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Petrography and palynology of Late Oligocene and Middle Miocene coals in the Gelibolu peninsula, NW Turkey

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Abstract: In this study, coal samples from two different coal zones located close to each other were examined. They occur in the Late Oligocene Osmancık and Miocene Gazhanedere formations in the Gelibolu peninsula, in the SW part of the Thrace Basin (NW Turkey). This paper focuses on the organic-petrographic composition and depositional conditions of the two coal zones by using coal petrography, including maceral ratios, and palynology. The maceral composition of the Oligocene coal samples is similar to that of the Miocene coal samples. The coal samples from both locations are characterized by a high content of huminite group macerals, ranging from 46% to 78%. The prevailing maceral from this group is gelinite (31%–65%), which is indicative of a high degree of gelification of organic matter. Relatively low contents of liptinite (not exceeding 9%) and inertinite (not exceeding 8%) were also determined. The tissue preservation of organic matter was poor. The content of mineral matter is inferred from microscopic studies and is variable but generally high, varying from 6% to 46%, similar to that of other Turkish coals; it consists mostly of quartz, calcite, clay minerals, and pyrite. This input of mineral matter is probably related to periodic inundations of swamp. The mean reflectance values of samples ranged from 0.42% to 0.50% Ro, suggesting that the rank of coal is subbituminous according to ASTM classification. Low tissue preservation index (TPI) and high gelification index values suggest that both coal zones were deposited in a limnic environment. The presence of framboidal pyrite and low TPI reflect high pH values (pH 6–7) and reducing conditions during peat deposition. Two different palynological assemblages may be distinguished based on the percentages of palynomorphs. The first assemblage including the stratigraphical marker species Dicolpopollis kockelii (Calamus) suggests the Late Oligocene. The age of the second assemblage is probably the end of Middle Miocene.

Key words: Coal petrography, palynology, Gelibolu peninsula, Oligocene, Miocene, Turkey

1. Introduction

The study area includes the Tayfur and Cumalı villages, which are located in the central part of the Gelibolu peninsula in NW Turkey (Figure 1). This area forms the southwestern part of the Thrace basin, which contains a significant amount of the coal and natural gas reserves of Turkey (Tuncalı et al., 2002; Hoşgörmez and Yalçın, 2005). This basin is, therefore, very extensively studied (e.g., Lebküchner, 1974; Sümengen and Terlemez, 1991; Siyako, 2006). The presence of coals in the Gelibolu peninsula has already been reported in previous studies (Saner, 1985; Önal, 1986; Sümengen and Terlemez, 1991; Temel and Çiftçi, 2002; Akgün et al., 2013). However, all of them have focused on the geology of the coal-bearing strata and there is no study regarding the coal petrographic and palynological properties of these coals.

The aim of this paper is to determine the maceral and palynological composition of the two different coal-bearing formations, which are the Late Oligocene Osmancık and Middle Miocene Gazhanedere (Figures 1 and 2). We also aim to determine the depositional conditions of the coals using coal petrography, including maceral ratios, by the contribution of sedimentological, palynological, and paleontological evidence.

Petrographic indices and diagrams, using maceral ratios, were widely applied to the coal samples in order to determine the depositional conditions of peat accumulation (e.g., Diessel, 1986; Mukhopadhyay, 1989; Calder et al., 1991; Diessel, 1992). However, some authors (e.g., Dehmer, 1995; Wüst et al., 2001; Scott, 2002; Moore and Shearer, 2003) who studied modern peat deposits reported difficulties in using maceral ratios by themselves as an environmental indicator. It is considered that coal petrography is a scientific tool that should be supported by other geologic disciplines including palynology, sedimentology, and organic geochemistry (Scott, 2002; Suárez-Ruiz et al., 2012). This study is based on petrographic indices and diagrams, including the

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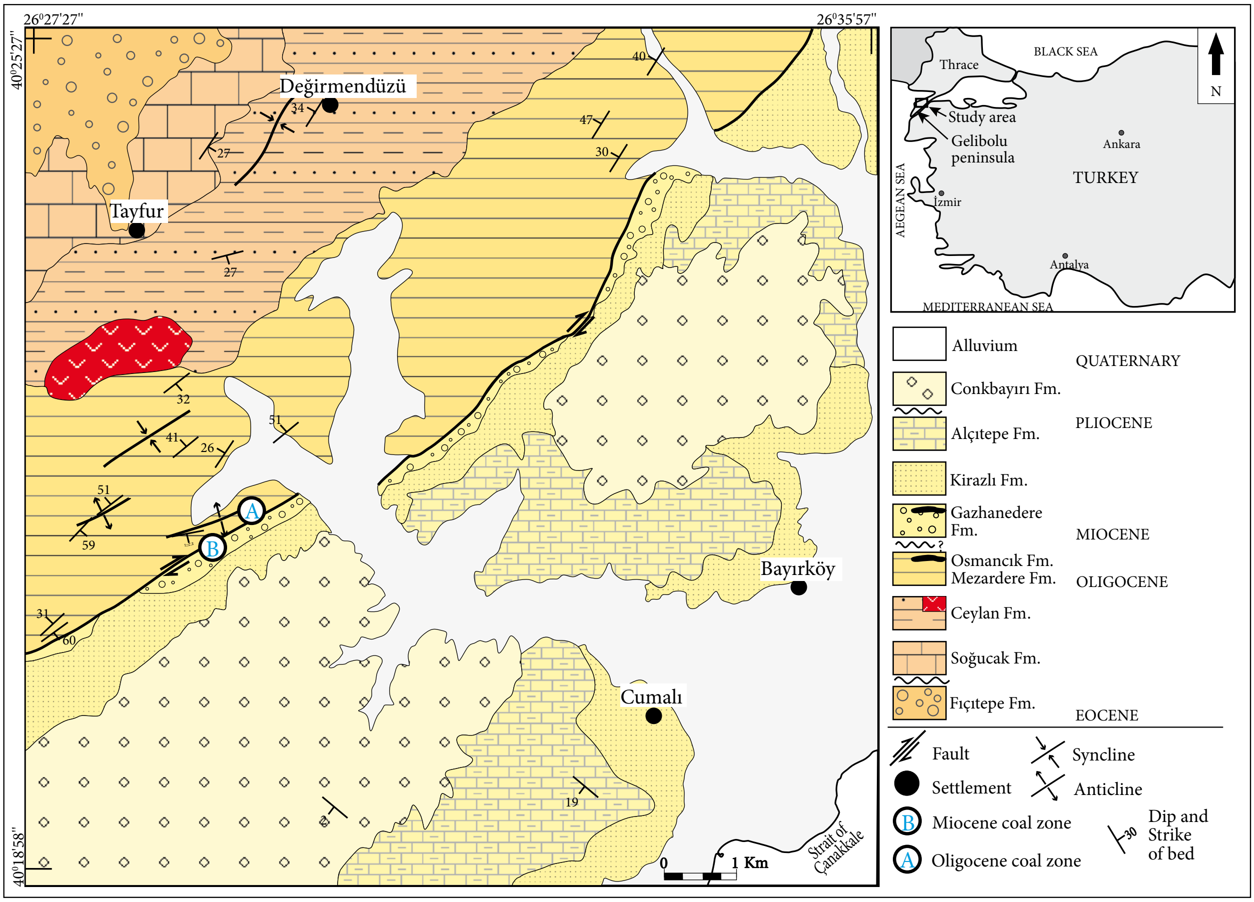

Figure 1. Geological and location map of the study area.

gelification index (GI), tissue preservation index (TPI), ABC ternary diagram, and palynology.

2. Materials and methods

The coal samples were collected from two coal zones in an abandoned open pit, each approximately 5 m thick and consisting of thin coal seams separated by intercalation of clastic materials (Figure 3). The samples were not assigned a specific level; they were collected perpendicular to the bedding of the coal zones within the Osmancık and Gazhanedere formations (Figures 1 and 2).

For organic petrographic analysis, sample preparation and reflectance measurements were performed at the General Directorate of Mineral Research and Exploration (Turkish acronym: MTA) according to International Committee for Coal and Organic Petrology (ICCP) methods (1993, 2001). Ten coal samples were examined under a microscope using reflected white light as well as blue-light excitation according to the nomenclature adopted by the ICCP (ICCP, 1993; Sýkorová et al., 2005). At least 500 points were counted to determine the maceral composition and mineral matter content of the ten coal samples. The reflectance values and coal petrographic composition of the samples were determined using a Leitz MPV microscope and the MPV-Geor software program with reflected white light.

Five of the 10 samples were analyzed by point counting for the palynological studies. The number of species counted ranged from 45 to 233 and the counting results were converted into percentages. TILIA software was used to calculate the sporomorphs according to composition of the pollen spectra, and TILIGRAPH was used to plot the sporomorph diagrams (Grimm, 1994). Selected palynomorphs were illustrated with the help of a Leica DM 3000 microscope.

3. Geological setting

The Gelibolu peninsula, which is in the SW part of the Thrace basin, consists of a Cenozoic sequence approximately 6000 m thick (Saner, 1985; Sümengen and Terlemez, 1991), and the strike of units is parallel to the long axis of the peninsula, oriented approximately NE–SW (Figure 1). The oldest units are located on the north side of the peninsula and the units become younger from north

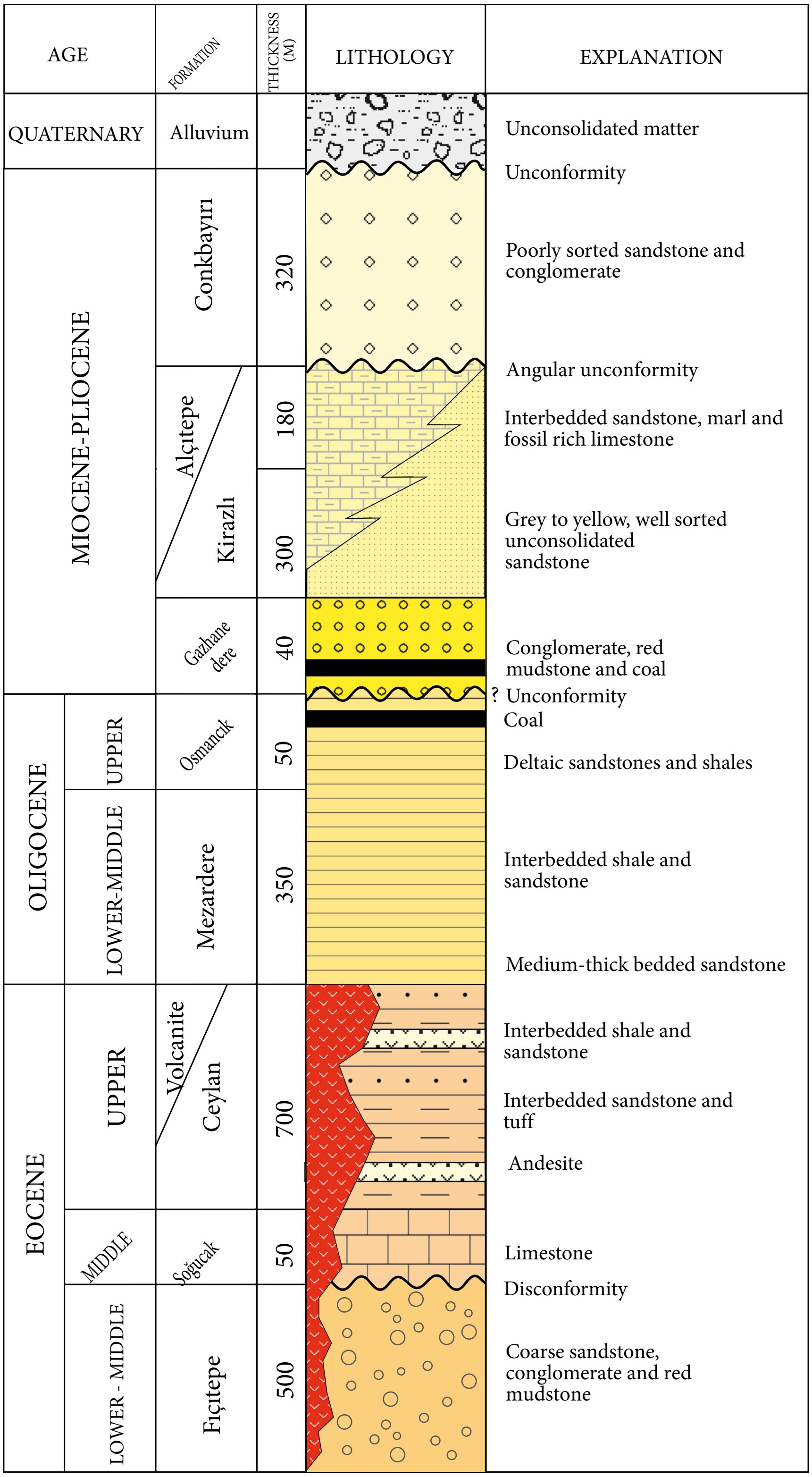

Figure 2. Generalized stratigraphic column of the study area (nonscaled).

to south. Eocene and Oligocene units strike NE–SW and dip towards the NW or SE, whereas Miocene and Pliocene units are horizontal or nearly horizontal. The basement of the Cenozoic stratigraphic units consists of Upper Cretaceous–Paleocene ophiolitic mélange (Şentürk and Okay, 1984; Okay et al., 1991; Sümengen and Terlemez, 1991) and are unconformably overlain by Paleogene units, which are subdivided into two parts by an unconformity (Siyako et al., 1989; Tüysüz et al., 1998; Temel and Çiftçi, 2002). The lower part consists of Lower–Middle Eocene regressive deposits starting with turbiditic sandstone–shale interactions and deltaic sediments (Karaağaç formation; Sfondrini, 1961) and gradually passing upward into fluvial deposits (Fıçıtepe formation; Sfondrini, 1961). The Karaağaç formation does not occur in the study area. The upper part is composed of an Upper Eocene–Oligocene sequence consisting of transgressive to regressive deposits (Sümengen et al., 1987; Tüysüz et al., 1998). It starts with a thin neritic limestone (Soğucak formation; Sümengen et al., 1987) and passes upward into turbiditic sandstone–shale interactions and volcanites (Ceylan formation; Ünal, 1967). The top of this part consists of deltaic and terrestrial sediments (Sümengen et al., 1987; Temel and Çiftçi, 2002). These sediments are represented by the Oligocene Mezardere and Osmancık formations (Ünal, 1967). In this study, the Armutburnu formation, mentioned in previous studies (e.g., Temel and Çiftçi, 2002), is incorporated into the Osmancık formation because the boundary between these formations is not distinct in the study area.

Miocene deposits rest on the Oligocene rocks above with an angular unconformity in the Gelibolu peninsula based on previous studies (Saltık, 1974; Saner, 1985; Sümengen et al., 1987); however, the boundary between Oligocene and Miocene rocks is not observed due to faulting. The fault separates the Oligocene and Miocene rocks in the study area and it is a high-angle normal fault. The Miocene sediments are divided into three formations, which are represented by terrestrial and marine-littoral deposits (Saltık, 1974; Şentürk and Karaköse, 1987; Sümengen et al., 1987; Siyako et al., 1989). The lower part of the Miocene is represented by the Gazhanedere formation (Saltık, 1974). This formation passes into the Kirazlı formation (Saltık, 1974), which is dominated by massive sandstone containing conglomerate and siltstone intercalations. The Gazhanedere and Kirazlı formations are followed by Alçıtepe formation; its depositional environment changes from shallow marine to littoral (Şentürk and Karaköse, 1987; Siyako et al., 1989; Temel and Çiftçi, 2002).

The Pliocene Conkbayırı formation identified by Şentürk and Karaköse (1987), which is represented by alluvial deposits, unconformably overlies all older formations.

3.1. Sedimentology of the coal-bearing formations

The coal zones in the study area are located on the southeastern side of Tayfur and the northwestern side of Cumalı (Figure 1). They occur in the Late Oligocene Osmancık and Miocene Gazhanedere formations. The Osmancık formation rests conformably upon the Mezardere formation and is composed of yellow to gray well-bedded sandstone and conglomerate at the base levels. Thin- to thick-bedded conglomerate consist of moderately to well-rounded and moderately sorted pebbles, floating in a sandy and muddy matrix. The sandstone occasionally shows cross-stratification. These coarse clastics pass into dark gray lenticular shale and marl deposits towards the upper part of formation. This formation also occasionally contains channel deposits that consist of sandstone and conglomerate. The depositional environment of the Osmancık formation indicates delta front and upper delta plain conditions (Temel and Çiftçi, 2002; Demirtaş, 2012). *Brotia escheri* (Brongniart) and *Polymesoda convexa* (Brongniart) were found in the coal zone (Demirtaş, 2012). According to these fossil data, a Late Oligocene age can be assigned to the Osmancık formation. This is also consistent with the age derived from palynological data (see Section 4.2). Several coal levels in this formation, with a thickness of 7 to 50 cm (Figure 3), are interbedded with mudstone, siltstone, and sandstone. This alternation suggests that the coal deposition was interrupted by inorganic sediments, probably due to small-scale subsidence, high rainfall, and intense clastic input to the peat. The coal levels are laterally discontinuous. XRD studies on two samples imply that the coal contains mostly quartz, pyrite, clinochlore, calcite, muscovite, and albite (Demirtaş, 2012). Sedimentological, palynological, and organic-petrographic properties of the coals indicate that the coal deposition occurred in a limnic environment (upper delta plain swamp and flood-plain).

The Gazhanedere formation identified by Saltık (1974), which extends in a line shape in the study area (Figure 1), overlies the Osmancık formation. The formation is composed of mainly meandering river and flood-plain environment clastic deposits, also containing lacustrine sediments and coal levels (Şentürk and Karaköse, 1987; Sümengen et al., 1987; Yaltırak et al., 1998; Demirtaş, 2012). The coarse-grained sedimentary rocks of the formation, which contain poorly sorted and moderately rounded clasts, laterally and vertically pass into red-brown mudstones frequently containing carbonate nodules and plant remains. The coal zone of the formation is composed of well-bedded and fine-grained clastics such as sandstone, claystone, and thin coal level alternations (Figure 2). XRD studies on three samples indicate that the coal contains mostly calcite, quartz, pyrite, cristobalite, gypsum, and kaolinite (Demirtaş, 2012). A lot of mollusks such as freshwater *Melanopsis* sp. and *Unio* sp. were found in the coal zone. The number of productive samples is low,

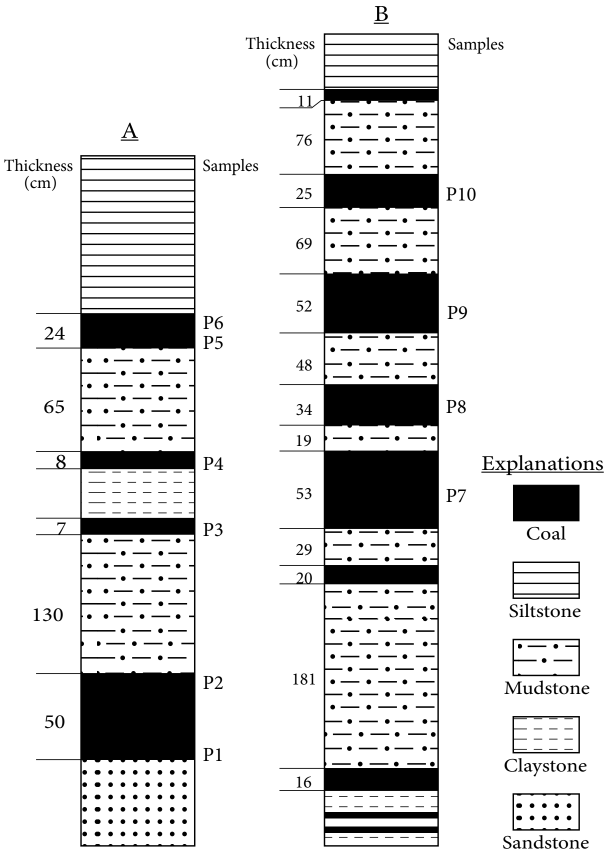

Figure 3. Stratigraphic column of the coal zones showing the sampling locations (a: Oligocene coal zone, b: Miocene coal zone).

however. Therefore, we were not able to obtain age data from the mollusks. A Middle Miocene age can be assigned to the Gazhanedere formation based on palynological data (see Section 4.2) and previous studies (Şentürk and Karaköse, 1987; Sümengen et al., 1987).

4. Results and discussion

4.1. Coal rank and petrographic composition

The rank of coal is determined by reflectance measurements from huminite macerals. The mean random huminite reflectance values range from 0.42% to 0.50% and indicate that the rank of coal is subbituminous according to ASTM classification (Stach et al., 1982).

Microscopic studies reveal that maceral distribution of the samples is relatively constant and the concentration of the maceral groups is similar throughout the coal sections (Table 1). Oligocene and Miocene coal samples are similar with respect to petrographic composition. The coal samples contain high percentages of huminite macerals (Figure 4), ranging from 46% to 78% (82% to 88%, mmf). Unstructured forms of huminite are more common than structured forms. Liptinite and inertinite macerals occur in low percentages, according to huminite. The petrographic compositions of the samples in terms of maceral and mineral matter contents along with mean random reflectance values are presented in Table 1. Characteristic maceral types of the studied samples are shown in Figures 5a–5h.

The maceral group of huminite is made up of three maceral subgroups; within them, gelohuminite is the dominant maceral subgroup, followed by telohuminite and detrohuminite. The gelohuminite subgroup includes gelinite and corpohuminite macerals derived from totally gelified organic matter (Stach et al., 1982). Gelinite is the most abundant maceral in all studied samples, ranging between 31% and 65% (Table 1; Figures 5d and 5e), indicating the high degree of gelification of organic matter (Stach et al., 1982). Corpohuminite (Figure 5b), the other member of the gelohuminite subgroup, was only observed in three samples, representing 1%. It appears with rounded shape and various sizes.

The telohuminite subgroup, which exhibits cell structures, includes the macerals textinite, texto-ulminite, and eu-ulminite. Textinite tissues are ungelified and still keep the original cell walls, being characterized by open cell lumens (Figure 5g). Based on the degree of gelification, texto-ulminite (partly gelified) and eu-ulminite (completely gelified) can be distinguished (Stach et al., 1982). In the samples, eu-ulminite is the prevailing telohuminite subgroup maceral, varying between 3% and 8%, and textinite and texto-ulminite are recorded with low concentrations.

The detrohuminite subgroup is subdivided into the macerals attrinite and densinite (Figure 5a); in the course of coalification, attrinite turns into densinite by gelification (Sýkorová et al., 2005). The dominance of densinite (up to 8%) over attrinite (up to 4%) can be easily seen in all samples (Table 1). This, along with an abundance of eu-ulminite in the telohuminite subgroup, implies increased gelification (Stach et al., 1982; Mavridou et al., 2003; Sýkorová et al., 2005). The macerals of this subgroup originated from the herbaceous and arborescent plants through the strong decay of parenchymatous and woody tissues of stems and leaves (Teichmüller, 1989; Diessel, 1992; Taylor et al., 1998; Sýkorová et al., 2005). The presence of these disintegrated grains and detrital maceral content may be associated with relatively aerobic conditions (Teichmüller et al., 1998; Iordanidis and Georgakopoulos, 2003). The minor amount of this maceral group in the samples indicate that aerobic conditions rarely occurred.

The group of liptinite macerals has a range of characteristic morphologies and a characteristic fluorescence. Through these properties, they can be easily recognized during microscopic studies. The content of

Table 1. Maceral distribution and reflectance values of the samples.

Sample no.	P1	P2	P3	P4	P5	P6	*P7	*P8	*P9	*P10	Range			Mean
Macerals														
HUMINITE	77	78	72	78	50	56	78	46	67	67	46	–	78	67
	(88)**	(88)	(84)	(83)	(83)	(84)	(86)	(85)	(82)	(82)	(82)	–	(88)	(84)
Telohuminite	7	15	12	10	8	9	11	9	10	5	5	–	15	10
Textinite	1	2	3	2	1	2	1	2	4	1	1	–	4	2
Texto-ulminite	0	5	4	2	2	3	2	3	2	1	0	–	5	2
Eu-ulminite	6	8	5	6	5	4	8	4	4	3	3	–	8	5
Detrohuminite	4	12	4	4	6	3	2	5	7	4	2	–	12	5
Densinite	3	8	4	4	5	3	2	5	5	3	2	–	8	4
Attrinite	1	4	0	0	1	0	0	0	2	1	0	–	4	1
Gelohuminite	66	51	56	64	36	44	65	32	50	58	32	–	66	52
Gelinite	65	51	55	64	36	44	65	31	49	58	31	–	65	52
Corpohuminite	1	0	1	0	0	0	0	1	1	0	0	–	1	0
LIPTINITE	3	6	9	8	4	7	6	2	8	8	2	–	9	6
	(3)	(7)	(10)	(9)	(7)	(10)	(7)	(4)	(10)	10	(3)	–	(10)	(10)
Sporinite	2	3	5	5	2	4	4	2	3	2	2	–	5	3
Alginite	1	1	2	2	1	2	0	0	2	4	0	–	4	2
Resinite	0	1	0	0	0	1	0	0	0	1	0	–	1	0
Cutinite	0	1	2	1	1	0	2	0	3	1	0	–	3	1
INERTINITE	8	5	5	8	6	4	7	6	7	7	4	–	8	6
	(9)	(5)	(6)	(9)	(10)	(6)	(8)	(11)	(9)	(9)	(6)	–	(11)	(8)
Macrinite	6	3	4	6	4	3	6	5	5	4	3	–	6	5
Fusinite	0	1	1	1	1	1	1	1	1	2	0	–	2	1
Funginite	2	1	0	1	1	0	0	0	1	1	0	–	2	1
MINERAL MATTER	13	11	14	6	40	33	9	46	18	18	6	–	46	21
Pyrite	3	3	2	1	4	5	4	9	4	7	1	–	9	4
Framboidal	2	2	2	1	3	4	3	6	3	4	1	–	6	3
Euhedral	1	0	0	0	1	1	1	2	1	2	0	–	2	1
Void Filling	0	1	0	0	0	0	0	1	0	1	0	–	1	0
Others	10	8	12	5	36	28	5	37	14	11	5	–	37	17
Ro %	0.47	0.48	0.45	0.47	0.44	0.46	0.50	0.47	0.42	0.48	0.42	–	0.50	0.46

*Miocene coal samples

**Figures in parentheses on mineral matter free basis.

liptinite in the samples does not exceed 9% and, within this group, sporinite, cutinite, alginite (Figure 5h), and resinite macerals are present. Sporinite is the most abundant liptinite maceral, occurring frequently as folded dark gray bodies (Figure 5a). The other members of this group, cutinite, alginite, and resinite, are present in minor amounts. Cutinite occurring with huminite macerals in most of the samples is easily distinguished by its linear aspect and toothed surface (Figure 5e), suggesting the presence of leafy shrubs or trees in the peat-forming environment (Stach et al., 1982). Resinite was only observed in three samples, in amounts of 1%, forming small rounded to oval-shaped dark-gray bodies (Figure 5c). It is derived not only from plant resins but also from a range of other chemicals such as balsams, latexes, fats, and waxes (Teichmüller, 1989; Scott, 2002).

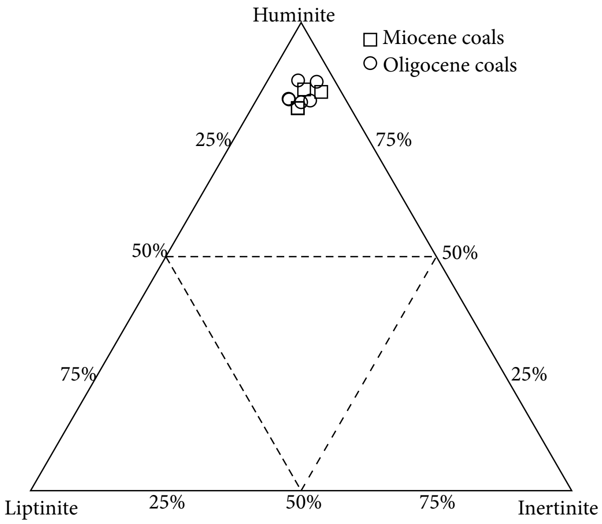

Figure 4. Maceral group distribution of the coal samples.

The origins of the inertinite group macerals are controversial. On the basis of their work on modern charcoal assemblages, Scott and Glasspool (2007) reported that the proportions of semifusinite, fusinite, and inertodetrinite are controlled by a range of factors, including fire type, temperature, and transport. In the studied samples, inertinite content varies from 4% to 8%, and this group is represented by macrinite, fusinite, and funginite macerals. Macrinite is the most abundant maceral from this group (Table 1; Figure 5f) and is found in all samples at a maximum content of 6%. Macrinite has been described as a 'gel-like' matter that has been 'fusinitized' (Taylor et al., 1998; Scott, 2002) and has been described as an 'oxidation' product (Scott, 2002). Funginite and fusinite are present in most of the samples but their content does not exceed 2%. Fusinite macerals were reported as lenses associated with huminite (Figure 5f). Funginites tend to associate mostly with clay minerals and tend to include inorganic materials, such as clay minerals and pyrites, within their cavities as in the studied samples. The minor amount of funginite indicates that aerobic conditions occurred in the peat for short time intervals (Mavridou et al., 2003).

The mineral content of the samples determined under a coal petrography microscope is variable; it varies from 6% to 46% with an average of 21%, similar to that of other Turkish coals (Karayiğit et al., 2000; Palmer et al., 2004; Toprak, 2009; Gürdal and Bozcu, 2011). It consists of clay minerals, quartz, calcite, and pyrite. This mineral input is probably related to periodic inundations. The pyrite content of the coals varies between 1% and 9%. It is usually present in the form of framboidal pyrite and suggests the activity of sulfate-reducing bacteria (Teichmüller et al., 1998).

The sulfur contents of the studied coal zones were reported by Demirtaş et al. (2014). According to this study, the coals have medium to high sulfur content (with only one exception), varying from 0.62% to 4.87% (2.46% on average). The sulfur content is closely linked with the depositional environment of coal-bearing strata based on the literature (e.g., Diessel, 1992; Chou, 2012). In general, medium and high sulfur contents are attributed to the influence of seawater during peat accumulation, and therefore seawater sulfate may be the primary source of sulfur in coal (Casagrande et al., 1980; Cohen et al., 1984; Given and Miller, 1985; Chou, 2012). On the other hand, high sulfur contents in coal deposited in the freshwater environment without seawater influence (e.g., Whateley and Tuncalı, 1995; Karayiğit et al., 2001; Gürdal and Bozcu, 2011) could be a consequence of neutral or weakly alkaline conditions induced by a calcium-rich environment (Teichmüller and Teichmüller, 1982). In the case of the studied samples, we did not find any data concerning the marine influence in the coal zones. The presence of sulfur in the coal samples is probably related to the depositional conditions (high water table and high pH).

4.2. Palynology

In this section the palynological properties of the samples from the Osmancık and Gazhanedere formations are briefly described. Ten samples were collected from these formations. However, only five of them were productive with respect to palynomorph content. These samples may be classified as follows: samples P3, P4, and P5 belong to the Oligocene coal zone (Osmancık formation, cluster A; Figure 6). Samples P8 and P10 belong to the Miocene coal zone (Gazhanedere formation, cluster B; Figure 6). Selected palynomorphs were illustrated in Figures 7 and 8.

The Oligocene coal samples (P3, P4, P5) are rich in angiosperms; however, spores and gymnosperms are rarely seen. Among the angiosperms, *Alnus*, Myricaceae, and *Calamus* occur in high quantities (Table 2). *Alnus* reaches its maximum value (58.8%) in sample P5 (Table 2). Myricaceae reaches a peak abundance of 41.2% in sample P4. The percentages of *Calamus* (morpho-species of *Dicolpopollis kockelii*) are about 10% and reach 13.3% in sample P4. The average content of *Castanea* is about 7%, with a peak abundance of 9.9% in sample P4. Additionally, the pollen of Taxodiaceae, *Engelhardia*, *Pterocarya*, Fagaceae, Cyrillaceae, and indeterminate *Tricolporopollenites* spp. occur in minor quantities. Though the pollen and spores defined from the Osmancık formation indicate a broad range over the Cenozoic, the pollen of *Calamus* makes an acme zone in the Late Oligocene of the Thrace Basin (Nakoman, 1966; Akyol, 1971; Ediger et al., 1990; Akgün et al., 2013). Its biostratigraphic importance had already been used by several researchers for the southwest Anatolian molasse basins (Kale-Tavas,

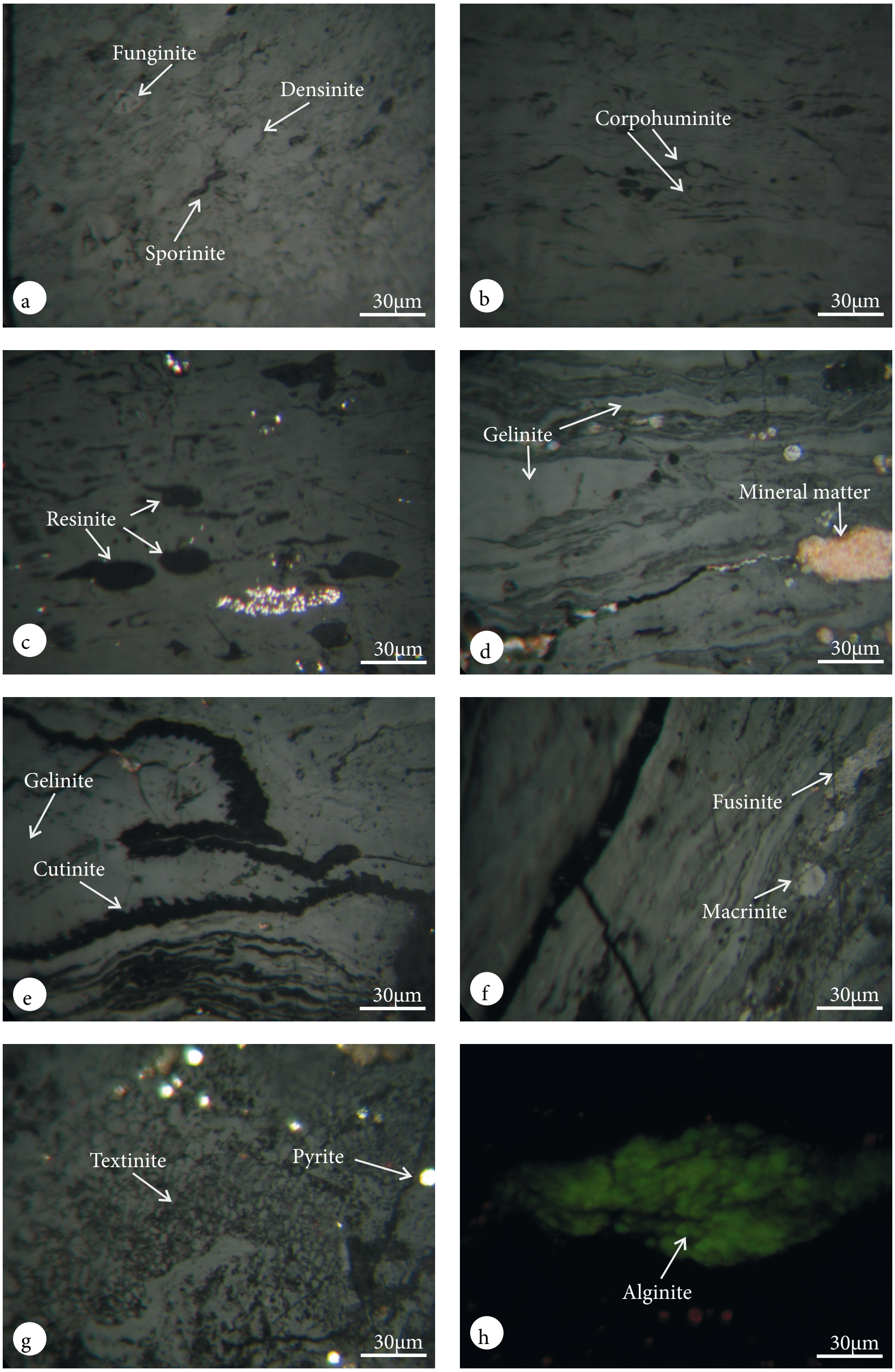

Figure 5. Photomicrographs of macerals. All photos in reflected white light except last one. a–c were prepared from the samples of the Osmancık formation (Late Oligocene), and d–h from the samples of the Gazhanedere formation (Middle Miocene). (a) Detrital huminite (densinite), sporinite, and funginite. (b) Corpohuminite. (c) Typical oval resinite macerals. (d) Gelinite maceral and mineral matter (pyrite, etc.). (e) Cutinite forms the long, thin dark bands and gelinite. (f) Macrinite and fusinite macerals. (g) Textinite and framboidal pyrite. (h) Alginite.

Table 2. Percent data for palynomorph taxa.

Taxa	Sample no.				
SPORE	P3	P4	P5	*P8	*P10
Osmundaceae	1.9	3.9	0.0	0.0	0.0
Polypodiaceae	0.0	1.3	2.0	0.0	29.3
Selaginellaceae	0.0	0.0	0.0	0.0	2.4
GYMNOSPERM					
Taxodiaceae	1.9	2.2	0.0	0.0	2.4
Cupressaceae	0.0	1.7	0.0	0.0	0.0
Pinaceae	0.0	1.3	0.0	2.1	2.4
Pinus diploxylon type	0.0	0.0	0.0	0.0	2.4
ANGIOSPERM					
Poaceae	0.0	0.0	0.0	13.7	19.5
Chenopodiaceae	0.0	0.0	0.0	0.0	2.4
Calamus	7.4	13.3	11.8	0.0	0.0
Myricaceae	7.4	41.2	0.0	24.2	4.9
Engelhardia	3.7	3.0	3.9	10.5	0.0
Carya	1.9	0.9	2.0	4.2	0.0
Carpinus	1.9	0.0	0.0	0.0	0.0
Pterocarya	5.6	0.0	0.0	0.0	0.0
Alnus	57.4	13.7	58.8	0.0	0.0
Ulmaceae	0.0	0.0	0.0	0.0	2.4
Fagaceae	3.7	0.9	5.9	2.1	0.0
Tricolpopollenites sp.	0.0	0.0	0.0	1.1	0.0
Salix	0.0	0.0	0.0	4.2	0.0
Quercus sp.	0.0	0.0	0.0	3.2	0.0
Nyssaceae	0.0	0.0	0.0	1.1	0.0
Oleaceae	0.0	0.0	0.0	6.3	14.6
Castanea	3.7	9.9	5.9	2.1	2.4
Araliaceae	0.0	0.0	0.0	2.1	0.0
Cyrillaceae	1.9	3.0	7.8	13.7	4.9
Tricolporopollenites sp.	1.9	3.9	2.0	7.4	4.9
Sapotaceae	0.0	0.0	0.0	2.1	2.4
Pediastrum	0.0	0.0	0.0	0.0	2.4
Total	100	100	100	100	100

*Miocene coal samples

Çardak-Tokça, İncesu) (Akgün and Sözbilir, 2001; Akkiraz and Akgün, 2005; Akkiraz et al., 2011). Because of this, a Late Oligocene age may be assigned to the Osmancık formation. This age is also confirmed by the mollusk fauna evidenced by *Brotia escheri* (Brongniart) and *Polymesoda convexa* (Brongniart).

The Miocene coal samples (P8, P10) are rich in angiosperms as well (Cluster B), similarly to Oligocene coals, but different angiosperms were described with high percentages. They also contain high amounts of spores, which are represented mainly by Polypodiaceae. They reach a peak abundance of 29.3% in sample P10. Angiosperms, represented mainly by Poaceae, Myricaceae, *Engelhardia*, Oleaceae, and Cyrillaceae, are present in high percentages. The pollen of Oleaceae has a maximum percentage (14.6%) in sample P10. *Engelhardia* reaches 10.5% in sample P8 (Figure 6). Components of herbaceous/reed vegetation are represented by Poaceae, Polypodiaceae, and Chenopodiaceae (Table 2). Average content of Poaceae is about 16% with maximum values of 19.5% in sample P10 (Figure 6; Table 2). In addition, pollen of *Quercus*, *Salix*, Chenopodiaceae, and Sapotaceae are represented by low percentages (Table 2). The palynological assemblage defined here includes the palynomorphs that have mostly been observed in the Miocene deposits of Turkey (Akgün and Akyol, 1987, 1999; Karayiğit et al., 1999; Akgün et al., 2000, 2007; Kayseri and Akgün, 2008; Akkiraz, 2011; Akkiraz et al., 2011, 2012). As a detail, the percentages of herbaceous pollen such as Poaceae and Chenopodiaceae rose during the Late Miocene (Akgün et al., 2000, 2007; Akkiraz et al., 2011). Unfortunately, the number of productive samples from the Gazhanedere formation is small. Mollusk fauna were not obtained in sufficient numbers for age determination, and comprise freshwater *Melanopsis* sp. and *Unio* sp. That is why it is difficult to interpret the age. In general, the age may be the end of the Middle Miocene (probably the end of the Serravallian). However, more precise dating is needed. The age of this formation is considered based on previous studies (Şentürk and Karaköse, 1987; Temel and Çiftçi, 2002). All palynological and mollusk data indicate that deposition did occur in a freshwater (lacustrine) environment. The existence of freshwater is also supported by *Pediastrum*.

4.3. Coal facies indices and depositional conditions

Depositional environments such as lake, lagoon, delta, and flood-plain, in which organic matter may accumulate, have specific chemical and physical conditions. With respect to these environments, coals have variable contents (maceral and inorganic matter) (Stach et al., 1982; Diessel, 1992). Based on this view, some researchers (e.g., Diessel, 1986; Mukhopadhyay, 1989; Calder et al., 1991; Kalkreuth et al., 1991; Lamberson et al., 1991; Diessel, 1992) have established relationships between petrographic composition (maceral and mineral matter) of the coals and peat-forming environments. They developed indices and diagrams to explain the conditions during peat formation. There are several indices and diagrams based on maceral ratios (see Suárez-Ruiz et al., 2012). In this study, among these indices and diagrams, the TPI and GI of Diessel (1986) and the ABC ternary diagram of Mukhopadhyay (1989) are applied to the coal samples.

The TPI and GI were developed by Diessel (1986) and were modified for low rank coal by Kalkreuth et al. (1991). The TPI may provide information on the degree of humification of plant material and the type of vegetation

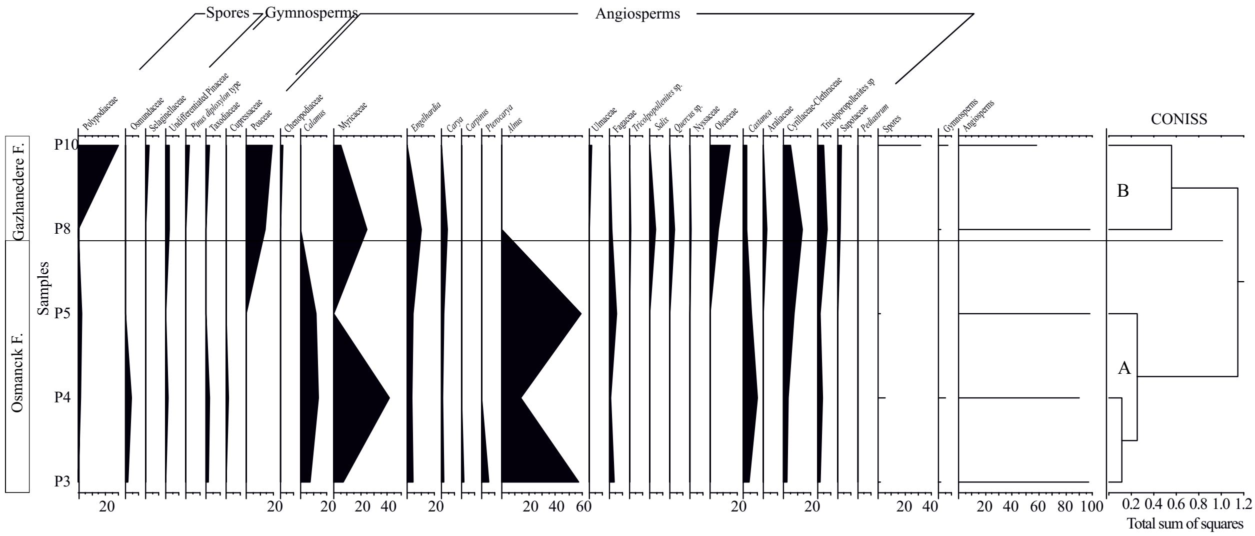

Figure 6. Simplified pollen diagram of the samples from the Osmancık and Gazhanedere formations.

(Diessel, 1992). The GI may provide information on the relative position of the water level and/or pH, as gelification requires continuous presence of water and microbial activity requires low acidity (Dehmer, 1989; Kolcon and Sachsenhofer, 1999). In the studied samples, GI values are variable and always higher than 5, due to a high amount of gelinite. TPI values are low, less than 1, as a result of a lack of structured macerals. A plot of the TPI index versus the GI index of all samples from both coal zones indicates that coals were deposited in a limnic (lacustrine or pod) environment (Figure 9).

A low TPI is explained in different ways in the literature. One is the significant contribution of herbaceous plants as a source, considering that herbaceous plants tend to decompose more quickly than woody plants (Diessel, 1992; Taylor et al., 1998; Kolcon and Sachsenhofer, 1999). However, angiosperm woods can also display poor tissue preservation (Teichmüller et al., 1998). In addition, it is concluded that gymnosperm (coniferous) forest coals display better preservation than angiosperm plants (Shearer and Moore, 1994). The other is depositional conditions that lead to strong decomposition of organic matter via microbial activity (Diessel, 1992). The palynological data revealed that the coals are rich in angiosperm plants and partly herbaceous/sedge plants (e.g., Polypodiaceae, Chenopodiaceae, Poaceae), especially in the Miocene coals. However, decay-resistant gymnosperms (conifers) such as Taxodiaceae, Cupressaceae, and Pinaceae were rarely recorded in the samples (Table 2). Poor tissue preservation in the samples is probably related to both the vegetation type (a high angiosperm/gymnosperm ratio and herbaceous plants) and to favorable conditions (high pH and wet conditions) for microbial destruction of plant remains. The high GI values and relatively high pyrite content (1%–9%) in the samples, especially the framboidal type, also indicate high bacterial activity and high pH conditions in the peat-forming environment (Diessel, 1992; Teichmüller et al., 1998).

Mukhopadhyay (1989) proposed a ternary diagram, based on maceral ratios (Figure 10), which provides information on the paleovegetation type and oxic/anoxic conditions dominant during peat accumulation. The ABC ternary plot indicates bacterial activity and dominant reed-marsh vegetation for all studied samples. Moreover, it indicates oxic to anoxic conditions (Figure 10).

Consequently, the overall petrographic composition of samples from the Late Oligocene Osmancık and Miocene Gazhanedere formations reveals that the Gelibolu coals are humic coals that were formed from terrestrial plant material. The mean random huminite reflectance values vary from 0.42% to 0.50% Ro and the rank of the coals is therefore subbituminous according to the ASTM classification system. On the other hand, the studied samples from both coal zones seem to have similar coal petrographic properties. The coals are characterized by high huminite content, which is dominated by gelinite macerals. Gelinite is indicative for a high degree of gelification of organic matter, and low liptinite and low inertinite contents. The mineral content, inferred from microscopic studies, is variable but generally high and consists mostly of clay minerals, quartz, calcite, and pyrite. Both coal zones contain high amounts of framboidal-type pyrite, suggesting the existence of bacterial activity and oxic to anoxic conditions during coal deposition, as also indicated by the ABC ternary plot. Based on the palynological studies, the type of vegetation from which

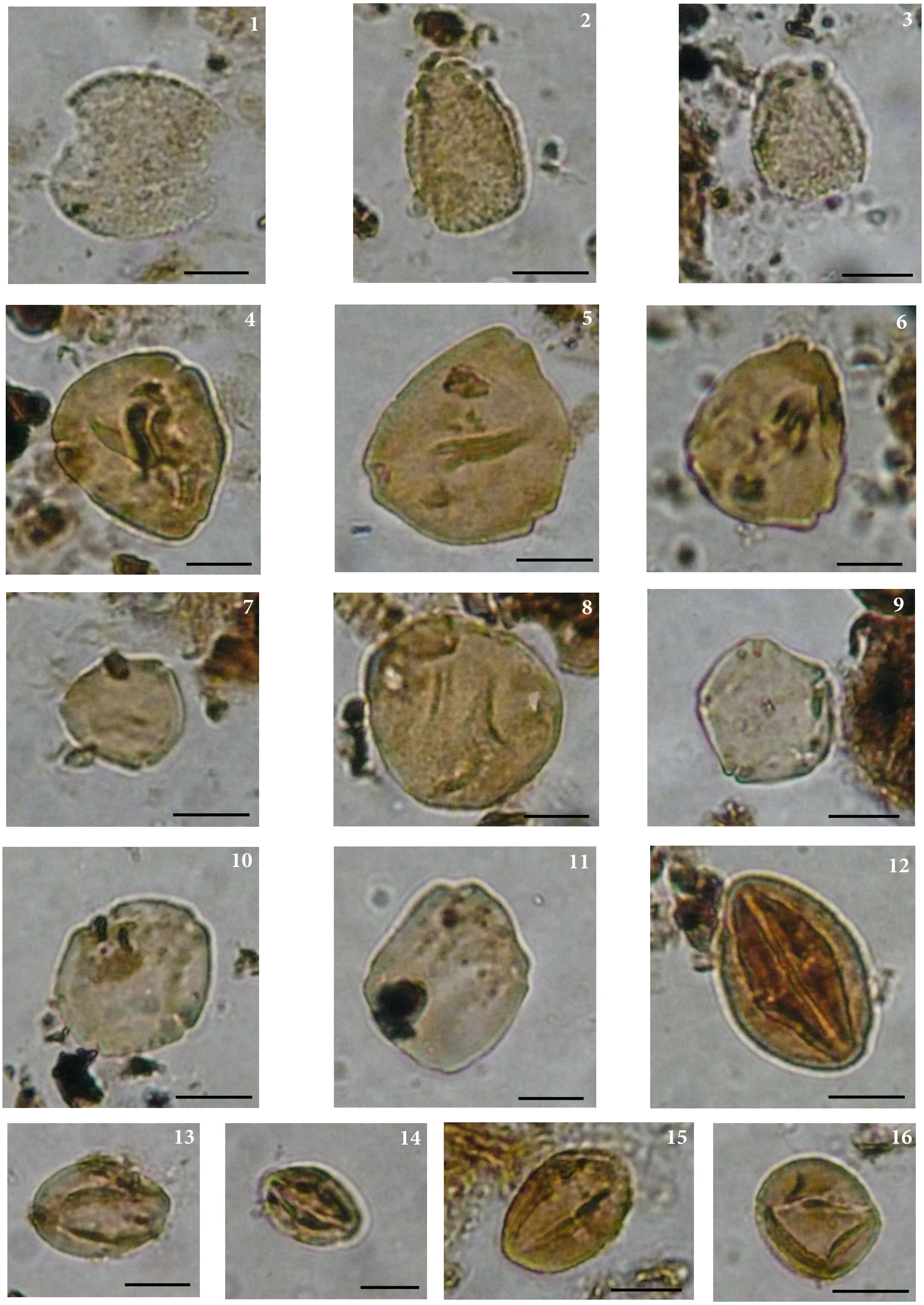

Figure 7. Selected palynomorph photomicrographs at the same scale (see 10-µm bar in the figure). This figure was prepared from the samples of the Osmancık formation (Late Oligocene). 1–3. *Calamus*, 4–6. Myricaceae, 7. *Engelhardia*, 8. *Carya*, 9–11. *Alnus*, 12. *Tricolporopollenites* sp., 13. Fagaceae, 14,15. *Castanea*, 16. Cyrillaceae.

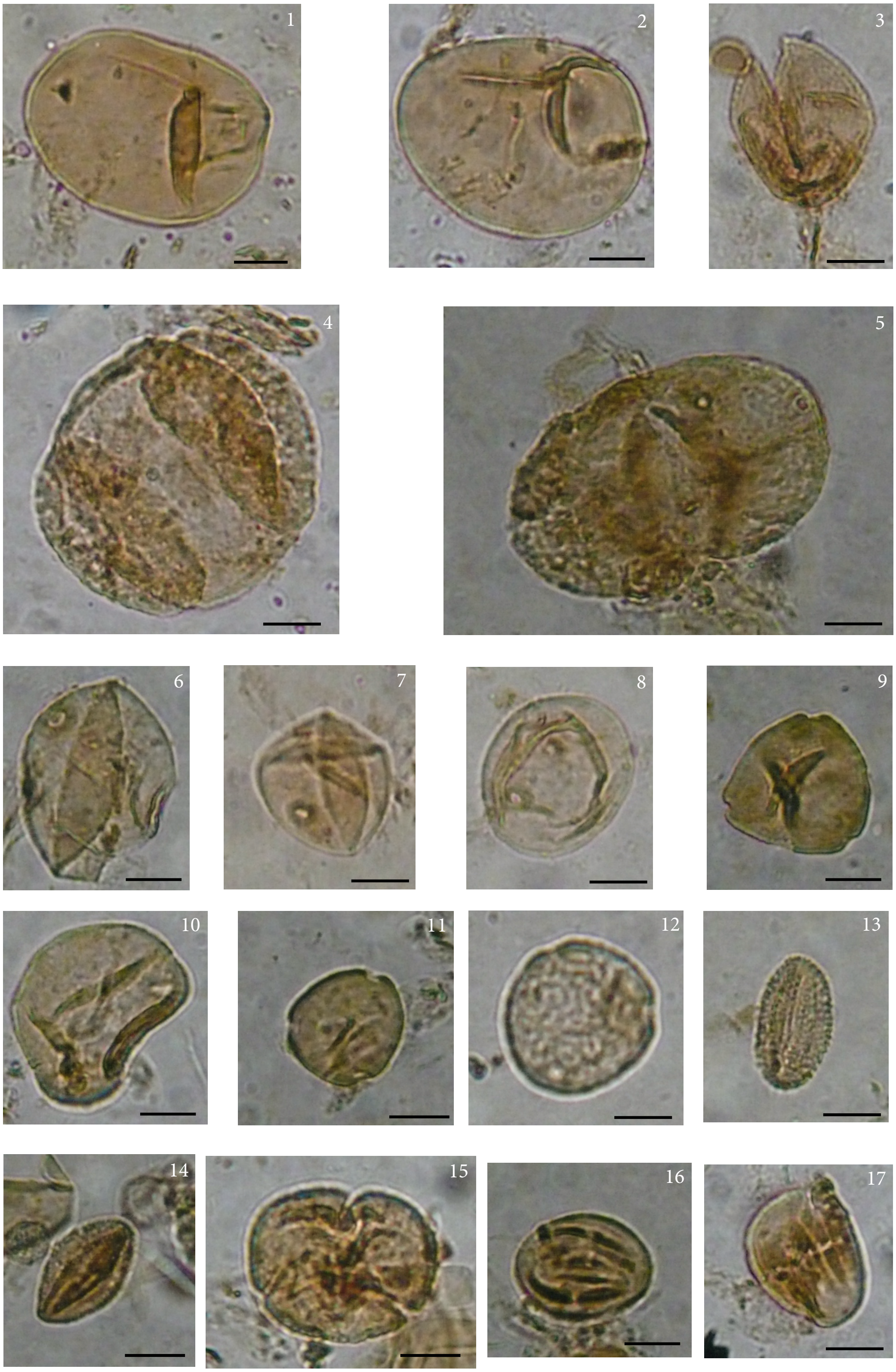

Figure 8. Selected palynomorph photomicrographs at the same scale (see 10-µm bar in the figure). This figure was prepared from the Gazhanedere formation (Miocene). 1,2. Polypodiaceae, 3. Taxodiaceae, 4. *Pinus diploxylon* type, 5. undifferentiated Pinaceae, 6–8. Poaceae, 9. Myricaceae, 10. *Carya*, 11. *Engelhardia*, 12. Ulmaceae, 13. *Salix*, 14. Oleaceae, 15. Nyssaceae, 16. Araliaceae, 17. Sapotaceae.

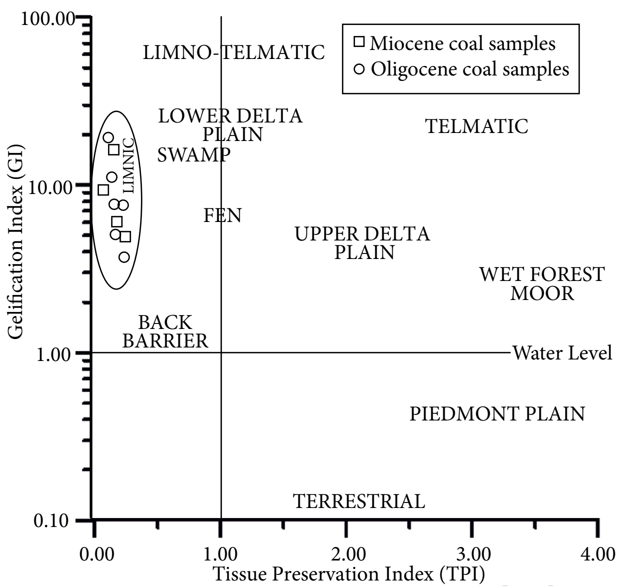

Figure 9. Facies diagram (TPI vs. GI) and depositional environment of coals (after Diessel, 1986; modified by Kalkreuth et al., 1991).

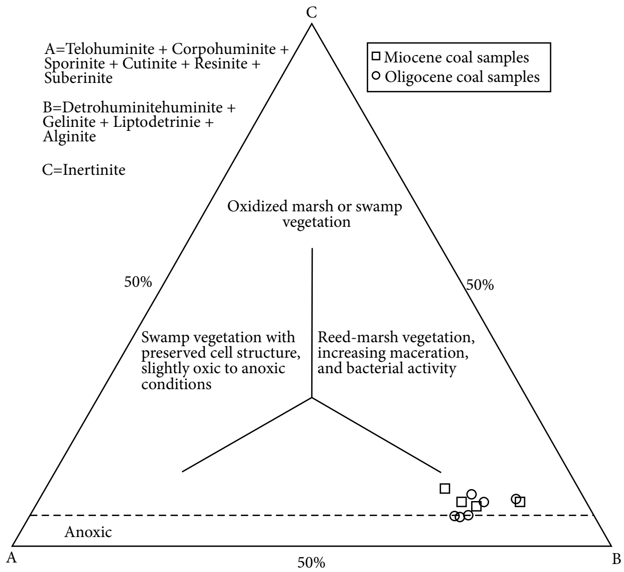

Figure 10. ABC ternary plot of the Gelibolu coals showing suggested peat-forming environments (after Mukhopadhyay, 1989).

the coals were formed was mainly angiosperm plants and spores (the Miocene coal samples in particular), whereas gymnosperm (conifer) plants are rarely seen in the samples. A diagram of TPI versus GI and palynological data of the two coal zones indicate that all of the coals were deposited in a limnic (lacustrine or pond) environment.

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