the Sinop basin.

It is observed that the seabed morphology of the region between the Turkey shelf and the Archangelsky ridge has a basin geometry. This basin structure has an indented morphology as it is eroded by the canyon and tributaries of the Yeşilırmak river. Our multi-beam bathymetric data show that submarine channel of Yeşilırmak River forms the axial submarine canyon of the present Sinop basin flowing towards the NW (Figure 6). A second submarine channel connecting to Yeşilırmak canyon and extending in the NNE-SSW direction was detected on our bathymetry map. This channel heads south towards the delta mouth of the Kızılırmak River. Accordingly, this channel can be interpreted as a paleochannel of the Kızılırmak River. This shows that the active bed of the Kızılırmak River has shifted towards the northwest over time.

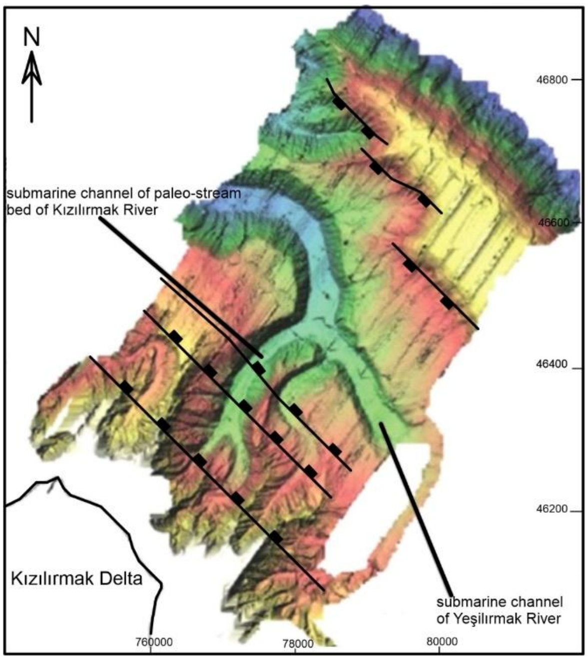

Figure 6. 3D Batymetric map of the Yeşilırmak Canyon according to our multi-beam bathymetric data (see Figure 2a for location of the high resolution DEM). Black lines marked with rectangular bulges indicate dip-slip normal faults.

As a result of the erosion of the tributaries of the Yeşilırmak River, the seabed morphology has been significantly deteriorated in certain parts of the section line. In these areas, a significant deformation is also observed in the Plio-Quaternary units under the sea floor. This situation can be thought that a fault passes here and the tributary branches of the Yeşilırmak River use these places due to the weakening of the material remaining in the fault zone that reaches the sea floor (Figure 5).

3. Discussion

There are two different views regarding the evolution of the Sinop basin: according to the first view, the Sinop basin continues its development as a young foreland basin that has formed as a flexural response to crustal thickening (Meredith and Egan, 2002). They claimed that, the effects of this compressional deformation are confined to the basin margins and there is a gradual change from compression to inversion to extensional tectonics with distance across the North and South shelf regions.

The second opinion claimed that the basin could have been formed during the late Miocene incipient dextral strike slip motion of the NAF that was initiated during extrusion of the Anatolian microplate (Rangin et al., 2002). According to this study, the Sinop trough was defined as a graben developed between the central Black Sea ridge and the Turkish coast. It is accepted that the current deformation in the region continues in the form of compressional/strike-slip tectonics due to the northward movement of the Arabian plate and the westward movement of the Anatolian Block along the NAF (Barka and Reilinger, 1997).

Our findings contain results that support both studies. Accordingly, when the basin geometry, seismic units and the faults we defined are evaluated together, it can be said that the Sinop basin resembles a negative flower structure developed under the control of strike-slip faulting (Figure 7). However, the compression-related anticline structures observed in the young units on the southwestern edge of the basin can be evaluated as data showing that the branches of the NAF could have reached the shelf edge with transpressional features. This may explain the recent earthquakes caused by transpressional faulting in the region (Kalafat, 2007).

It is seen that the majority of earthquakes that have occurred in the Black Sea in recent years have developed along reverse/thrust faults under the influence of compressional tectonics (Kalafat, 2007; Softa et al., 2018, 2021). However, there are earthquakes that show that the strike-slip component is observed as well, especially in the part of the Central Black Sea Ridge close to the Turkish coast.

In this case, considering all available literature data, the faults bordering the Mid Black Sea Ridge, which is accepted to have developed as a transform fault zone during the rifting phase of the western and eastern Black Sea basins, and then was acted as a tear fault between the thrust faults formed along the eastern and western Pontides under the effect of N-S compressional forces. Finally, it can be evaluated that it turned into a strike-slip fault zone when the NAF reached the region during the neotectonic period. According to avaliable literature, the northern coast of the black sea is characterized by earthquakes with a thrust mechanism, while the southern coast is relatively aseismic or shows limited earthquakes.

According to Dondurur (2008), normal fault zones bordering the Archangelsky Ridge are buried today due to excessive sedimentation in the Black Sea. They claimed that neither of these fault zones appear to have active faulting that extends to the seafloor. And thus, the probability of earthquakes occurring in these fault zones to cause a displacement of the sea floor is very low. However, our detailed observations in seismic sections show that some of these faults cut the sea floor and cause significant strike to dip-slip displacements. These displacements may correspond to traces of paleo earthquakes.

The medium-sized earthquakes that have occurred in this region in recent years prove that the findings we will present in this article should be taken into account (Kalafat, 2007).

The length of the active fault segments mapped in this study along the northeastern and southwestern borders of the Sinop basin varies between 10 km and 20 km. The formula of Wells and Coppersmith (1994), M = 4.86 + 1.32 x log (SRL= surface rupture length) which is based on a worldwide investigation on different normal faults, is used to calculate magnitude of mapped submarine faults. By considering the 10 to 20 km length, the southern basin margin faults can produce an earthquake of magnitude 6.2 and 6.6 respectively. The 3 fault segments between the Sinop basin and the Central Black Sea ridge are 3, 5 and 8 km long, respectively, and these segments have the potential to produce earthquakes of magnitude 3, 4 and 5, respectively. Since faults are able of producing earthquakes of greater than magnitude 5, they can be classified as seismogenic faults (McCalpin, 2009).

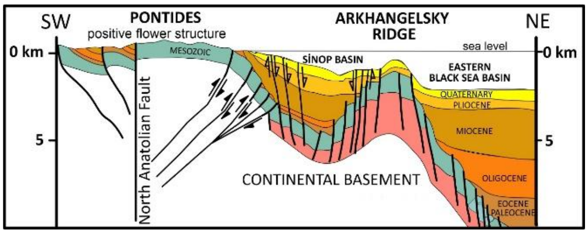

Figure 7. Regional scale seismic section passing through the Sinop basin and the eastern Black Sea basin (modified after Finetti et al., 1988). As seen in the section, the Sinop basin presents a negative flower structure. Note Sinop basin is separated from the eastern Black Sea basin by the central Black Sea ridge. In addition, branches that may be connected to the North Anatolian Fault cause a transperssional activity in a form of positive flower structure (Racano et.al. 2023) on the southwestern edge of the Sinop basin.

4. Conclusion

In this study, the Sinop basin and its surroundings are examined with Multi-Channel Seismic and Multi-Beam Bathymetric Data. Here, the submarine morphology of the Yeşilırmak Canyon was revealed and the faults bordering the Sinop basin were mapped. The seismic sections extend in the SW-NE direction from the Turkish coast to the Archangelsky Ridge. In the southern parts of the seismic sections, the submarine floor has been eroded because it remains within the drainage basin of the Yeşilırmak canyon. The northern parts of the seismic sections end on the Archangenselky ridge.

The seismic stratigrafic results obtained from the seismic sections show four seismic units. These units are distinguished from each other by changes in reflection configurations and unconformity surfaces. The oldest units (U4) is referred as acoustic basement with wavy reflectors, while its top is marked by high amplitude reflection indicating an unconformity. This uniconformity is overlain by parallel or less parallel Unit 3 deposits. Upper surface of Unit 2 is marked by an erosional surface which is overlain by parallel reflector of Unit 1. Unit 1 is the youngest sediments and mainly truncated by Yeşilırmak canyon.

The seismic units 4 to 1 can be corresponded to Paleocene-Upper Cretaceous, Eocene, Oligo-Miocene ve Plio-Quaternary units, respectively.

Three fault types of different ages were determined according to the irregularities and sudden breaks in the seismic reflectors. The oldest fault could reach only top of unit 4 has been interpreted as inactive fault. Faults that border the Sinop basin and reach the sea floor by cutting all seismic units are considered in the active fault class. However, the faults that remain within Unit 1 and do not reach the seafloor are considered as faults that are coeval with sedimentation.

The bathymetric and seismic data we have show that active faults cutting the sea floor in the region between the Archangelsky Ridge and the Turkish coast where the Sinop basin is located. Accordingly, two active fault sets bordering the Sinop basin were mapped and the earthquake hazard of the coast of Samsun was evaluated based on the relationship between the lengths of these faults and the earthquake magnitude they will produce. According to these data, faulting in the Central/Eastern Pontide structural block should be reconsidered in the context of the seismic activity of the region and re-evaluated as an earthquake hazard that will pose a risk in the future.

Author Contributions

Özel Füzün, S: Literature review, writing, data processing, Çifci, G: Financial resource, Supervision and consultation, Sözbilir, H: Writing & Review & Editing, Okay Günaydın, S: Data collection, Atgın, O: Data processing, Özel, Ö: Data processing.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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