New evidences for the formation of and for petroleum exploration in the fold-thrust zones of the central Black Sea Basin of Turkey

Şamil Şen

ABSTRACT

The central Black Sea Basin of Turkey is filled by more than 9 km (6 mi) of Upper Triassic to Holocene sedimentary and volcanic rocks. The basin has a complex history, having evolved from a rift basin to an arc basin and finally having become a retroarc foreland basin. The Upper Triassic–Lower Jurassic Akgöl and Lower Cretaceous Çağlayan Formations have a poor to good hydrocarbon source rock potential, and the middle Eocene Kusuri Formation has a limited hydrocarbon source rock potential. The basin has oil and gas seeps. Many large structures associated with extensional and compressional tectonics, which could be traps for hydrocarbon accumulations, exist.

Fifteen onshore and three offshore exploration wells were drilled in the central Black Sea Basin, but none of them had commercial quantities of hydrocarbons. The assessment of these drilling results suggests that many wells were drilled near the Ekinveren, Erikli, and Ballıfakı thrusts, where structures are complex and oil and gas seeps are common. Many wells were not drilled deep enough to test the potential carbonate and clastic reservoirs of the İnaltı and Çağlayan Formations because these intervals are locally buried by as much as 5 km (3 mi) of sedimentary and volcanic rocks. No wells have tested prospective structures in the north and east where the prospective İnalti and Çağlayan Formations are not as deeply buried. Untested hydrocarbons may exist in this area.

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EDITOR'S NOTE

Color versions of Figures 1–12 may be seen in the online version of this article.

INTRODUCTION

The Turkish sector of the Black Sea Basin is currently an area of increased interest for the petroleum industry. Fifteen offshore exploration wells in the Black Sea Basin (Figure 1) have been drilled by ExxonMobil-Petrobras-Turkish Petroleum Company (TPAO) (Sinop 1, Kastomonu 1, and Sürmene 1 wells in 2011), Chevron-TPAO (Yassıhöyük 1 well in 2010), TPAO (Ağva 1, Cide 1, and İnebolu 1 wells in 2007; and İgneada 1, Karadeniz-1, Akçakoca 1, 2, in the 1970s), British Petroleum-TPAO (Hopa 1 well in 2005), Treador-Stratic-TPAO (Ayazlı 1 well in 2004), and Arco-TPAO (Limanköy 1, 2 wells in 1999) (Menlikli et al., 2009; Şahintürk, 2012). However, only gas has been discovered by the Akçakoca 1, 2, and Ayazlı 1 wells.

The central Black Sea Basin of Turkey is a prospective area for petroleum exploration. Many researchers suggest that the Upper Triassic–Lower Jurassic Akgöl Formation and the Lower Cretaceous Çağlayan Formation have poor to good oil and gas source rock potential with types II and III organic matter (Gedik and Korkmaz, 1984; Korkmaz, 1992; Sonel et al., 1990; Sarı, 1994, Aydın et al., 1995a; Robinson et al., 1996). Aydın et al. (1995a) showed that the middle Eocene Kusuri Formation has moderate gas source rock potential. Oil and gas seeps occur north of Boyabat (Figure 1), near the Ekinveren and Bürnük thrusts (Sonel et al., 1989; Derman and İztan, 1997). Gas seeps are also found northwest of the Sinop Peninsula (Derman and İztan, 1997; Figure 1). The basin has several potential structural traps in fold-thrust

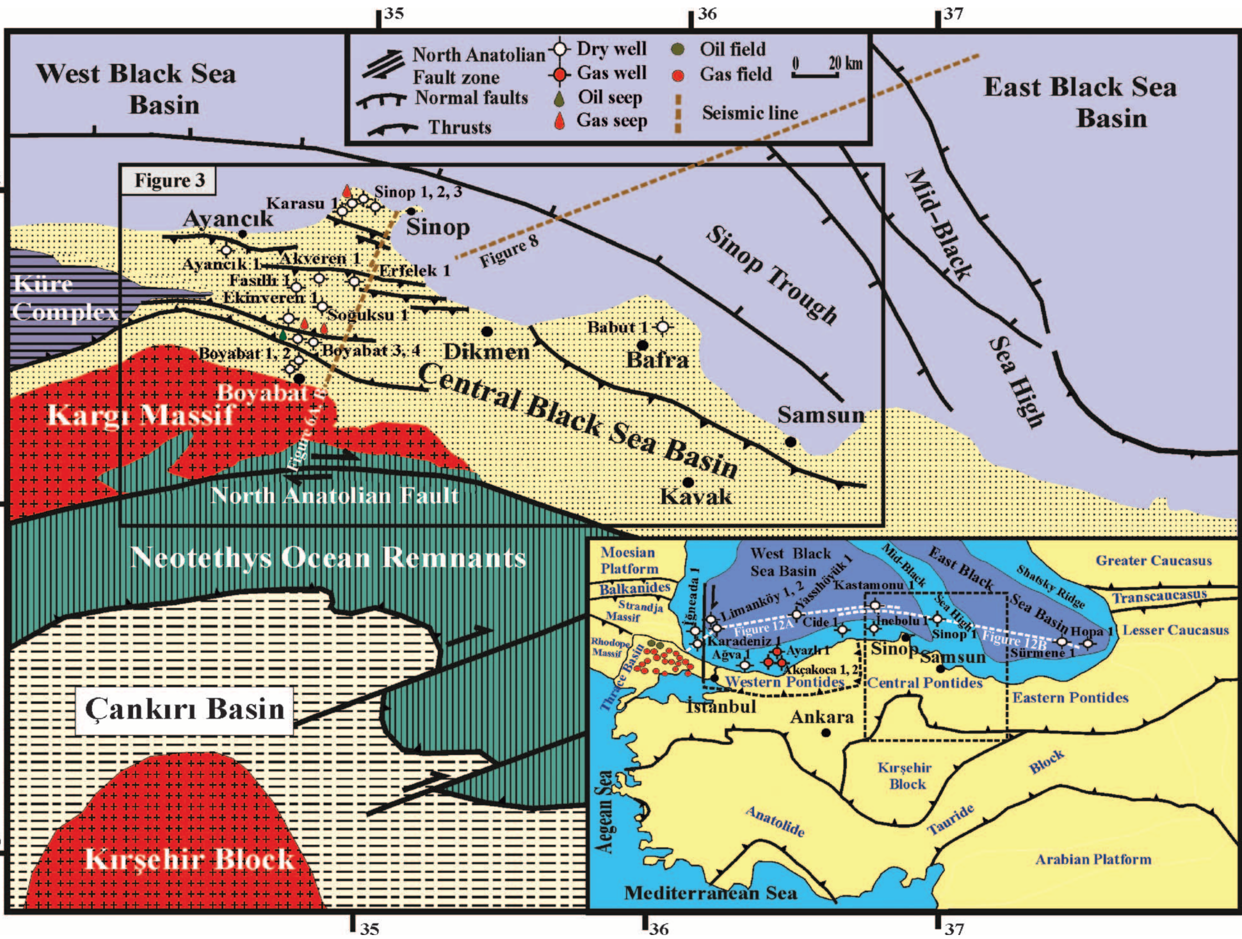

Figure 1. Simplified geologic map of the study area and surroundings (modified from Robinson et al., 1996; Yılmaz et al., 1997; Tüysüz, 1999; Cloetingh et al., 2003; Nikishin et al., 2003; Okay et al., 2006).

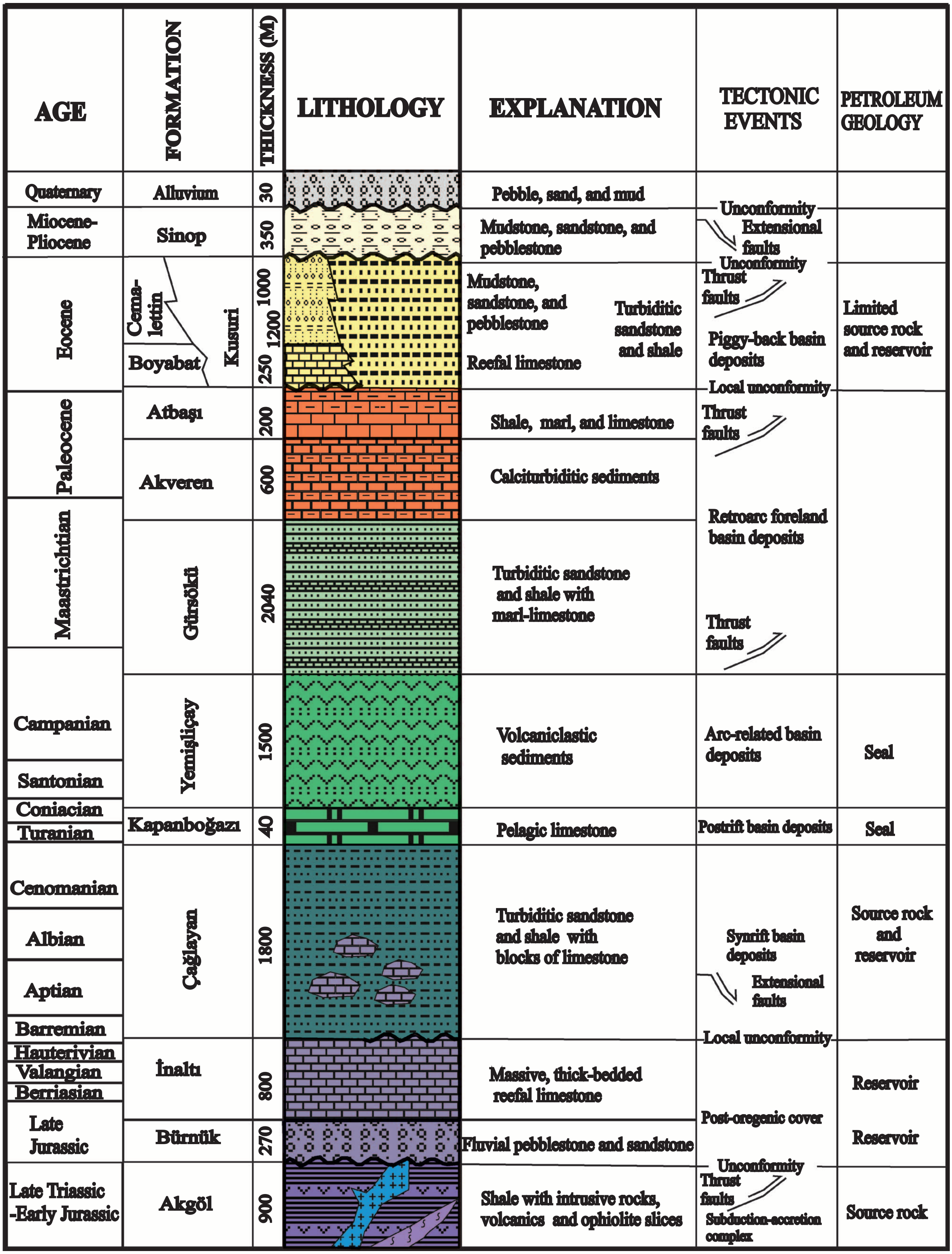

Figure 2. Generalized stratigraphic columnar section of the study area (modified from Gedik and Korkmaz, 1984; Aydın et al., 1986, 1995a, b; Korkmaz, 1992; Tüysüz, 1999; Janbu et al., 2007; Leren et al., 2007).

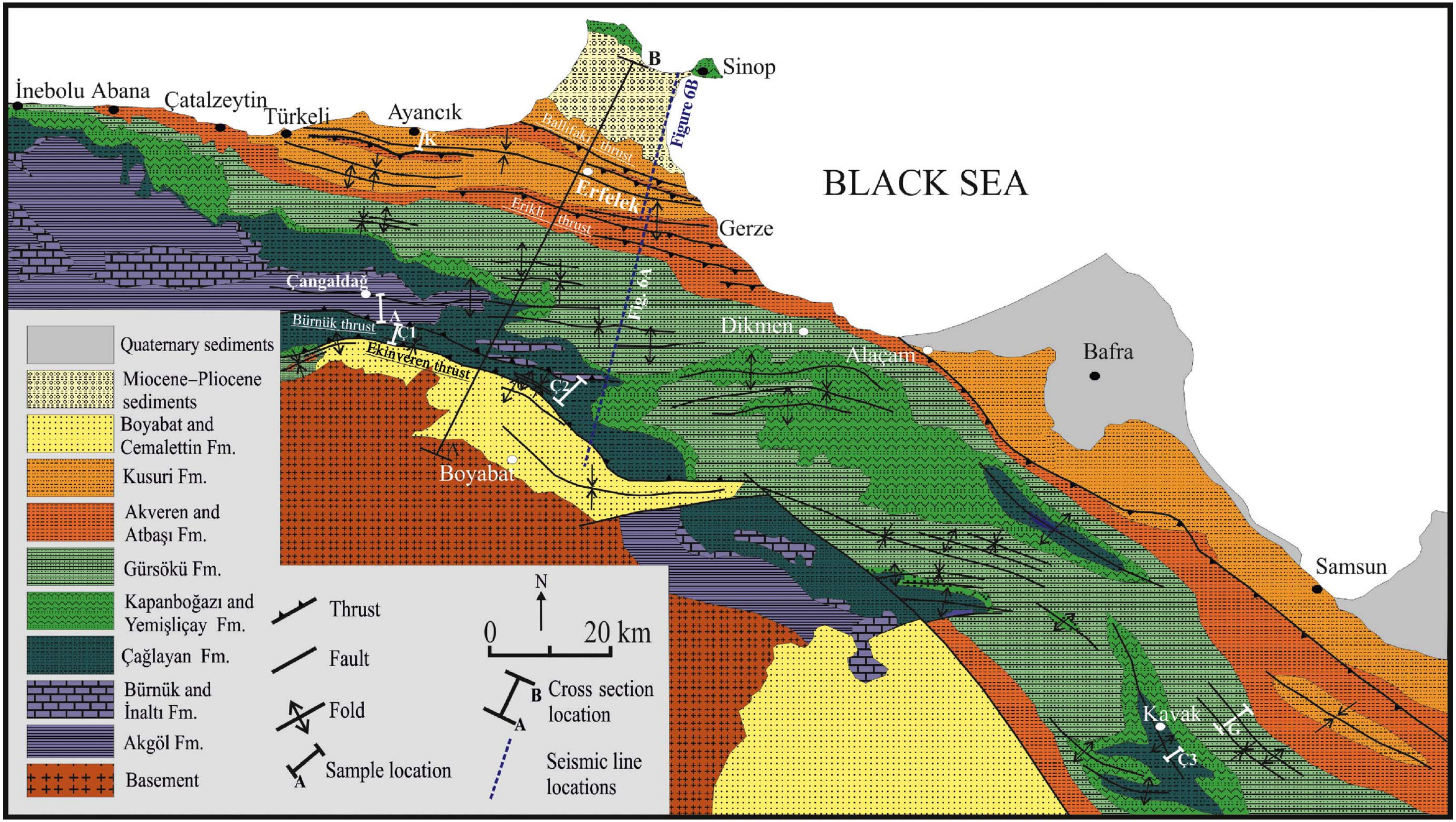

Figure 3. Geologic map of the study area (modified from Aydın et al., 1986, 1995a; Korkmaz, 1992; Tüysüz, 1999; Okay et al., 2006; Janbu et al., 2007; Leren et al., 2007; Uğuz and Sevin, 2007). Fm = Formation.

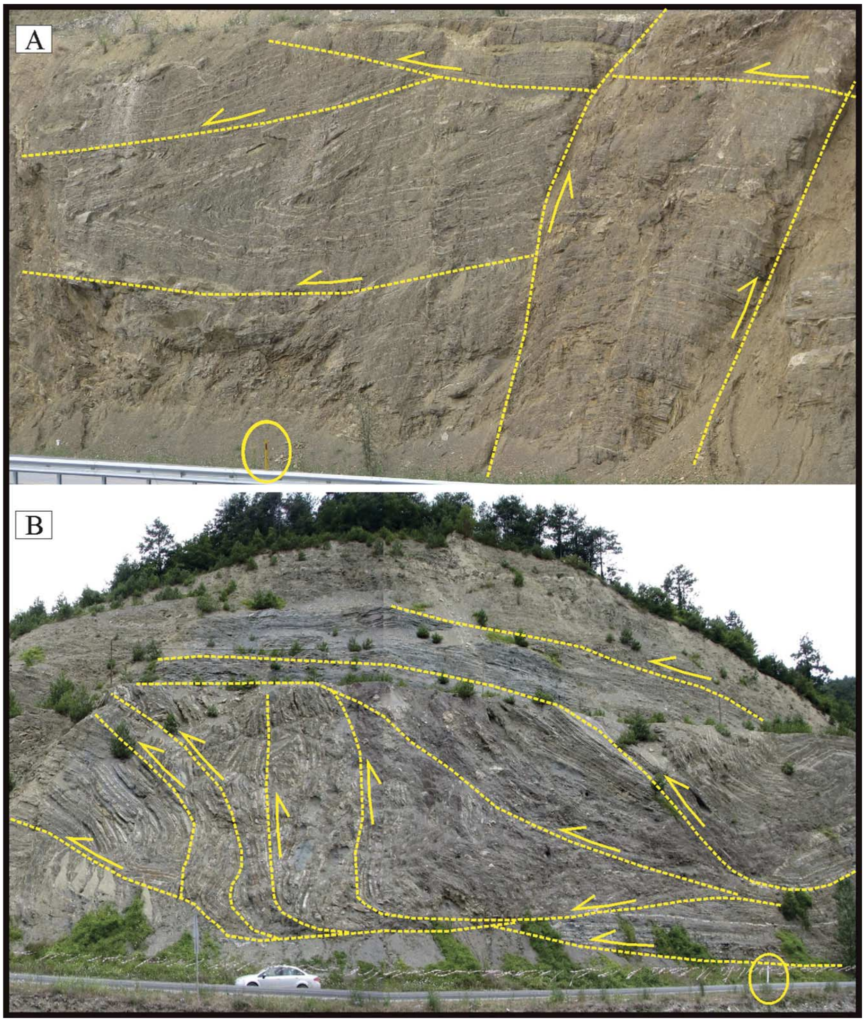

Figure 4. (A) Photograph of the duplex structures in the Yemişliçay Formation (road reflector nearly 1 m [3 ft] high for scale). (B) Photograph of the duplex structures in the Kusuri Formation.

zones (Aydın et al., 1986, 1995a; Robinson et al., 1996; Görür and Tüysüz, 1997; Tüysüz, 1999). Although 15 onshore exploration wells were drilled in the 1960s to 1990s (Figure 1), no economical oil or gas accumulation was discovered.

The aim of this article is to show why exploration in the basin has been unsuccessful to date and to show where future exploration opportunities can be found. To achieve these aims, I will first describe the sedimentary and structural settings of the basin based on 4 yr of field work and tens of seismic data. Second, data from the 15 exploration wells are reinterpreted. Third, the petroleum geology of the basin is summarized based on basin modeling, oil-to-source analysis, reservoirs, Rock-Eval–total organic carbon (TOC) analysis and organic petrographical data.

REGIONAL SETTING

The Pontides orogenic belt formed after the Paleozoic as a result of subduction and accretion during the closure of the Paleotethys and Neotethys oceans at the southern Eurasian margin (Figure 1; Okay et al., 2006). The central Black Sea Basin is located in the central Pontides, which consists of sub-Jurassic flysch and volcanics with ophiolite rocks of the Küre complex and the Kargı massif represented by the Paleotethys Ocean remnants. The southern margin of the basin is bounded by Upper Cretaceous Neotethys Ocean ophiolites and ophiolitic mélange. The Neotethys Ocean, lying between the Pontides and Anatolide-Touride and Kırşehir blocks, was mostly closed between the Upper Cretaceous and Paleocene, with a final phase

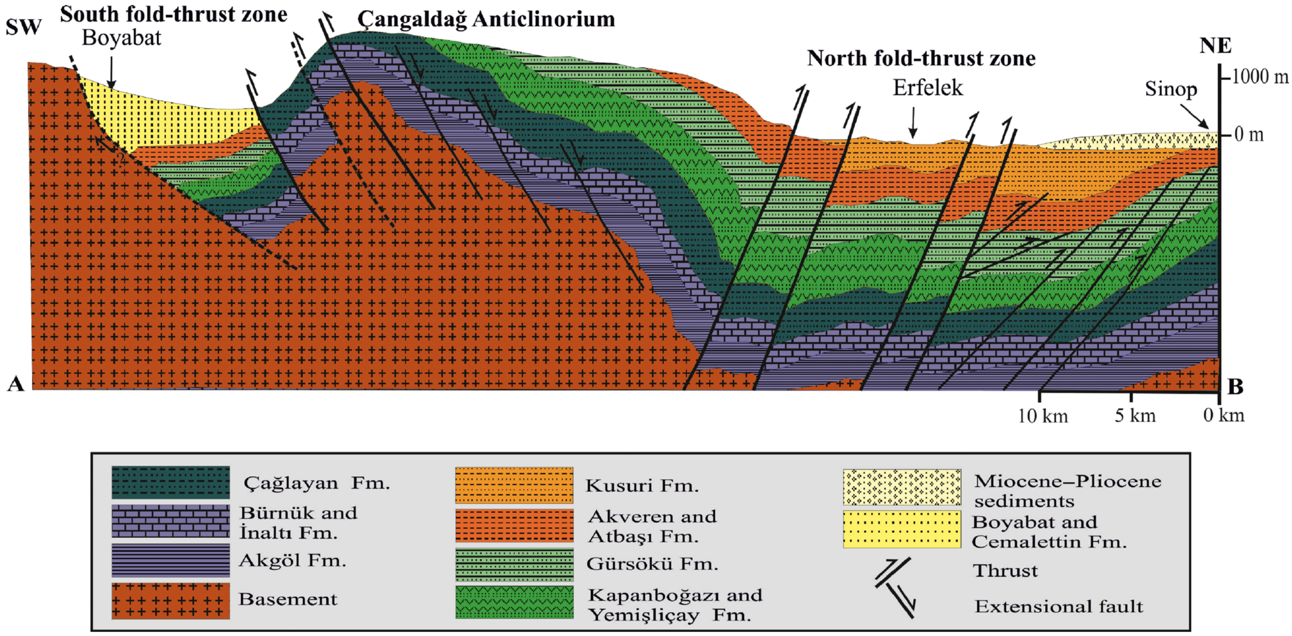

Figure 5. Simplified cross sections of the study area (see Figure 3 for location) (modified from Aydın et al., 1995a). Fm = Formation.

of closing in the late Eocene. The Çankırı foreland basin overlies the Kırşehir Block. The area south of the central Black Sea Basin has been cut by the North Anatolian fault (Aydın et al., 1986; Görür and Tüysüz, 1997; Ustaömer and Robertson, 1997; Yılmaz et al., 1997; Tüysüz, 1999; Okay et al., 2006; Meijers et al., 2010).

The offshore areas of the central Black Sea Basin comprise two major (western and eastern) subbasins separated by the mid–Black Sea High (Okay et al., 1994; Robinson et al., 1995; 1996; Görür and Tüysüz, 1997; Tüysüz, 1999; Meredith and Egan, 2002; Rangin et al., 2002; Cloetingh et al., 2003; Nikishin et al., 2003; Hippolyte et al., 2010) (Figure 1). Despite the absence of subduction-related arc magmatism in the Lower Cretaceous (Tüysüz, 1999; Hippolyte et al., 2010), the Black Sea Basin is commonly considered as a back-arc basin that was formed by the extension of northward subduction of the Neotethys Ocean (Hsu et al., 1977; Letouzey et al., 1977; Zonenshain and Le Pichon, 1986; Görür, 1988, 1997; Görür and Tüysüz, 1997). Okay et al. (1994) indicate that the opening of the western Black Sea Basin is recorded by a Paleozoic sedimentary unit (the İstanbul zone) rifted from Laurasia by two transform faults (the western Black Sea and the western Crimean faults) during the Early Cretaceous to early Eocene. The eastern Black Sea opened the rotation of the Shatsky ridge away from the mid-Black Sea High. However, on one hand, Şen et al. (2001) show that the western Black Sea fault was also active after the Eocene. On the other hand, the eastern boundary of the western Pontides is a thrust (Aydın et al., 1986; Yiğitbaş et al. 1999; Şen, 2001) (Figure 1). Stephenson and Schellart (2010) suggest that the back-arc extension of the Black Sea Basin is driven by asymmetrical slab rollback. Alternatively, it may have opened under an extensional regime following the Paleo-Tethyan collision and overthickening of the crust (Yiğitbaş et al., 1999). However, basin analysis studies suggest that the Black Sea basins were developed by both rift to back-arc extensional and retroarc foreland compressional tectonics from the Early Cretaceous to the Holocene (Şen, 2002; Meredith and Egan, 2002; Cloetingh et al., 2003; Nikishin et al., 2003; Leren et al., 2007; Janbu et al., 2007).

As the Neotethys Ocean began to close with northerly subduction in the Late Cretaceous, arc magmatism (Yılmaz et al., 1997; Tüysüz, 1999), an inner-arc basin, a back-arc basin (Tüysüz et al., 2012), and a fore-arc basin (Yiğitbaş et al., 1999) formed in the region. Subduction and arc development ended in the early Maastrichtian. Afterward,

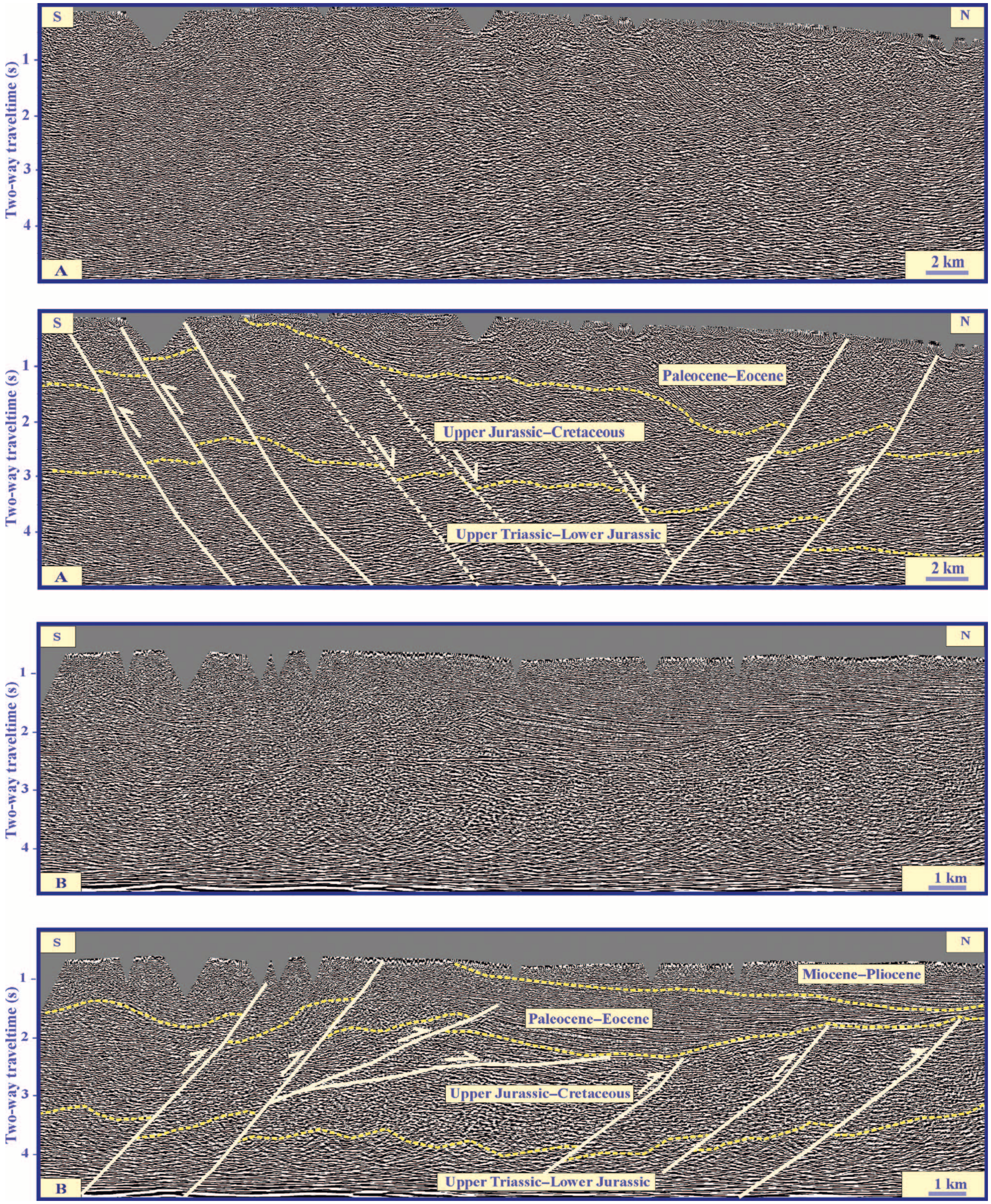

Figure 6. (A and B) Seismic lines and their interpretations along the basin (see Figures 1, 3 for location).

Figure 7. (A and B) Photographs of the anticlines in the Akveren Formation in the south of the Ayancık and Erfelek, respectively. (C) Photograph of the second-order anticlines and synclines of the Çangaldağ anticlinorium in the Gürsükü Formation in the north of the Çangaldağ.

collision of the central Pontides and the Kırşehir Block deformed the magmatic arc region into a fold-thrust zone (Şen, 2002; Sunal and Tüysüz, 2002). The Upper Cretaceous–Holocene sediments of the Black Sea Basin were deposited in a retro-arc foreland basin (Şen, 2002; Leren et al., 2007; Janbu et al., 2007). After the final collision of the continents in the late Eocene, many folds and thrusts developed in the basin (Gedik and Korkmaz, 1984; Aydın et al., 1986, 1995a; Sonel et al., 1990; Tüysüz, 1999). The basin was cut in the Pliocene by the North Anatolian fault, a major strike-slip fault (Figure 1).

TECTONOSEDIMENTARY FEATURES OF THE CENTRAL BLACK SEA BASIN

The central Black Sea Basin is filled by more than 9 km (6 mi) of Upper Triassic to Holocene sedimentary and volcanic rocks (Figures 2, 3). The Upper Triassic–Lower Jurassic Akgöl Formation is the basal sedimentary unit in the basin. It is composed of 900 m (2953 ft) of shale, sandstone, and volcanics cut by intrusive rocks and ophiolite slices. The formation is interpreted as a subduction-accretion complex related to the closure of a Paleotethys marginal basin (Aydın et al., 1986; 1995a, b;

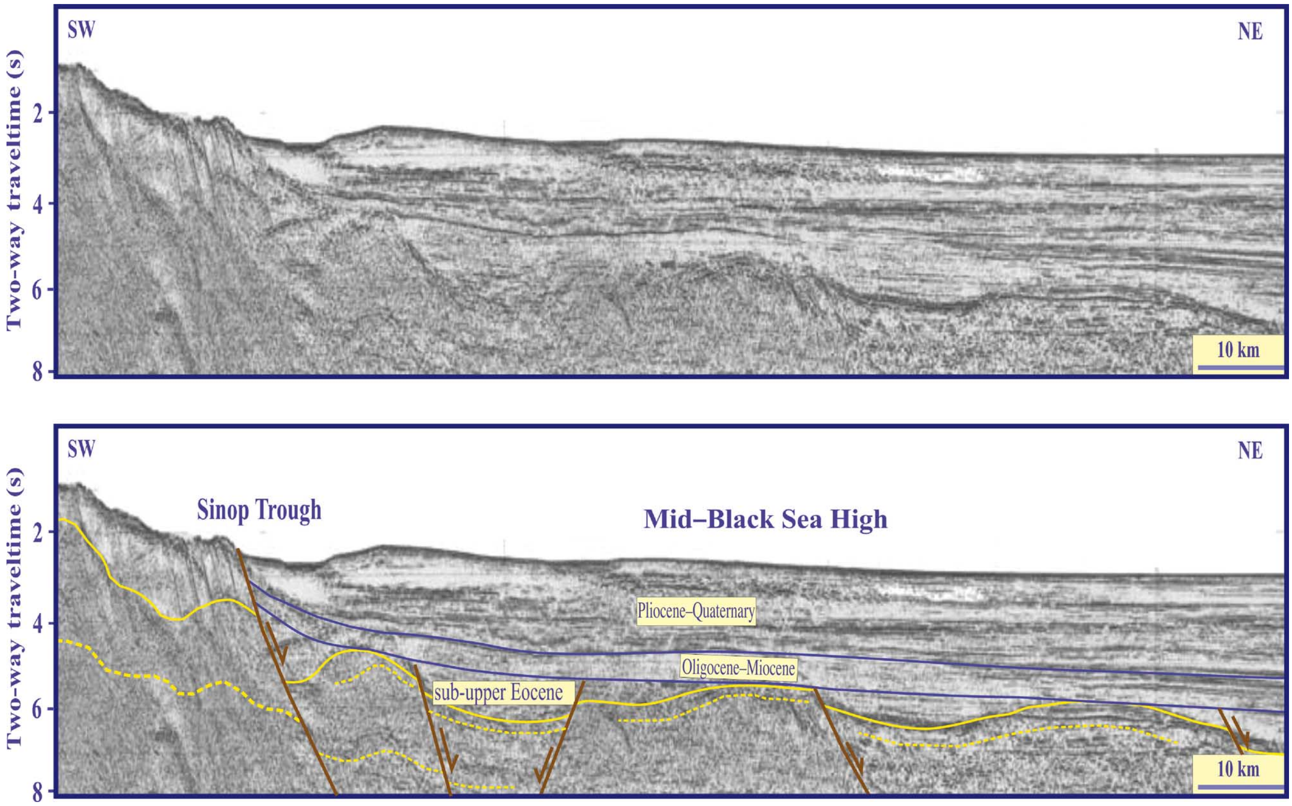

Figure 8. A seismic line and its interpretation shows the offshore area of the central Black Sea of Turkey (modified from Robinson et al., 1996; Meredith and Egan, 2002; Rangin et al., 2002) (see Figure 1 for location).

Ustaömer and Robertson, 1997). The Akgöl Formation is unconformably overlain by the Bürnük Formation, which is composed of 270 m (886 ft) of conglomerate and sandstone interpreted as the deposits of alluvial fans. The succeeding İnaltı Formation consists of 800 m (2625 ft) of Upper Jurassic–Lower Cretaceous platform carbonates (Derman and Sayılı, 1995). These carbonates are unconformably overlain by the Lower Cretaceous (Barremian–Cenomanian) Çağlayan Formation, which consists of 1800 m (5906 ft) synrift turbidites intercalated with olistrostromal breccias and large slide blocks (Gedik and Korkmaz, 1984; Aydın et al., 1986; Görür 1997; Görür and Tüysüz, 1997; Tüysüz, 1999). Hippolyte et al. (2010) alternatively suggested that these are deposits of a Neotethys accretionary prism. The Çağlayan Formation is unconformably overlain by red pelagic limestones and marls of the Kapanboğazı Formation, deposited during a Turonian–Coniacian decline of sediment supply to the basin, probably during the postrift phase of thermal subsidence (Görür et al., 1993). The Kapanboğazı Formation grades upward into the Yemişliçay Formation. This 1500 m (4921 ft) package of volcanic and volcanoclastic sediments was deposited from the Coniacian to the Campanian during an episode of arc magmatism (Gedik and Korkmaz, 1984; Aydın et al., 1986, 1995a; Korkmaz, 1992; Yılmaz et al., 1997; Tüysüz, 1999). These sediments contain duplex structures (Figure 4A). Tüysüz et al. (2012) suggested that the Yemişliçay Formation (subdivided to the Dereköy, Unaz, and Cambu units) contains arc-related magmatic rocks and inner-arc and back-arc volcanoclastic sediments. However, Yiğitbaş et al. (1999) offer that this volcanosedimentary sequence consists of fore-arc basin fills. According to this study, the Yemişliçay Formation records arc-magmatic rocks and inner-arc, back-arc, and fore-arc basin volcanoclastic sediments. The Yemişliçay Formation is followed by 2040 m (6693 ft) of turbiditic sandstone, marl, shale, and limestone of the Gürsökü Formation (Tüysüz, 1999; Leren et al., 2007). Although it has been suggested that these

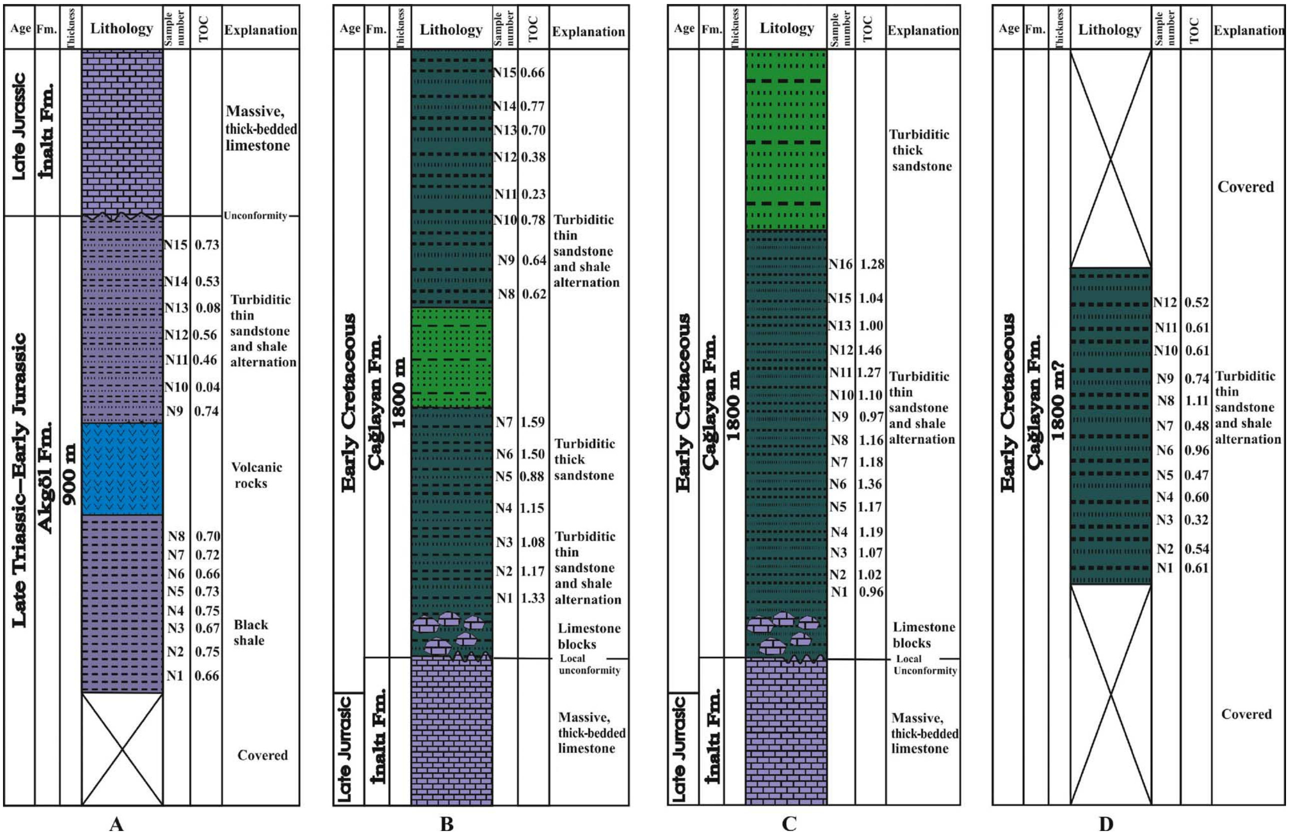

Figure 9. (A) Sedimentary log and sample locations of the Akgöl Formation (see A section in Figure 3 for location). (B, C, and D) Sedimentary logs and sample locations of the Çağlayan Formation (see Ç1, Ç2, and Ç3 sections in Figure 3 for locations). Fm = Formation; TOC = total organic carbon.

are fore-arc sediments (Okay et al., 2006; Akdağ and Kırmacı, 2008; Hippolyte et al., 2010), the lack of volcanic rocks suggests that they are retroarc foreland basin deposits instead (Şen, 2002; Janbu et al., 2007; Leren et al., 2007). These sediments grade into calciturbidites of the Akveren Formation deposited during the Maastrichtian to the Paleocene. The Atbaşı Formation has a conformable contact with the underlying Akveren Formation and consists of upper Paleocene to lower Eocene red marls, shales, and marly limestone (Aydın et al., 1986, 1995a; Leren et al., 2007). The Akveren and Atbaşı Formations accumulated in an area of flexural subsidence, which was caused by thrust-sheet crustal loading in a retroarc foreland basin (Şen, 2002; Janbu et al., 2007; Leren et al., 2007). In the southern part of the basin, the overlying deposits are middle Eocene reefal limestones of the Boyabat Formation and coarse-grained deltaic and fluvial sediments of the Cemalettin Formation. In the northern part of the basin, duplex-structures (Figure 4B) containing 1200 m (3937 ft) of siliciclastic turbidites of the Kusuri Formation are deposited (Aydın et al., 1986, 1995a; Tüysüz, 1999). These formations are accumulated within piggyback basins (Janbu et al., 2007).

STRUCTURAL FEATURES OF THE CENTRAL BLACK SEA BASIN

Şengör (1995) suggests that the structures of the basin consist of the Sinop-Ayancık fault-thrust belt, the Çangaldağ anticlinorium, the Ekinveren thrust, and the Boyabat syncline, which are developed over the intra-Çağlayan detachment. According to Robinson et al. (1996) and Meredith and Egan (2002), structures of the region are represented by one anticline in the center and two synclines in the north and south cut by low-angle thrust faults. However, this study suggests that

Table 1. Rock-Eval and Total Organic Carbon Data of Samples Taken from the Akgöl Formation and Organic Petrographical Data of Selected Samples Taken from the Akgöl Formation*

Rock-Eval and Total Organic Carbon Data**

Sample Number	TOC	S_1	S_2	S_3	T_{max}	HI	OI	PI	RC (%)	PC (%)	MINC (%)
A 1	0.66	0.01	0.06	0.19	N/A**	9	29	0.09	0.65	0.01	0.15
A 2	0.75	0.01	0.02	0.34	605	3	45	0.22	0.74	0.01	0.03
A 3	0.67	0.01	0.04	0.14	608	6	21	0.17	0.66	0.01	0.15
A 4	0.75	0	0.06	0.19	608	8	25	0.07	0.73	0.02	0.21
A 5	0.73	0.01	0.05	0.05	605	7	7	0.12	0.72	0.01	0.03
A 6	0.66	0.01	0.06	0.1	N/A	9	15	0.09	0.65	0.01	0.15
A 7	0.72	0.03	0.08	0.22	N/A	11	31	0.27	0.70	0.02	0.15
A 8	0.70	0.01	0.03	0.21	609	4	30	0.20	0.69	0.01	0.03
A 9	0.74	0.01	0.01	0.38	609	1	51	0.39	0.72	0.02	0.03
A 10	0.04	0.01	0.02	0.03	443	50	75	0.22	0.04	0	0.02
A 11	0.46	0.01	0.04	0.09	N/A	9	20	0.18	0.45	0.01	0.07
A 12	0.56	0.01	0.02	0.07	493	4	12	0.27	0.55	0.01	0.09
A 13	0.08	0	0.01	0.18	441	12	225	0.20	0.07	0.01	8.80
A 14	0.53	0.03	0.32	0.36	446	60	68	0.09	0.48	0.05	0.40
A 15	0.73	0.03	0.65	0.17	448	89	23	0.05	0.67	0.06	0.08

Organic Petrographical Data†

Sample Number	R_o (%)	Amorphous (%)	Herbaceous (%)	Woody (%)	Coaly (%)
AK 2	1.95	100	0	0	0
AK 4	2.20	100	0	0	0
AK 6	1.43	0	0	60	40
AK 8	N/A	0	0	60	40
AK 10	N/A	20	40	30	10
AK 12	1.71	0	0	30	70

*See Figure 3 for sample locations.

**TOC = total organic carbon; S_1 = the amount of volatile organic compounds in the sample; S_2 = the amount of hydrocarbon compounds generated from the thermal cracking of the kerogen; S_3 = the amount of CO_2 generated from the kerogen; T_{max} = pyrolysis temperature at the maximum rate of kerogen conversion; HI = hydrogen index; OI = oxygen index; PI = petroleum index; RC = residual carbon; PC = pyrolyzed carbon; MINC = mineral carbon; N/A = wrong data caused by weak S_2 and HI.

†R_o = vitrinite reflectance.

the detachment of Şengör (1995) or the low-angle thrusts of Robinson et al. (1996) and Meredith and Egan (2002) are fault bends flat areas of retroarc basin thrusts (Figures 4A, B; 5; 6A, B). Okay et al. (2006) shows that the southern part of the basin has a fold-thrust zone. Similar to the model of Aydın et al. (1995a), this study proposes that the structures of the basin are represented by a duplex structure containing two fold-thrust zones (the southern fold-thrust zone and the northern thrust zone) and the Çangaldağ anticlinorium (Figures 3; 4A, B; 5; 6A, B; 7A, B, C).

The central Black Sea offshore contains the sub–upper Eocene and Oligocene–Miocene to Pliocene–Quaternary sediments. Older sediments are deformed by the late Eocene fold-thrusts and probably inverted by extensional faults in the Sinop Trough and the mid–Black Sea High. Later sediments consist of undeformed Oligocene–Miocene to Pliocene–Quaternary sediments formed by abrupt subsidence caused by flexural loading and associated regional subsidence (Robinson et al., 1995, 1996; Meredith and Egan, 2002; Rangin et al., 2002; Cloetingh et al., 2003; Nikishin et al., 2003) (Figures 1, 8).

Table 2. Rock-Eval and Total Organic Carbon Data of Samples Taken from the Çağlayan Formation and Organic Petrographical Data of Selected Samples Taken from the Çağlayan Formation*

Rock-Eval and Total Organic Carbon Data**											
Sample Number	TOC	S_1	S_2	S_3	T_{max}	HI	OI	PI	RC (%)	PC (%)	MINC (%)
Ç1 1	1.33	0.15	2.26	0.06	440	170	5	0.06	1.12	0.21	0.63
Ç1 2	1.17	0.14	1.63	0.03	442	139	3	0.08	1.02	0.15	0.69
Ç1 3	1.08	0.01	0.52	0.91	445	48	84	0.02	1.00	0.08	0.09
Ç1 4	1.15	0.01	0.81	0.88	440	70	77	0.02	1.05	0.10	0.48
Ç1 5	0.88	0.11	2.76	0.19	432	314	22	0.04	0.62	0.26	4.74
Ç1 6	1.50	0.08	4.12	0.33	431	275	22	0.02	1.13	0.37	1.07
Ç1 7	1.59	0.07	4.28	0.41	430	269	26	0.02	1.20	0.39	1.10
Ç1 8	0.62	0.01	0.30	0.05	439	48	8	0.03	0.59	0.03	2.55
Ç1 9	0.64	0.00	0.21	0.34	439	33	53	0.02	0.61	0.03	2.36
Ç1 10	0.78	0.01	0.39	0.05	436	50	6	0.03	0.74	0.04	2.35
Ç1 11	0.23	0.00	0.03	0.01	436	13	4	0.01	0.23	0.00	1.60
Ç1 12	0.38	0.02	0.16	0.03	436	42	8	0.12	0.36	0.02	3.53
Ç1 13	0.70	0.02	0.37	0.05	435	53	7	0.05	0.66	0.04	1.92
Ç1 14	0.77	0.05	0.50	0.10	437	65	13	0.09	0.71	0.06	3.18
Ç1 15	0.66	0.01	0.32	0.04	435	48	6	0.02	0.63	0.03	2.00
Ç2 1	0.96	0.02	1.21	0.18	431	126	19	0.01	0.84	0.12	0.84
Ç2 2	1.02	0.01	1.45	0.20	433	142	20	0.01	0.88	0.14	1.51
Ç2 3	1.07	0.05	1.60	0.04	431	150	4	0.03	0.93	0.14	0.81
Ç2 4	1.19	0.04	1.36	0.04	433	114	3	0.03	1.07	0.12	0.65
Ç2 5	1.17	0.05	2.48	0.06	430	212	5	0.02	0.95	0.22	0.90
Ç2 6	1.36	0.09	2.61	0.10	430	192	7	0.04	1.12	0.24	0.87
Ç2 7	1.18	0.15	2.98	0.03	432	253	3	0.05	0.91	0.27	0.50
Ç2 8	1.16	0.08	2.58	0.19	428	222	16	0.03	0.93	0.23	1.13
Ç2 9	0.97	0.07	1.29	0.04	430	133	4	0.05	0.85	0.12	0.69
Ç2 10	1.10	0.06	2.39	0.04	430	217	4	0.03	0.89	0.21	1.18
Ç2 11	1.27	0.10	3.11	0.22	430	245	17	0.03	0.99	0.28	0.96
Ç2 12	1.46	0.12	3.95	0.40	428	271	27	0.03	1.09	0.37	0.96
Ç2 13	1.00	0.06	2.27	0.12	431	227	12	0.03	0.79	0.21	0.98
Ç2 15	1.04	0.06	1.97	0.34	428	189	33	0.03	0.85	0.19	1.04
Ç2 16	1.28	0.07	2.67	0.16	432	209	12	0.03	1.03	0.25	0.65
Ç3 1	0.61	0.03	0.23	0.04	466	38	7	0.11	0.58	0.03	0.06
Ç3 2	0.54	0.04	0.23	0.01	455	43	2	0.14	0.51	0.03	0.03
Ç3 3	0.32	0.02	0.15	0.01	461	47	3	0.10	0.30	0.02	0.13
Ç3 4	0.60	0.03	0.31	0.03	449	52	5	0.08	0.57	0.03	0.16
Ç3 5	0.47	0.01	0.14	0.08	491	30	17	0.08	0.45	0.02	1.45
Ç3 6	0.96	0.05	0.53	0.12	449	55	12	0.08	0.90	0.06	0.23
Ç3 7	0.48	0.07	0.23	0.04	461	48	8	0.23	0.45	0.03	0.10
Ç3 8	1.11	0.10	0.58	0.00	451	52	0	0.15	1.05	0.06	0.05
Ç3 9	0.74	0.11	0.47	0.17	448	64	23	0.19	0.68	0.06	1.57
Ç3 10	0.61	0.05	0.30	0.22	451	49	36	0.15	0.57	0.04	0.42
Ç3 11	0.61	0.06	0.28	0.01	456	46	2	0.18	0.58	0.03	0.27
Ç3 12	0.52	0.02	0.07	0.67	427	13	129	0.21	0.49	0.03	0.04

Table 2. Continued

	Organic Petrographical Data†				
Sample Number	R_o (%)	Amorphous (%)	Herbaceous (%)	Woody (%)	Coaly (%)
Ç1 2	0.81	35	20	30	15
Ç1 4	0.59	10	40	40	10
Ç1 6	0.59	45	40	10	5
Ç1 8	0.59	5	10	75	10
Ç1 10	0.59	5	10	75	10
Ç1 12	0.59	5	15	75	5
Ç1 14	0.54	5	10	80	5
Ç2 2	0.61	15	20	50	15
Ç2 4	0.47	10	25	45	20
Ç2 6	0.48	50	20	25	5
Ç2 16	0.62	40	20	25	15
Ç3 2	0.66	0	20	50	30
Ç3 4	0.76	5	20	45	30
Ç3 6	0.77	20	15	35	30
Ç3 8	0.78	0	20	45	35
Ç3 10	0.71	15	10	40	35

*See Figure 3 for sample locations.
**TOC = total organic carbon; S_1 = the amount of volatile organic compounds in the sample; S_2 = the amount of hydrocarbon compounds generated from the thermal cracking of the kerogen; S_3 = the amount of CO_2 generated from the kerogen; T_{max} = pyrolysis temperature at the maximum rate of kerogen conversion; HI = hydrogen index; OI = oxygen index; PI = petroleum index; RC = residual carbon; PC = pyrolyzed carbon; MINC = mineral carbon.
†R_o = vitrinite reflectance.

The Southern Fold-Thrust Zone

This zone is represented by the Ekinveren and Bürnük thrusts and many parallel folds. The Ekinveren thrust was formed as the Çağlayan Formation thrusted over the Cemalettin Formation in the south of the study area (Aydın et al., 1986, 1995a; Sonel et al., 1989; Korkmaz, 1992; Tüysüz, 1999).

Table 3. Rock-Eval and Total Organic Carbon Data of Samples Taken from the Gürsökü Formation*

Sample Number	TOC**	S_1**	S_2**	S_3**	T_{max}**	HI**	OI**	PI**	RC** (%)	PC** (%)	MINC** (%)
G 1	0.40	0.00	0.01	0.20	N/A**	2	50	0.00	0.39	0.01	0.61
G 2	0.53	0.00	0.01	0.44	494	2	83	0.08	0.51	0.02	0.71
G 3	0.33	0.00	0.00	0.27	446	0	82	0.39	0.32	0.01	1.62
G 4	0.23	0.00	0.02	0.35	N/A	9	152	0.21	0.22	0.01	1.07
G 5	0.24	0.00	0.07	0.09	464	29	38	0.04	0.23	0.01	6.93
G 6	0.28	0.00	0.01	0.27	N/A	4	96	0.04	0.27	0.01	0.37
G 7	0.37	0.00	0.11	0.00	482	30	0	0.04	0.36	0.01	0.74
G 8	0.40	0.00	0.09	0.01	476	22	2	0.01	0.39	0.01	1.11
G 9	0.32	0.00	0.02	0.34	N/A	6	106	0.02	0.31	0.01	0.71
G 10	0.28	0.00	0.00	0.36	N/A	0	129	0.13	0.27	0.01	0.79
G 11	0.43	0.00	0.09	0.01	465	21	2	0.03	0.42	0.01	0.48
G 12	0.45	0.01	0.14	0.03	462	31	7	0.04	0.44	0.01	2.36

*See Figure 3 for sample locations.
**TOC = total organic carbon; S_1 = the amount of volatile organic compounds in the sample; S_2 = the amount of hydrocarbon compounds generated from the thermal cracking of the kerogen; S_3 = the amount of CO_2 generated from the kerogen; T_{max} = pyrolysis temperature at the maximum rate of kerogen conversion; HI = hydrogen index; OI = oxygen index; PI = petroleum index; RC = residual carbon; PC = pyrolyzed carbon; MINC = mineral carbon; N/A = wrong data caused by weak S_2 and HI.

Table 4. Rock-Eval and Total Organic Carbon Data of Samples Taken from the Kusuri Formation*

Sample Number	TOC**	S_1**	S_2**	S_3**	T_{max}**	HI**	OI**	PI**	RC** (%)	PC** (%)	MINC** (%)
K 1	0.54	0.03	0.31	0.07	425	57	13	0.08	0.50	0.04	1.96
K 2	0.91	0.03	0.56	0.32	437	62	35	0.05	0.84	0.07	2.12
K 3	0.43	0.01	0.19	0.17	437	44	40	0.06	0.40	0.03	2.87
K 4	0.32	0.10	0.16	0.07	430	50	22	0.38	0.29	0.03	1.80
K 5	0.19	0.01	0.07	0.07	435	37	37	0.13	0.18	0.01	1.06
K 6	0.33	0.02	0.13	0.14	434	39	42	0.10	0.31	0.02	3.56
K 7	0.64	0.00	0.15	0.26	434	23	41	0.02	0.61	0.03	4.11
K 8	0.08	0.00	0.01	0.02	437	12	25	0.08	0.08	0.00	3.11

*See Figure 3 for sample locations.
**TOC = total organic carbon; S_1 = the amount of volatile organic compounds in the sample; S_2 = the amount of hydrocarbon compounds generated from the thermal cracking of the kerogen; S_3 = the amount of CO_2 generated from the kerogen; T_{max} = pyrolysis temperature at the maximum rate of kerogen conversion; HI = hydrogen index; OI = oxygen index; PI = petroleum index; RC = residual carbon; PC = pyrolyzed carbon; MINC = mineral carbon.

The Bürnük thrust was formed as the İnaltı Formation thrusted over the Çağlayan Formation. The age of the folds and thrusts is post-middle Eocene. This thrusting resulted in the formation of many anticlines and synclines. The southern fold-thrust zone cut the southern flank of the Çangaldağ anticlinorium. In addition, synrift extensional faults are also present in the Lower Cretaceous sediments (Figures 3, 5, 6A).

The Northern Fold-Thrust Zone

This zone is defined by the post-middle Eocene Erikli, Ballıfakı, and many minor thrusts. These

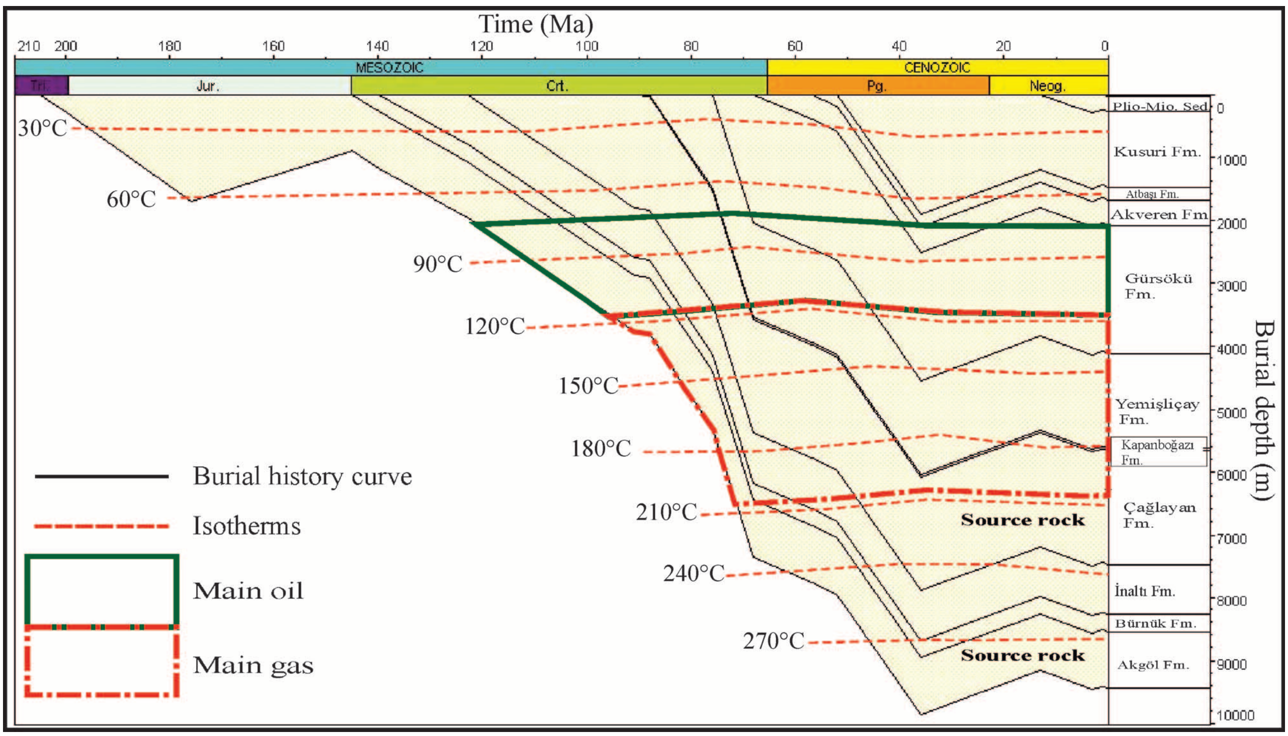

Figure 10. Generalized petroleum system graph showing burial history, isotherms, and maturity windows of the northern part of the central Black Sea Basin. Isotherms are accepted as mean 30°C/1000 m (30°C/3281 ft) (rift and arc sediments are higher than and passive margin and retroarc sediments are lower than 30°C/1000 m [30°C/3281 ft]). Fm = Formation; Jur = Jurassic; Plio-Mio = Pliocene–Miocene; Crt = Cretaceous; Pg = Paleogene; Neog = Neogene.

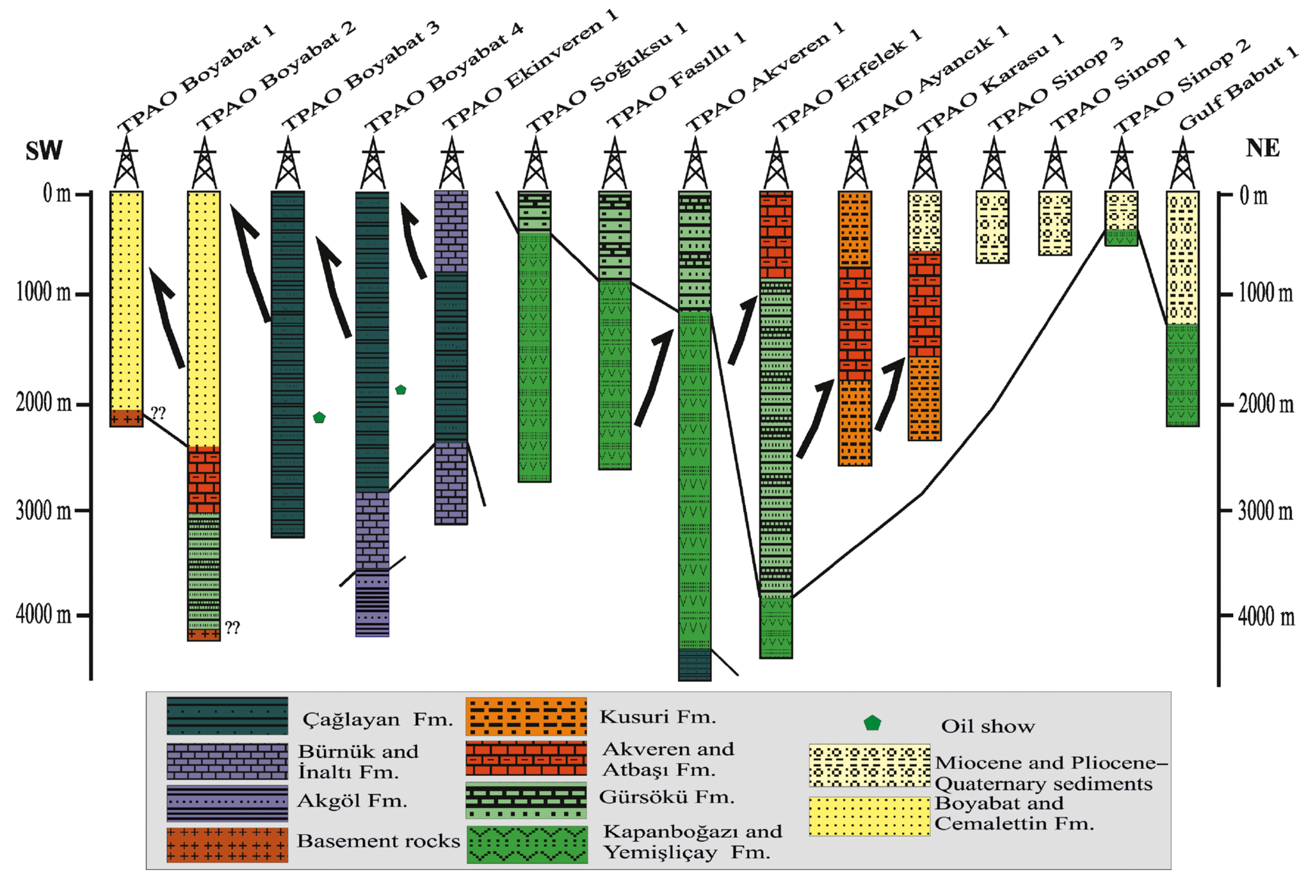

Figure 11. Lithology logs of the exploration wells drilled in the onshore area. Fm = Formation; TPAO = Turkish Petroleum Company.

thrusts were formed as the Akveren and Atbaşı Formations were thrusted over the Kusuri Formation (Aydın et al., 1986; Korkmaz, 1992; Tüysüz, 1999). Some syntectonic retroarc basin thrusts are also present. Many folds exist near the thrusts. The fold-thrust zone shows typical duplex structures (Figures 3; 5; 6B; 7A, B). The fold-thrust zone is nearly 250 km (mi) long, extending from the southwest of the Sinop in the west to the south of Samsun in the east (Figure 3). The zone is parallel to the Black Sea margin (Figure 3).

The Çangaldağ Anticlinorium

The Çangaldağ area in the center of the basin is composed of a zone, measuring tens of kilometers in length, of many post–middle Eocene folds that define the Çangaldağ anticlinorium (Aydın et al., 1986; Korkmaz, 1992; Yılmaz et al., 1997; Tüysüz, 1999). As previously explained, the southern fold-thrust belt cuts across the southern flank of the Çangaldağ anticlinorium. However, field studies suggest that the anticlinorium continues to the south of Samsun (Figures 3, 5, 6A, 7C), extending from the southwest of the Sinop in the west to the south of Samsun in the east. The Çangaldağ anticlinorium is parallel to the Black Sea margin (Figure 3).

PETROLEUM PROSPECTS OF THE CENTRAL BLACK SEA BASIN

Organic-rich shales were collected from four formations (Akgöl, Çağlayan, Gürsökü, and Kusuri Formations) at six different locations within the basin to determine the source rock potential (Figure 3). Rock-Eval–TOC data analyses used a Rock-Eval–6 (RE-6) apparatus calibrated to the Institut Français du Pétrole (IFP 160000) standards. Samples were

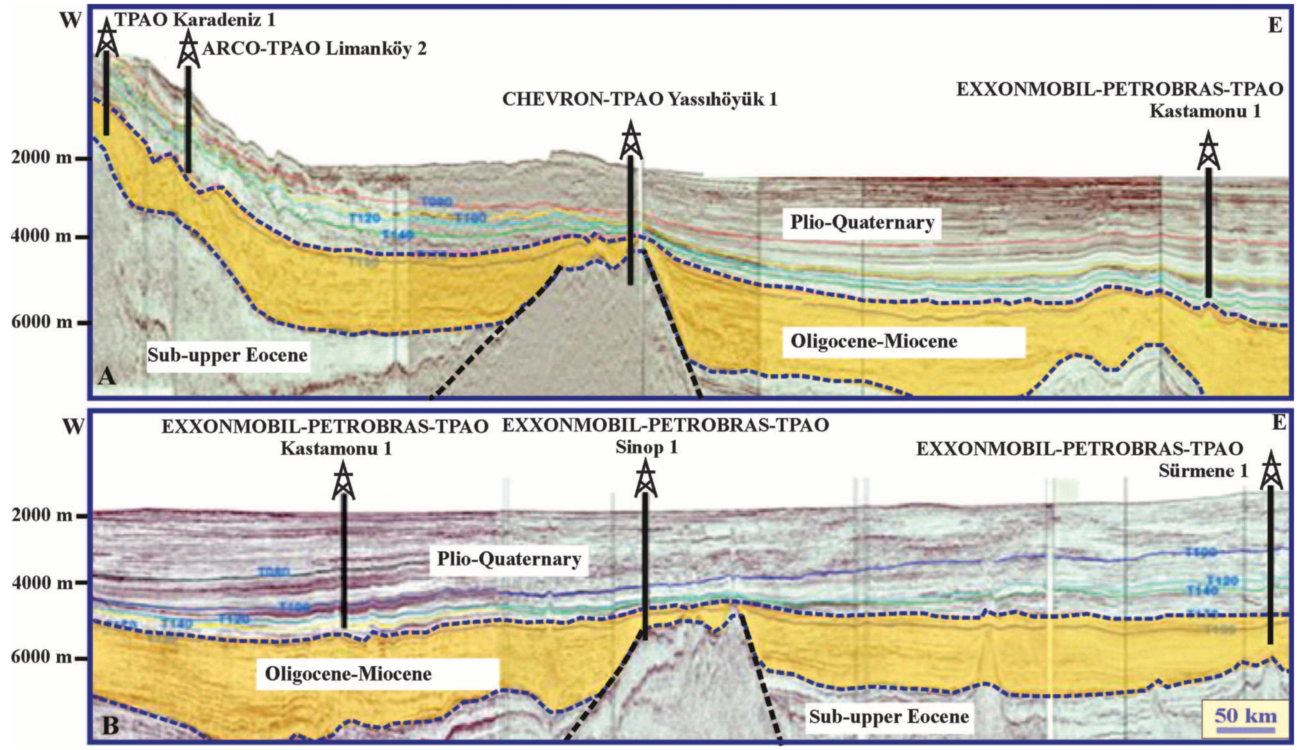

Figure 12. (A and B) Seismic lines along the offshore area of the Black Sea (modified from Şahintürk, 2012) (see Figure 1 for location).

analyzed by Rock-Eval pyrolysis using the procedures of Espitalié et al. (1980). Organic petrographic analyses were performed using a Zeiss Axioplan microscope following the procedures and definitions of Burgess (1974), Combaz (1980), and Tissot (1984). Samples were analyzed in the Turkish Petroleum Company Research Center.

The Akgöl Formation contains sandstone to shale ratios between 1:3 and 1:5. Fifteen samples from Çangaldağ (A section in Figures 3, 9A) show that these turbiditic sediments have poor to fair source rock potential, with TOC content ranging from 0.08% to 0.75% (Tissot and Welte, 1984) (Table 1). Values of T_{max} (pyrolysis temperature at the maximum rate of kerogen conversion) and R_o (vitrinite reflectance) were measured as 446 to 609°C and 1.43% to 2.20%. Thus, the sediments are overmature (Table 1A). According to organic petrographical analyses, the Akgöl Formation is represented by types II and III organic matter (Table 1B).

The turbiditic sediments of the Çağlayan Formation contain sandstone and shale ratios between 1:2 and 1:5. The 15 samples taken from Çangaldağ (Ç1 section in Figures 3, 9B), 16 samples taken from the northern part of Boyabat (Ç2 section in Figures 3, 9C), and 12 samples taken from Kavak (Ç3 section in Figures 3, 9D) show fair to good source rock potential with TOC content ranging from 0.23% to 1.59% (Tissot and Welte, 1984) (Table 2). The T_{max} values have been measured between 427 and 491°C. Thus, these sediments are mature to overmature (Table 2A). According to organic petrographical analyses, the Çağlayan Formation is represented by types II and III organic matter (Table 2B).

The Gürsükü Formation consists of turbiditic sandstone, mudstone, and marl. The Gürsükü Formation has very limited source rock potential because the TOC content of 12 surface samples of the mudstone and marl levels taken from the northeastern part of Kavak (G section in Figure 3) (Table 3) determined in this study was lower than 0.5% (except for only one sample; Table 3). The T_{max} values have been measured between 446 and 494°C. These data suggest that the Gürsokü

Formation ranges from mature to overmature (Table 3). Overmaturity may be related to the heating by volcanic rocks of the underlying Yemişliçay Formation (Korkmaz, 1992; Gries et al., 1997).

The Kusuri Formation is made up of turbiditic sandstone and shale. The sandstone to shale ratios ranges from 1:2 to 1:3. This formation has very limited source rock potential because the TOC content of the eight surface samples taken from the northern part of Ayancık (K section in Figure 3) determined in this study was lower than 0.5% (except for only three samples; Table 4). T_{max} values have been measured between 425 and 437°C. The Kusuri Formation sediments are early to middle mature (Table 4). The formation has type III organic matter according to the organic petrographical analyses in this study.

According to the basin modeling studies of Aydın et al. (1995a), hydrocarbon generation began with the deposition of the Upper Cretaceous Yemişliçay Formation. Maximum hydrocarbon generation occurred during the deposition of the Paleocene Akveren Formation. Source rocks in the basin became overmature by the time of deposition of the middle Eocene Kusuri Formation. Figure 10 shows a representative burial history for the northern part of the central Black Sea Basin. Modeling of the basin suggests that oil was generated between 122 and 84 Ma and gas was generated between 98 and 78 Ma from the source rocks of the Akgöl and Çağlayan Formations, respectively. The basin is generating gas today (Figure 10). As described above, many of the potential traps in the southern and northern fold-thrust zones and the Çangaldağ anticlinorium were formed post–middle Eocene (38 Ma). Therefore, many hydrocarbons sourced from the Akgöl and Çağlayan Formations were generated before the main trap formation. Some hydrocarbons were generated later and have accumulated in these traps. Some oil and gas seeps are found in the basin (Figure 1). According to oil-source correlation (Derman and İztan, 1997), the most probable source rock to the oil seep is the Çağlayan Formation.

Carbonates of the İnaltı Formation (800 m (2625 ft) thick, 24% porosity, and 4-md permeability; Aydın et al., 1995a) and turbiditic sandstones of the Çağlayan Formation (1800 m (5906 ft) thick, 1:2–1:5 sandstone-shale ratio, 3%–22% porosity, and 0.3–10.7-md permeability; Aydın et al., 1995a) are also potential reservoir rocks in the basin (Figure 2). The main potential seal rocks in the basin are Çağlayan Formation shales, micritic limestones of the Kapanboğazı Formation, and volcanic rocks of the Yemişliçay Formation.

Although 15 onshore exploration wells (Figures 1, 11) were drilled by the Turkish Petroleum Company (TPAO) and Gulf Oil in the central Black Sea Basin in the 1960s to 1990s, no oil or gas fields have yet been discovered. However, well-log assessments suggest that 12 wells (Boyabat 1 and 2; Soğuksu 1; Fasıllı 1; Akveren 1; Erfelek 1; Ayancık 1; Karasu 1; Sinop 1, 2, and 3; and Babut 1) interestingly did not drill deep enough to encounter any potential reservoirs defined in this study because of a thick (>5000 m [16,404 ft]) section overlying the Kusuri, Atbaşı, Akveren, Gürsökü, and Yemişliçay Formations (Figures 10, 11). The sediments are also thickened by thrusting and folding (Figures 3; 4A, B; 5; 6A, B; 7A, B, C; 11).

Six shallow wells in the north of the basin (Ayancık 1; Karasu 1; Sinop 1, 2, 3; and Babut 1) were drilled to test the Eocene and Miocene to Pliocene–Quaternary reservoirs, although sufficient source rock potential did not exist for the accumulation of hydrocarbons at the time. These wells should have been drilled deeper because the area surrounding the cities of Sinop and Bafra (also offshore of the areas) is prospective for testing the İnaltı and Çağlayan Formation reservoirs where the overlying Kusuri, Atbaşı, Akveren, and Gürsökü Formations were eroded. Note that the area is represented by a giant anticline or anticlinorium cut by normal faults in the Sinop Trough (look at the northern part of Figures 5, 6B, the southwestern part of Figure 8).

Three wells (Boyabat 3 and 4, and Ekinveren 1) did penetrate the potential reservoirs of the İnaltı and Çağlayan Formations in the traps of the southern fold-thrust zone. Note that oil and gas shows were detected in the Boyabat 3 and 4. Erosion of the seal rocks of the Kapanboğazı and Yemişliçay Formations and effects of the Ekinveren and Bürnük thrusts may have caused top seal failures in these wells (Figure 11).

Unfortunately, no exploration wells have been drilled in the most prospect reservoirs of the fold traps near the eastern areas. Because thick sediments of the Kusuri, Atbaşı, Akveren, and Gürsökü Formations were eroded in the anticlines around Kavak City and south of Bafra, Alaçam, and Dikmen cities (Figure 3), reservoirs of the Çağlayan and İnaltı Formations with suitable seal rocks of the Kapanboğazı and Yemişliçay Formations are excellent prospects to future exploration wells because reservoirs are relatively shallow.

Three offshore exploration wells in the Central Black Sea and 15 offshore exploration wells in all Black Sea basins have been drilled by TPAO and partners: ExxonMobil, Chevron, British Petroleum, Petrobras, Arco, Treador, and Stratic (Figure 1). However, only gas is produced by the Eocene Kusuri Formation from Akçakoca 1, 2, and Ayazlı 1 wells (Figure 1). The offshore wells were generally drilled to test the potential oil and gas sourced from the Oligocene–Lower Miocene Maikop equivalent sediments in the Caspian Sea. Equivalent sediments to the Maikop in the onshore of the Turkish Black Sea are only present in the Thrace Basin and north of Istanbul, northwestern Turkey. Organic geochemical studies suggest that the Oligocene–lower Miocene coal-bearing deltaic-fluvial sediments have fair to excellent source rock potential with types II and III organic matter content. However, the upper section of these sediments is immature in the Black Sea onshore (Şen, 2011a, b) and immature to early mature in the Black Sea offshore (Tekin, 1995). Very limited oil and some gas (1.5 million m^3/day) are produced by the Eocene source rocks and the Oligocene–early Miocene Maikop equivalent source rocks in the Thrace Basin and western Black Sea offshore (Gürgey et al., 2005; Hoşgörmez and Yalçın, 2005; Menlikli et al., 2009; Şen and Yıllar, 2009; Şen, 2011a, b) (Figure 1). Although the Maikop equivalent sediments were penetrated by the Karadeniz 1, Limanköy 1, İgneada 1, Yassıhöyük 1, Sürmene 1 and Sinop 1 offshore wells, no oil or gas fields have been discovered (Figure 12A, B) (Tekin, 1995; Aksu et al., 2002; Menlikli et al., 2009; Şahintürk, 2012). Unfortunately, note that the 15 offshore wells also did not penetrate potential reservoirs of the Jurassic–Lower Cretaceous İnaltı carbonates and Çağlayan turbidites because they were drilled through thick Pliocene–Quaternary and Oligocene–Miocene sediments, and the Kusuri, Atbaşı, Akveren and Yemişliçay Formations.

CONCLUSIONS

The central Black Sea Basin contains more than 9 km (6 mi) thick of Upper Triassic–Holocene sediments. The basin has a complex history and evolved from rift to arc basins and, finally, a retroarc foreland basin. The Upper Triassic–Lower Jurassic Akgöl Formation and the Lower Cretaceous Çağlayan Formation in the basin have poor to good hydrocarbon source rock potential, and the middle Eocene Kusuri Formation has limited hydrocarbon source rock potential. Carbonates of the İnaltı Formation and turbiditic sandstones of the Çağlayan Formation are potential reservoirs. The main potential seal rocks in the basin are the Çağlayan Formation shales, the Kapanboğazı Formation micritic limestone, and the Yemişliçay Formation volcanic rocks. Main traps in the basin are formed in the post–middle Eocene southern and northern fold-thrust zones and the Çangaldağ anticlinorium. Modeling study shows that source rocks began to generate oil and gas before the main period of trap formation in the late Eocene. However, gas generation continues to the present.

Although fifteen onshore and three offshore exploration wells were drilled in the central Black Sea Basin, no oil or gas fields have been discovered. The assessment of these drilling results suggests that the wells did not penetrate potential Upper Jurassic–Lower Cretaceous reservoirs because of a more than 5000 m (16,404 ft) thick section of Upper Cretaceous–Tertiary sediments. Only three wells penetrated potential reservoir intervals in locations where the major seal rocks had previously been eroded and traps were disrupted by thrusts. Because thick sediments of the Kusuri, Atbaşı, Akveren, and Gürsökü Formations were eroded in the anticlines around the cities of Kavak, Bafra, Alaçam, Dikmen, and Sinop, reservoirs of the Çağlayan and İnaltı Formations in these fold traps are excellent prospects for future exploration targets.

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