

A short-term establishment of forest fen habitat during Pliocene lignite formation in the Ptolemais Basin, NW Macedonia, Greece

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Abstract

The intermontane basin of Ptolemais is part of a major tectonic trench, located in NW Greece and includes around 65% of Greek coal reserves. The Upper Xylite Layer (UXL) is a distinct lignite layer, being 3–6 m thick and outcropping in the upper part of the Pliocene Lignite-bearing Sequence at the Notio Field and Tomeas Eksi Mines of Ptolemais. Compared with the xylite-rich lithotypes, the matrix lithotypes within UXL contain more ash. Micropetrographic studies suggest that the Upper Xylite Layer is rich in huminite (>90%). Textinite dominates in the xylite-rich lithotypes, while attrinite dominates in the matrix lithotypes. The liptinite content is < 10%, while inertinite rarely occurs. Palaeobotanical determination revealed that the xylite-rich coal originated from Coniferous vegetation, specifically from *Glyptostrobus europaeus*. The occurrence of *G. europaeus* as a coal-forming element is significant because, though this kind of vegetation was common in many Greek coals of Miocene age, this is the first time it has been recorded from the Pliocene. This study suggests that the Upper Xylite Layer is autochthonous. According to coal-facies diagrammes, peat accumulated under pure telmatic conditions in a relatively wet forest fen. Both herbaceous and arboreal vegetation contributed to peat formation.

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1. Introduction

In Greece, lignite is abundant in more than 60 intermontane and paralic basins (Koukoulas and Koukoulas, 1995), the most important of which is the West-Macedonian tectonic trench (Fig. 1a), where more than 65% of the total Greek lignite reserves are hosted. The lignite is mined in open pits for power

generation, and satisfies nearly 70% of the domestic energy demand.

Geological studies carried out in recent decades in this area provided significant information concerning the tectonic and the stratigraphic evolution of Neogene and Quaternary sedimentary in-filling of the tectonic basin, as well as descriptions of the petrographic and geochemical features of the lignite seams (e.g., Anastopoulos and Koukoulas, 1972; Cameron et al., 1984; Velitzelos and Gregor, 1990; van Vugt et al., 1998; Steenbrink et al., 1999, 2000; Georgakopoulos and Valceva, 2000; Kalaitzidis et al., 2000; Koukoulas et al., 2000; Papanicolaou et al., 2000;

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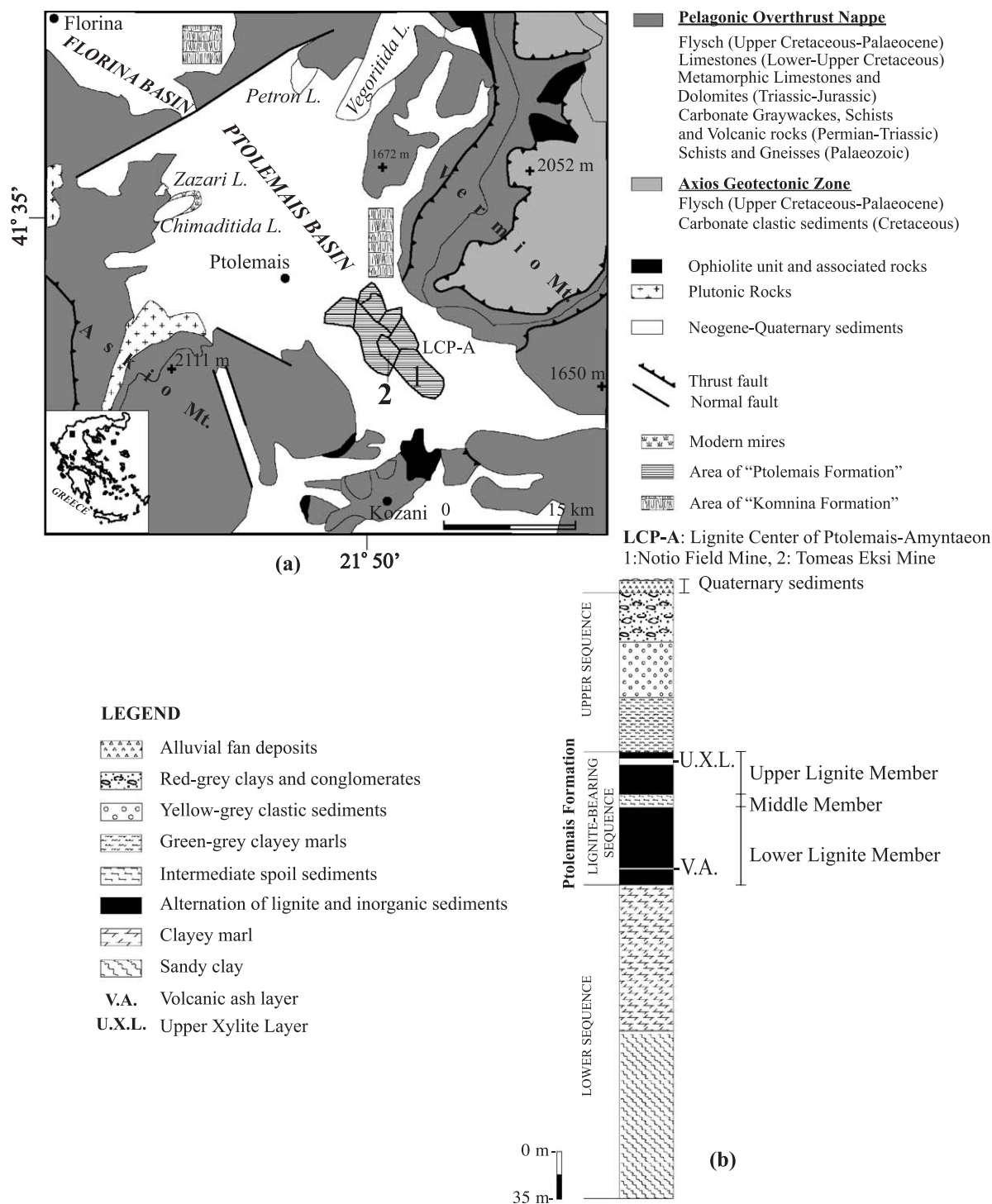


Fig. 1. (a) Geological map of the Ptolemais Basin (after Kiliyas and Mountrakis, 1989); (b) lithologic column of the Ptolemais Formation (after Anastopoulos and Koukouzas, 1972).

Antoniadis et al., 2001). In the Middle Miocene, peat derived mainly from arboreal vegetation and accumulated under limnotelmatic to telmatic conditions in the northern and eastern marginal areas of the basin, resulting in the formation of the xylite-rich lignites of the Komnina Formation (Fig. 1a). Progressively, peat formation extended southwards, towards the central part of the Ptolemais Basin, resulting in deposition of the Ptolemais Formation, which contains mainly matrix lignite. Matrix lignite is the lithotype, which consists of fine-detrital humic groundmass, homogenous in appearance that derives mainly from herbaceous plants with <10% woody remains (International Committee for Coal and Organic Petrology, ICCP, 1993). The lignite originated from herbaceous plants, which thrived under limnotelmatic to telmatic conditions. Peat accumulation was influenced by increased clastic influx. Today, peat formation in the Ptolemais Basin is restricted to the western margins of the Ptolemais Basin, in the vicinity of Chimaditida Lake (Bouzinou et al., 1997).

In the upper part of the Ptolemais Formation, a distinct layer, a few meters thick, is dominated by xylite-rich lignite (Fig. 1b). This layer is heretofore referred to as the “Upper Xylite Layer” (UXL). During geological exploration of the Notio Field (Fig. 1a), this layer was regarded as allochthonous, being derived from woody material, which was transported by surface waters from the surrounding forested mountains towards the lowland (Anastopoulos and Koukoulas, 1972). Several Greek basins, for example Kalavryta, Aliveri, Vegora and Almyros Basins, include xylite-rich lignites that have been dated back to the Upper Miocene (Riegel et al., 1995; Bouzinou et al., 2000; Papanicolaou et al., 2000). These xylite-rich lignites are usually overlain by more or less thick lignite benches of matrix lithotype and, thus, Riegel et al. (1995) concluded that forest swamps declined in Greece, in the Early Pliocene, with the exception of the Chomatero-Koroni Basin in the southwestern part of the country (Antoniadis et al., 1992). Therefore, the study of the UXL in the Upper Lignite-bearing Sequence of the Ptolemais Formation (Early–Middle Pliocene) provides valuable information concerning the Pliocene mire vegetation and contributes to a more precise reconstruction of the peat-forming palaeoenvironments in the Ptolemais Basin.

2. Geological setting

The 120-km-long tectonic trench of western Macedonia extends in a NNW–SSE direction between the town of Prilep, Former Yugoslavian Republic of Macedonia, in the north, and the Aliakmon River in the south (Fig. 1a). The margins and the basement of the basin consist of crystalline rocks of the Pelagonian nappe and the Axios geotectonic zone (Kilias and Mountrakis, 1989). A group of normal faults oriented NW–SE was active during the post-alpidic extension tectonic phase and formed a Middle Miocene–Early Pliocene trench. During later extension phases, NE–SW and ENE–WSW to E–W oriented normal faults were activated, separating the initial trench into several smaller subbasins such as the Ptolemais subbasin (Anastopoulos and Koukoulas, 1972; Pavlides and Mountrakis, 1987; Doutsos and Koukouvelas, 1998; Koukoulas et al., 2000; Doutsos and Kokkalas, 2001).

The sediments filling the southern part of the Ptolemais Basin include the following stratigraphic sequences (Fig. 1b) (Anastopoulos and Koukoulas, 1972): (a) the Lower Sequence, which consists of a basal conglomerate, sandy marls and clays; (b) the Lignite-bearing Sequence (Ptolemais Formation), which consists of lignite seams intercalated with marl and clay layers; (c) the Upper Sequence, which includes limnic and terrestrial sediments such as sandy clays, clayey marls, calcareous sands, sandy marls, and conglomerates; and, finally, (d) Quaternary sediments, consisting of terrestrial and fluvio-terrestrial conglomerates, talus cones and alluvial deposits.

The maximum thickness of the Lignite-bearing Sequence (130 m) occurs in the southern part of the concession of the Public Power Corporation S.A. (P.P.C.), in the open pit of the Notio Field. This sequence is further divided into three members (Fig. 1b): (a) the Lower Member (80 m thick), which consists of alternations of lignite benches up to 4 m thick with marls and marly clays; (b) the Middle Member (up to 14 m thick), which consists mainly of inorganic sediments such as marls, sandy marls, clays and chalk, with minor occurrence of lignite benches; and (c) the Upper Member (30 m thick), which consists of lignite benches (each up to 2 m thick), alternating with clayey, marly and sandy

layers. The Upper Xylite Layer occurs in the upper part of this Member and has a thickness of 3–6 m in the open pits of both the Notio Field and the Tomeas Eksi (Fig. 1a).

Some researchers have attributed a Middle to Late Pliocene age to the Ptolemais Formation (Anastopoulos and Koukouzas, 1972; Ioakim, 1982), while others have assigned a Late Miocene to Early Pliocene age (van de Weerd, 1983; Kirittopoulos, 1984). Other recent studies have concluded that this Formation was deposited during the Early Pliocene between 5.23 and 3.94 Ma (van Vugt et al., 1998; Steenbrink et al., 1999).

3. Methodology

Based on data from 64 boreholes that were completed by the Greek Institute of Geology and Mining Exploration (I.G.M.E.) (Anastopoulos and Koukouzas, 1972), we traced the lithostratigraphic features of the UXL. Using channel sampling at the bench stopes, six

samples were collected from the Notio Field open pit and seven samples from the Tomeas Eksi (Fig. 2a–c). The samples were obtained from the top to the bottom of the lignite layer, representing an interval of 10 cm each (Table 1). At both sites, the lithological features were macroscopically described and the lignite lithotypes were determined according to guidelines established by the International Committee for Coal and Organic Petrology (ICCP, 1993). Samples with more than 10% by volume woody tissues were logged as xylite-rich.

Palaeobotanical examinations of three woody samples were conducted by Prof. Dr. Nicolae Țicleanu, Department of Geology and Palaeontology, University of Bucharest, Romania. The wood samples were longitudinally and transversally sliced and thin sections were prepared, which were examined using transmitted light under magnification of $132\times$.

Proximate analyses were performed at the facilities of the West-Macedonian Lignite Center of P.P.C. according to American Society for Testing and Materials (ASTM) D3174 (1989), American Society for

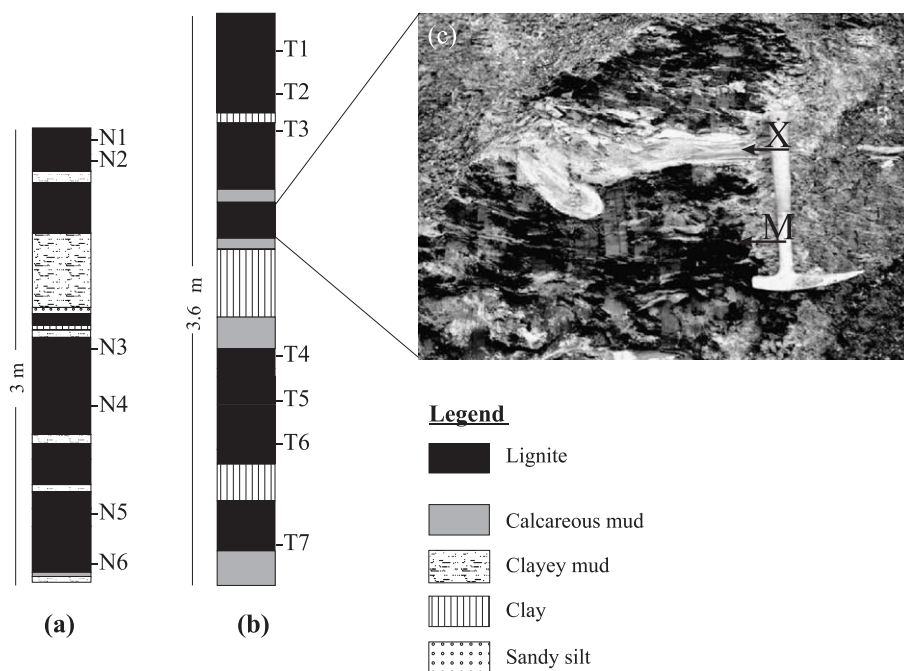


Fig. 2. (a) Lithologic column of the Upper Xylite Layer in the Notio Field (N1–6, samples), (b) in Tomeas Eksi (T1–7, samples), and (c) sampling channel in the Notio Field (X: xylite-rich lignite, M: matrix lignite).

Table 1
Samples and lithotypes of the Upper Xylite Layer

Sample	Macroscopic description	Sample	Macroscopic description
Notio Field		Tomeas Eksi	
N1	matrix	T1	matrix
N2	xylite-rich	T2	clayey-xylite-rich
N3	matrix	T3	xylite-rich
N4	xylite-rich	T4	matrix
N5	matrix	T5	xylite-rich
N6	xylite-rich	T6	matrix
		T7	xylite-rich

Testing and Materials (ASTM) D3302 (1989), and American Society for Testing and Materials (ASTM) D388 (1992). The samples were crushed ($\varnothing < 1$ mm) and moisture and ash yield were thermogravimetrically determined using a LECO MAC 500. Gross calorific values were determined using a LECO AC 300. Ultimate analyses were conducted at the Instrumental Analysis Laboratory of the University of Patras, using a CARLO ERBA EA1108 C-H-N-S analyzer.

Polished blocks ($\varnothing$ 3 cm) were prepared according to American Society for Testing and Materials (ASTM) D2797 (1990) and examined using a LEITZ ORTHOPLAN 307 microscope. Point counting for maceral analyses (500 counts) was conducted under both white reflected light and blue-light excitation following the Stopes-Heerlen terminology (ICCP, 1963, 1971, 2001; Taylor et al., 1998). Semi-quantitatively mineralogical analyses of the fine-powdered bulk lignite samples were carried out using a PHILIPS PW1050 X-ray diffractometer. The scanning area covered the interval $2\theta = 3\text{--}60^\circ$, with a scanning step of 0.2° and a step time of 1.5 s.

4. Results

4.1. Stratigraphy and macroscopic features

The UXL extends in the area of the Notio Field and Tomeas Eksi open pits at the southern part of the Ptolemais Basin (Figs. 1a and 3a). Stratigraphically, the UXL belongs to the Upper Lignite-bearing Sequence of the Ptolemais Formation (Fig. 1b). By evaluating core data from a previous study in the

Notio Field (Anastopoulos and Koukouzas, 1972), the stratigraphic and lithological features of the UXL have been assessed (Fig. 3). Coring data for Tomeas Eksi are not available. The UXL extends between altitudes of +509 to +625 m, generally striking SW and deeping up to 5° . Normal faults trending WNW to NW and ENE, with displacements up to 39 m, interrupt and deform the whole sedimentary sequence (Fig. 3b). The UXL consists mainly of lignite benches alternating with thin layers of chalk, clays, marls (limnic facies) and clayey mud, and calcareous mud (limnotelmatic facies). Floodplain facies such as sand and sandy clays occur rarely. The maximum thickness of the UXL (6 m) is found in the WNW part of the Notio Field; it gradually decreases towards the southern and southeastern parts.

The main feature of the UXL at both sampling sites (Fig. 2a and b) is the dominance of trunks and stems of arboreal vegetation (Fig. 2c). In the southwestern part of Notio Field, the UXL overlies a marl layer, but northwards the marl is progressively replaced by matrix lignite (Fig. 3c). In the southwestern area of the lignite occurrence, marly layers overlay the UXL, whereas clay layers constitute the overburden in the northeastern region. Internally, the UXL alternates between organic and inorganic layers; it contains mainly clay layers in the northern, and marly layers in the western and southwestern parts of Notio Field. In contrast, calcareous mud and clay layers intercalate with the lignite in the Tomeas Eksi profile. During fieldwork it was noticed that thin clay- and less silt-rich layers with lateral expansion less than 1 m occur within the UXL lignite layers. These small-scale facies probably represent traces of small streams that flowed through the palaeomire.

Syn-sedimentary normal faults were active during the entire lignite-formation period in the Ptolemais Basin (Anastopoulos and Koukouzas, 1972; Doutsos and Koukouvelas, 1998). Such tectonic elements have also been identified within the UXL, and this indicates tectonic activity during peat accumulation.

4.2. Palaeobotanical examination

Palaeobotanical examination showed that the xylitic tissues originated from Coniferous wood, specifically *Glyptostrobus europaeus*, which represented one of the most significant coal-forming plants across

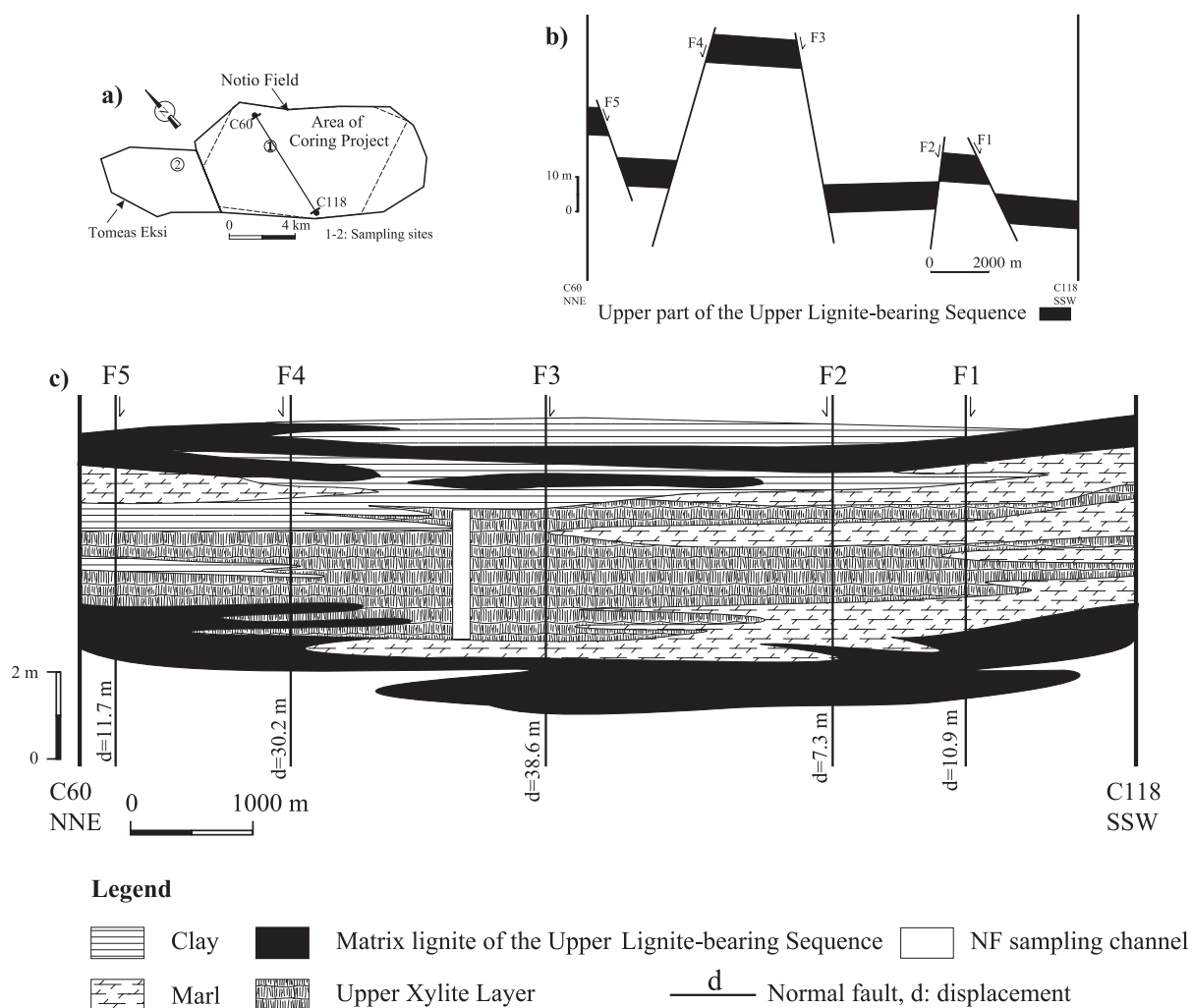


Fig. 3. (a) Sketch of the Notio Field and Tomeas Eksi, (b) simplified tectonic sketch of the Upper Lignite-bearing Sequence in Notio Field, and (c) simplified cross-section of the Upper Xylite Layer in the Notio Field between the cores C118 and C60.

Europe during the Tertiary (Kovar-Eder et al., 2001). In Greece its occurrence has been demonstrated in many Miocene coal-bearing sequences, such as those of Vegora, Komnina, Vevi, Lava and Aliveri (Velitzelos et al., 1984). Antoniadis and Rieber (1995) have noted the occurrence of *G. europaeus* seeds in the Apophyse lignites (Upper Pontian) in the western part of the Ptolemais Basin. Thus, the UXL provides the first evidence that this species has significantly contributed to peat formation after Miocene in Northern Greece. Additional peat-forming helophytes (from the Greek words helos = mire, phyto = plant) contributing

to UXL formation include Cyperaceae (*Carex* spp. and *Cladium mariscus*), reeds (*Phragmites australis*), and aquatic macrophytes such as Nymphaeaceae and *Potamogeton* spp. (Weyland and Pflug, 1960; Velitzelos and Gregor, 1990; Kloosterboer-van Hoeve et al., 2001).

4.3. Laboratory analyses

4.3.1. Proximate analysis

Moisture, ash yields and gross calorific values are listed in Table 2. In general, the obtained ash values

Table 2

Results of proximate and ultimate analyses of the UXL (ar: as received, M: moisture, GCV: gross calorific value, NCV: net calorific value, db: dry basis, dmmf: dry and mineral matter-free basis)

Samples	Notio Field						Tomeas Eksi						
Parameters	N1	N2	N3	N4	N5	N6	T1	T2	T3	T4	T5	T6	T7
M (% , ar)	50.0	54.0	51.0	54.0	50.0	56.0	46.0	44.0	50.0	46.0	49.0	49.0	45.0
M (% , ash free)	57.0	55.0	56.0	56.0	56.0	58.0	57.0	54.0	52.0	60.0	50.0	56.0	52.0
Ash (% , db)	22.8	5.3	18.4	7.2	23.2	7.7	36.5	34.2	6.6	42.2	4.0	24.6	22.2
GCV (MJ/kg, ar)	10.0	11.6	9.9	10.9	9.7	10.8	8.6	9.3	13.0	7.8	13.0	9.7	9.6
NCV (MJ/kg, ar)	8.3	9.8	8.3	9.1	8.1	9.0	7.1	7.8	11.2	6.3	11.3	8.0	8.1
GCV (MJ/kg, moist and ash free)	11.3	11.8	10.9	1.3	11.0	11.2	10.7	11.5	13.4	10.1	13.3	11.0	11.0
C (% , db)	46.4	59.9	53.2	57.8	48.4	64.6	33.8	35.9	59.5	41.8	55.8	63.1	51.5
H (% , db)	4.5	6.1	4.8	6.0	4.8	6.8	3.2	3.7	6.2	4.2	5.6	6.8	5.1
N (% , db)	<0.1	<0.1	<0.1	0.4	0.8	<0.1	1.4	0.7	0.5	0.8	0.8	0.4	<0.1
S (% , db)	2.3	2.3	3.0	1.6	2.3	1.7	2.3	4.4	1.7	1.8	2.1	1.0	1.3
Mineral matter (%) ^a	25.9	7.0	21.5	8.7	26.3	9.2	40.7	39.4	8.1	46.5	5.5	27.1	24.7
C (% , dmmf)	62.5	64.4	67.8	63.2	65.6	71.2	57.0	59.1	64.7	78.3	59.0	86.2	66.4
H (% , dmmf)	6.1	6.6	6.1	6.6	6.1	7.5	5.3	6.0	6.7	7.9	6.0	9.3	6.8
N (% , dmmf)	<0.1	<0.1	<0.1	0.4	1.1	<0.1	2.3	1.2	0.5	1.5	0.8	0.6	<0.1
S (% , dmmf)	1.7	1.3	1.1	0.8	1.3	0.6	1.0	4.8	0.9	0.1	1.5	<0.1	0.4
O (% , dmmf) ^b	30.1	27.3	25.0	29.0	25.9	20.7	34.4	28.9	27.1	12.1	32.7	3.8	26.5
H/C	1.2	1.2	1.1	1.2	1.1	1.3	1.1	1.2	1.2	1.2	1.2	1.3	1.2
O/C	0.4	0.3	0.3	0.3	0.3	0.2	0.5	0.4	0.3	0.1	0.4	0.08	0.3

^a Calculated using the Parr formula: $MM = 1.08 \times \text{ash} + 0.55 \text{ sulphur}$.

^b Calculated by subtraction.

reveal high inorganic input during peat accumulation, which was more intense in Tomeas Eksi (mean ash 24.3 wt.%) than in Notio Field (mean ash 14.1 wt.%). Using moisture and gross calorific value (on a moist, ash-free basis) for rank classification, the UXL is lignite (Weichbraunkohle) according to American Society for Testing and Materials (ASTM) D388 (1992) or lignite C according to ECE-UN (1998).

4.3.2. Ultimate analysis

Results of ultimate analysis on bulk samples are shown in Table 2. However, in order to have a view of the C, H, N and S contents of the inorganic matter, we also carried out the analyses on the 550 °C ashes of the same lignite samples. Only in samples T6 and T7 (Fig. 2b) does $C_{\text{inorganic}}$ have relatively high values (1.1 and 6.7 wt.%, respectively), where carbon was probably derived from carbonates. The sulphur contents of the 550 °C ashes are also relatively high (up to 18 wt.%) revealing that a significant part of S_{total} is inorganic. However, S content can only be regarded as approximate since, during ashing, part of S_{organic} reacts with Ca producing sulphates (anhydrite). Sub-

tracting the values obtained from the ashed samples from those of the bulk samples, the organic C, H, N, and S fractions were calculated and the values on dry and mineral matter-free basis were used to calculate O/C and H/C ratios (Table 2). Although this method is not accurate regarding the organic values of C, H, N, S, as well as those of oxygen being calculated and not measured, it can provide a general sense of the degree of coalification of the samples. Using the H/C vs. O/C atomic ratio diagramme (Fig. 4), the samples are projected to lie in the area above the field of lignite and subbituminous coal mainly because of high H/C values (1.1–1.3).

4.4. Maceral analysis

The microscopic examination of the UXL revealed almost identical distributions of macerals at both sampling sites (Table 3). Some interesting differences between the xylite-rich and the matrix lithotypes are also evident.

Huminite is the dominant maceral group (up to 93 vol.%), with humotelinite being the most prevalent maceral subgroup in the majority of the

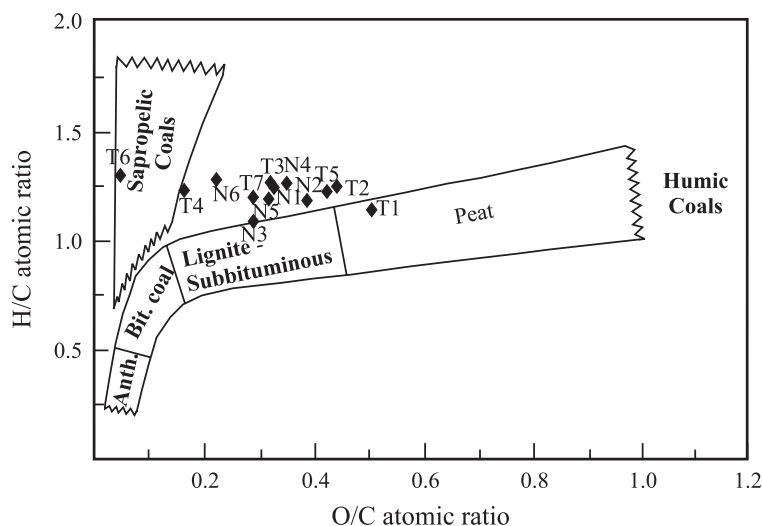


Fig. 4. H/C vs. O/C diagramme (after van Krevelen).

samples. Interesting is to notice that textinite is the most abundant maceral of humotelinites and, further, that the xylite-rich lithotype displays higher amounts of red textinite (mean 12 vol.%) than the matrix one (mean 5 vol.%). The term “red textinite” is used in this study to describe textinite with a strong red reflectance under white incident light and strong yellow to orange fluorescence under blue-light excitation. This kind of textinite could be identical to the red textinite introduced by Esterle et al. (1989). It is believed to indicate a low humification degree and the presence of cellulose and/or lignin. Texto-ulminite contributes mainly in the form of texto-ulminite A and reveals distribution similar to that of textinite (e.g. higher values in the xylite-rich lithotype). Eu-ulminite occurs only as A type and its contents seem to be independent of the lithotype, since the higher values occur in the matrix samples N3, T1 and T4. Regarding humode-trinite, attrinite is the dominant maceral of the matrix lithotype. Attrinite and densinite represent the residues of the mechanical decomposition of herbaceous plants, as well as the soft plant materials of the arboreal vegetation. Humocollinite displays low to moderate values (6–24 vol.%), with corpohuminite being the predominant maceral. Corpohuminite, which frequently is accompanied by suberinite, reveals higher values in the matrix lithotype than in the xylite-rich. The relatively high values (up to 17 vol.%) suggest au-

tochthonous peat accumulation, since the co-occurrence of both macerals excludes peat transportation. Levigelinite occurs up to 10 vol.% and porigelinite up to 5 vol.%. The coal-petrographic data indicates that gelification affected more the matrix than the xylite-rich lignite.

The values of liptinite vary according to the lithotype and more specifically, the xylite-rich samples display liptinite contents with an average of 11 vol.%, while the matrix samples 6 vol.%. Resinite and cutinite are the most frequent macerals, while the rest of the liptinites have a minor contribution. Inertinite does not exceed values greater than 6 vol.%. The most common are fusinites and inertodetrinites.

Clay minerals dominate in samples with amounts up to 14 vol.%. Pyrite also contributes with values as high as 9 vol.% and constitutes the main inorganic part of mineral matter from the xylite-rich lithotype. Carbonates and quartz contribute only low to moderate amounts in both lithotypes. It should be noted, however, that the identification of minerals using reflected-light microscope is problematic and, thus, is only approximate.

4.5. Coal facies indicators

A complete assessment of coal depositional environment has to provide data for the hydrological and the tectonic regime of the area, as well as for the

Table 3

Composition of maceral (vol.% on dry, mineral matter-free basis) and mineral matter (vol.% on total sample) of the UXL

Samples	Notio Field						Tomeas Eksi						
Maceral	N1	N2	N3	N4	N5	N6	T1	T2	T3	T4	T5	T6	T7
Textinite A	16	23	12	15	10	6	8	26	26	10	19	13	19
Red Textinite	5	10	1	9	4	25		3	18	1	4	9	13
Texto-Ulminite A	6	19	5	24	12	13	4	11	13	9	17	10	12
Texto-Ulminite B	5	5	3	7	11	3			2	5		4	
Eu-Ulminite A	3	5	10	8	4	10	18	4	6	13	2	5	2
Eu-Ulminite B													
Humotelinite	35	62	31	63	41	57	30	44	65	38	42	41	46
Attrinite	21	9	26	7	20	4	27	20	6	21	23	23	16
Densinite	14	9	15	8	8	9	17	14	13	15	7	16	6
Humodetrinite	35	18	41	15	28	13	44	34	19	36	30	39	22
Levigellinite	6	2	10	2	3	3	4	4	2	6	6	5	3
Porigellinite	5	2			4			1		2	4	1	1
Corpohuminite	13	2	11	4	17	12	5	4	4	11	7	7	16
Humocollinite	24	6	21	6	24	15	9	9	7	19	17	13	20
HUMINITE	94	86	93	84	93	85	83	87	91	93	89	93	88
Fusinite		1	1			1	6				1		1
Semifusinite				1				2			1	1	
Inertodetrinite	1			1	1		6		1	2		1	
Micrinite													
Funginite					1		1						
INERTINITE	1	1	1	2	2	1	13	2	1	2	2	2	1
Sporinite	1	2	1	2	1	2	1	2	2	1	2	1	2
Cutinite	2	4	2	3	1	3		2	2		2	2	2
Resinite	2	4	2	5	1	4	1	3	2	2	3	2	3
Suberinite	0	1				1			1				2
Alginate	0		0		1	1		1	0				7
Liptodetrinite	1	2	1	4	2	3	2	2	2	2	1	1	2
LIPTINITE	6	13	6	14	6	14	4	10	9	5	8	6	11
Total organic	100	100	100	100	100	100	100	100	100	100	100	100	100
Clay minerals	8	1	8	7	12	4	12	14	1	14	1	1	7
Quartz										4			4
Carbonates	3	1	3		2	1	3		1	5	1	2	1
Pyrite	5	5	3	3	3	1	9	5	3	5	1	5	1
Mineral matter	16	7	14	10	17	6	24	19	5	28	3	17	13
Indices													
GI	1.2	1.0	1.4	1.6	1.6	1.4	1.0	0.8	0.8	1.8	0.9	1.0	0.8
TPI	1.0	2.8	0.8	3.7	1.6	4.5	0.8	1.2	3.0	1.1	1.3	1.0	2.4
GWI	1.0	0.3	0.9	0.3	0.8	0.5	0.9	0.6	0.3	1.1	0.4	0.7	0.6
VI	1.1	3.6	0.9	3.7	1.4	4.1	0.8	1.5	3.4	1.0	1.7	1.1	2.3

climatic conditions that affect peat accumulation. It is thought that coal depositional environment can be assessed through the presence or absence of certain macerals (Teichmüller, 1989) and, hence, maceral indices were applied in order to describe some genetic features of coals (e.g. von der Brellie and Wolf, 1981; Diessel, 1986, 1992; Kalkreuth et al., 1991a,b; Lambersson et al., 1991; Hawke et al., 1999; Singh and

Singh, 2000). However, there are some limitations regarding the application of maceral ratios to define the depositional environment, as recent studies in peatlands that represent modern analogue of coal environments have demonstrated (Crosdale, 1993; Wüst et al., 2001; Moore and Shearer, 2003). These studies refer mainly to ombrogenous peats, indicating that the petrographic features of the organic matter

displayed no significant correlation with the tectonic setting or the climate. In topogenous mires, however, the tectonic and the sedimentary regimes in the surrounding area strongly control coal formation and, thus, tracks of alterations are more evident than in ombrogenous mires. However, the exclusive use of coal petrography to interpret the palaeoenvironment should be avoided. A combination of sedimentological, geochemical, palynological and biological studies should be applied to define the origin of coal deposits (Collinson and Scott, 1987; Shearer et al., 1995; Scott, 2002; Moore and Shearer, 2003). In this study, the use of maceral ratios is only indicative and complementary to the sedimentological features and not panacea for the delineation of the palaeoenvironmental conditions.

The ternary diagramme proposed by Mukhopadhyay (1989) provides a first view of the depositional conditions. By plotting the results of maceral analysis (Fig. 5), it seems that the peat accumulated under highly saturated and intensely anoxic conditions. Exception is revealed for sample T1, which had undergone a partial oxidative process. Most of the samples are plotted close to apex A, suggesting forested vegetation and good preservation.

The tissue preservation (TPI) and gelification indices (GI) proposed by Diessel (1992), as well as the groundwater influence (GWI) and vegetation indices (VI) proposed by Calder et al. (1991) have been used for evaluating the depositional palaeoenvironment. The TPI is an indicator of the degree of organic tissue preservation in the palaeomire, as well as a function of the contribution of arboreal vegetation to peat formation. The GI reflects the homogenization (*sensu* gelification) of the organic matter. Additionally, the GWI and the VI are indicators of the hydrological conditions and the nature of the peat-forming vegetation, respectively. Although it can be argued that GWI and TPI are similar to GI and VI, respectively, these indices have inherent differences regarding mainly the questions they are designed to respond to. In the case of UXL as discussed below, the application of both pairs of indices is complementary.

The TPI and GI indices had been previously modified (Kalkreuth et al., 1991a; Markic and Sachsenhofer, 1997) so as to apply to the Tertiary low-rank coals. In our study, we use the ratios as being modified by Kalaitzidis et al. (2001); modifications were applied in the indices that were proposed by

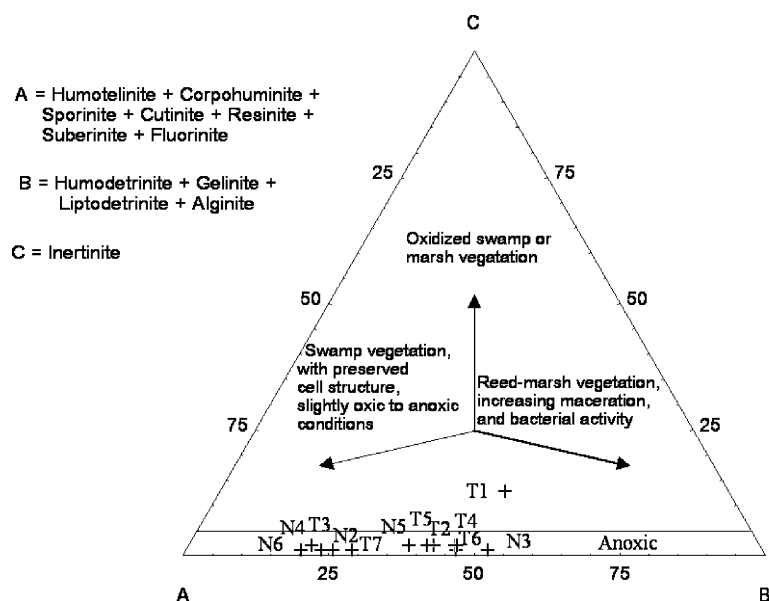


Fig. 5. Ternary diagramme illustrating peat-forming conditions of the Upper Xylite Layer in the Ptolemais Basin, after Mukhopadhyay (1989).

Markic and Sachsenhofer (1997), and include the introduction of gelinite and inertodetrinite as non-structured macerals in the denominator of TPI and the introduction of gelinite in the numerator of GI. Previous coal-petrographic studies in Greek lignites (Kalaitzidis et al., 1998, 2000, 2001; Antoniadis et al., 2001; Papazisimou, 2002) showed that, by using these indices, the assessment of the peat-forming palaeoenvironments corresponds better to the conditions of lignite formation in Greece. Moreover, a recent study concerning the Amyntaeon lignite in the Ptolemais Basin (Mavridou et al., 2003) was based on the same indices. The formulas used for TPI and GI are:

$$\text{TPI} = \frac{\text{Humotelinite} + \text{Corpohuminite} + \text{Fusinite}}{\text{Attrinite} + \text{Densinite} + \text{Gelinite} + \text{Inertodetrinite}} \quad (1)$$

$$\text{GI} = \frac{\text{Ulminite} + \text{Humocollinite} + \text{Densinite}}{\text{Textinite} + \text{Attrinite} + \text{Inertinite}} \quad (2)$$

The TPI values range between 0.8 and 4.5 (Table 3; Fig. 6) with the higher values corresponding to

xylite-rich samples. It is suggested that the organic matter preservation was moderately to intensely favoured, since most of the samples display $\text{TPI} > 0.1$. However, the mean TPI value of Notio Field samples (2.4) is higher than for the Tomeas Eksi (1.5), suggesting better preservation of the organic tissues in Notio Field. The values of GI are similar in both fields ranging between 0.8 and 1.8 and revealing low to moderate gelification of the organic matter. The calculated TPI and GI values are within the range of Taxodiaceae coal proposed by Diessel (1992) and Taxodiaceae–Cupressaceae coal proposed by Kolcon and Sachsenhofer (1999). From the TPI vs. GI plot, it is suggested that the UXL formed in an environment that was intermediate between dry and wet forest swamp (Fig. 6).

In order to obtain a more comprehensive view of the hydrological conditions, the GWI vs. VI plot proposed by Calder et al. (1991) has been used. In this study, the GWI and VI are also modified by Kalaitzidis et al. (2001) and are calculated as follows:

$$\text{GWI} = \frac{\text{Humocollinite} + \text{Densinite} + \text{Mineral Matter}}{\text{Humotelinite} + \text{Attrinite}} \quad (3)$$

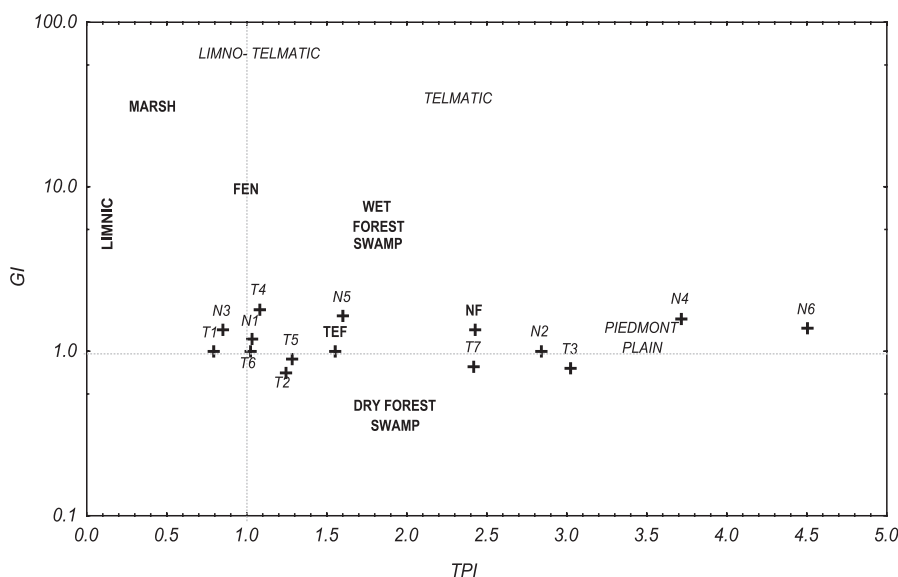


Fig. 6. Modified coal-facies diagramme after Diessel (1992) (NF, TEF: mean values of Notio Field and Tomeas Eksi, respectively).

$$VI = \frac{\text{Humotelinite} + \text{Fusinite} + \text{Semifusinite} + \text{Cutinite} + \text{Sporinite} + \text{Suberinite} + \text{Resinite}}{\text{Humodetrinite} + \text{Inertodetrinite} + \text{Other Liptinites}} \quad (4)$$

The GWI values range between 0.3 and 1.1, without revealing any differences between the Notio Field and the Tomeas Eksi samples (Table 3; Fig. 7). However, the lowest values ($GWI \leq 0.5$) correspond to the xylite-rich samples, causing a masking effect in the interpretation. The values of matrix samples ($0.7 \leq GWI \leq 1.1$) are more reliable for interpreting the groundwater influence. In this sense, a moderate influence of the groundwater table is obvious. The values of VI range between 0.8 and 4.1, with the VI_{mean} of Notio Field ($VI_{\text{mean}} = 2.5$) being slightly higher than the VI_{mean} of Tomeas Eksi samples ($VI_{\text{mean}} = 1.7$). In the GWI vs. VI plot (Fig. 7), the xylite-rich samples N2, N4, N6 and T3 are projected in the field of bog forest, reflecting the primary origin from arboreal vegetation; however, all the samples should be considered for palaeoenvironmental reconstruction. Most of the samples are projected into the field that implies an intermediate between fen and limnic peat-forming environment, under mesotrophic hydrological conditions.

The overall assessment of the UXL depositional conditions, as obtained from the coal-petrographic features and indices, corresponds to a telmatic environment with fluctuating watertable, where hydrological conditions were mesotrophic, meaning that there was a moderate supply of inorganic material during peat accumulation. The groundwater table was consistently above the sediment surface, preventing oxidation of the organic matter. The peat-forming vegetation consisted both of arboreal and herbaceous species. The above features represent an open forest-swamp environment. The preservation of the structured tissues, as an index of the humification intensity, was low to moderate for the soft cellulose-rich plant materials (herbaceous species) and high for the lignin-rich plant materials (woody species). Because of the relatively high values of well-preserved corpohuminite along with suberinite, it is also evident that (1) the subsurface organic mass (i.e. roots) significantly contributed to peat accumulation, and (2) peat accumulated in situ or it was at least hypo-autochthonous, meaning

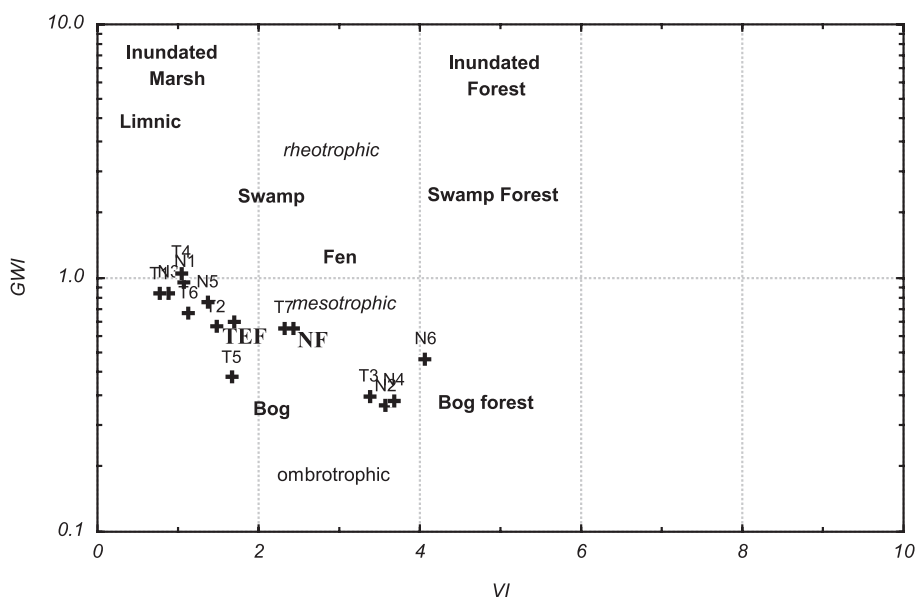


Fig. 7. Modified coal-facies diagramme after Calder et al. (1991) (NF, TEF: mean values of Notio Field and Tomeas Eksi, respectively).

Table 4

Frequency of occurrence of minerals (M: major phases, m: minor, tr: traces)

Mineral	Notio Field						Tomeas Eksi						
	N1	N2	N3	N4	N5	N6	T1	T2	T3	T4	T5	T6	T7
Clay minerals ^a	M		M	tr	M	tr	M	M	m	M		M	m
Quartz	M	m	M		M		M	M		M		m	tr
Feldspars ^b	M		M	tr	M		M	M		M		m	
Pyrite	M	M	M	m	M	m	M	M	m	m	tr	M	m
Calcite				m								M	M
Kaolinite	M						m	m					
Gypsum	m		M		m		M	M	M		tr		m
Amphiboles							tr						

^a Mixed-layer clays.

^b K-feldspars and plagioclases.

there was limited transportation and low destructive intensity.

4.6. Mineralogical determinations

Silicates are the most abundant mineral phases in both profiles (Table 4; Fig. 8). They are represented mainly by clay minerals (predominately illite), quartz, K-feldspars and plagioclase. However, gypsum and pyrite also have a significant presence. Minor contri-

butions are revealed for calcite and kaolinite, whereas chlorites and amphiboles occur in traces. Semi-quantitative evaluation reveals major differences between both lithotypes. In xylite-rich lignite, pyrite is the dominant mineral (as previously stated), while silicates are rare. Furthermore, calcite occurs mainly in samples T6 and T7. The identified minerals can be distinguished into a clastic fraction (i.e. quartz, clay minerals, K-feldspars, plagioclases, chlorites and amphiboles) and an authigenic fraction (i.e. calcite, gypsum, pyrite and kaolinite).

The mineralogical features of the coals strongly depend on the conditions that dominated during peat accumulation and, thus, contribute to the interpretation of coal facies (McCabe, 1984). The predominance of clastic silicate grains implies increased inorganic input from the surrounding metamorphic rocks and the flysch sediments by enhanced weathering and transportation activity of streams. Moreover, the low content of carbonates such as calcite is peculiar since the entire lignite-bearing sequence is characterized by intense authigenic carbonate sedimentation (Anastopoulos and Koukouzas, 1972). It seems that the limited occurrence of authigenic calcite was compensated by the in situ formation of gypsum, which is a major phase in almost all samples. It is

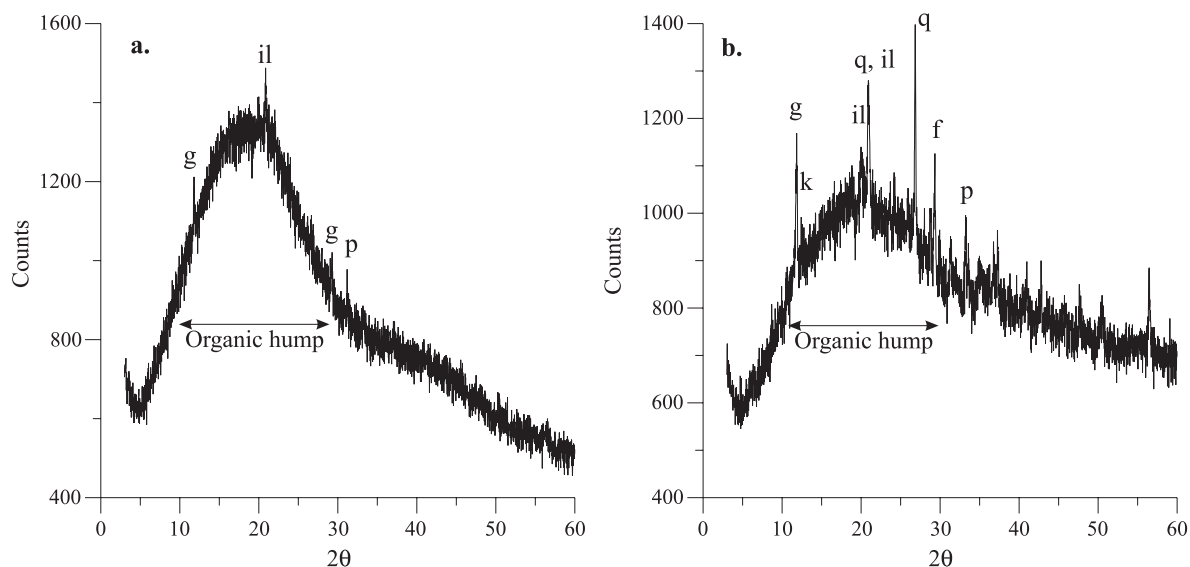


Fig. 8. X-ray diffraction pattern of (a) sample T2, xylite-rich lignite, and (b) sample T3, matrix lignite (f: feldspars, g: gypsum, il: mixed illite–montmorillonite layers, k: kaolinite, q: quartz, p: pyrite).

suggested that the Ca-rich surface waters that flowed into the palaeomire washed out the previously deposited peat in the marginal areas, where oxidation of pyrite took place establishing a surplus of SO_4^{2-} . This function resulted to the formation of gypsum against calcite.

The mineralogical features suggest intense surface-water influx and supply of inorganic material, mainly by the activity of small streams that ran through the area of peat formation. Moreover, Ca-rich waters controlled the in situ precipitation of gypsum and, rarely, deposition of calcite, whereas pyrite formation was controlled by the bacterial activity under anaerobic conditions.

5. Discussion

5.1. *Glyptostrobus* sp. as a peat-forming element

With the onset of Tertiary an expansion of *Glyptostrobus* species has been recorded in many ancient swamp habitats of the Northern Hemisphere (Shearer et al., 1995). Coal basins in which *Glyptostrobus* contributed as peat-forming taxa include these of Lower Rhine Basin in Germany (Figueiral et al., 1999), the Oberdorf Basin in Austria (Kovar-Eder et al., 2001), the Oltenia Basin in Romania (Țicleanu, 1995) and the Saskatchewan area in Canada (Sykes et al., 1994).

Taxodiaceae require humid climate and their occurrence in coal-forming environments reflects high level of the groundwater table (± 1 m) (Stach et al., 1982; Țicleanu, 1995; Taylor et al., 1998). They grow in almost permanently flooded areas, where low water conditions occur for only 1 or 2 months in the year. Such conditions are indicative of telmatic to subaquatic (limnic) environments, where peat accumulation is mostly autochthonous to hypo-autochthonous. *G. europaeus* frequently is accompanied by intense growth of herbaceous vegetation and open-water elements (Țicleanu and Diaconiță, 1997; Kovar-Eder et al., 2001). Moreover, this kind of vegetation implies a wet and warm climate with average temperatures of the coldest winter month $+6$ °C for *Taxodium* and $+5$ to $+10$ °C for *Glyptostrobus*, while for the warmest months temperature may reach $+30$ °C (Mai, 1995, in Kloosterboer-van Hoeve, 2000). The actual equivalent nowadays is *Glyptostrobus heterophyllus* that

grows in SE China (Prof. Dr. Nicolae Țicleanu, personal communication).

Glyptostrobus swamps have also prevailed in the Palaeocene Powder River Basin in USA, resulting in the formation of the Anderson and Smith coal beds, which have been thoroughly studied (Pocknall and Flores, 1987; Moore et al., 1990). Smith coal bed overlies crevasse-splay, lacustrine-delta and lake lithofacies (fine-grained limestones, shales, siltstones and sandstones) and formed in a topogenous swamp proximate to a lake. On the contrary, the Anderson coal bed overlies meander-belt and flood-plain facies (sandstones and siltstones) and represents mainly a raised swamp. Combined palynological and coal-petrographic results (Moore et al., 1990) suggested that, initially, peat accumulation in the Smith coal-bed area took place under highly saturated conditions, whereas in later stages it became less saturated, and oxidation occurred. Thus, a transition between low to moderate degree of plant-litter degradation, as obtained from humotelinite values, is observed. On the contrary, the Anderson coal bed formed in a well-drained swamp mostly under conditions promoting degradation and humification, except the upper layers, where oxidation took place.

It is not easy to compare the palaeoenvironment of UXL with that of Anderson and Smith coal beds, since there are significant differences regarding the hydrological regime of the basins and the accompanying to *Glyptostrobus*, peat-forming plants (i.e. *Platanus*, *Ulmus*, *Sphagnum* spp. in Powder River Basin vs. Cyperaceae in Ptolemais Basin). However, similarities concerning the sedimentological and coal-petrographic features can be traced mainly with Smith coal bed; the proximity to the lake and the deposition of lake sediments (i.e. limestones), the frequent occurrence of both xylite-rich and matrix coal types and the low to moderate degradation of organic matter are similar to the features of UXL.

5.2. Interpretation of UXL palaeoenvironmental conditions in the Ptolemais Basin

Climatic conditions are one of the most important parameters of peat formation, since they exercise fundamental control over the type of vegetation that can inhabit and the rate of growth in the peatland. Under cool and arid climate conditions primary plant

production is restricted, whereas in warm and humid conditions plant growth is enhanced (Moore, 1989). Palynological studies show the presence of Taxodiaceae pollen in the Ptolemais Formation (van de Weerd, 1983), which requires wet and warm climate. In addition, recent palynological investigations (Kloosterboer-van Hoeve et al., 2001) revealed the presence of Taxodiaceae-type pollen (*Taxodium* or *Glyptostrobus* spp.) in lignite seams that underlie the UXL. The results of the petrographic analyses of the UXL and the palaeobotanical determinations of this study make evident that *G. europaeus*, which belong to the Taxodiaceae family, contributed significantly to the formation of the UXL.

The presence of Taxodiaceae-type trees in the UXL palaeomire is in agreement with the obtained coal-petrographic results. The dominance of huminite and the relatively high resinite content have also been observed by Cohen (1973) in the Okefenokee swamps in USA; moreover, the dominance of type A humotelinite has been reported also by Sykes et al. (1994) from the woody tissues of a *Glyptostrobus*-type lignite in Saskatchewan, Canada. Similar coal-petrographic features have been described by Moore et al. (1990) from the study of *Glyptostrobus*-type coals in Powder River Basin in USA. The low preservation of the matrix lignite and the scattered values of TPI have been also reported from previous studies from analogue coals (Diessel, 1992). From the results obtained, it is concluded that the peat accumulation model of the UXL reflects a telmatic to subaquatic (limnic) environment, where trees, along with herbaceous vegetation and open-water elements, grew and the decomposed organic matter was moderately saturated. The occurrence of *G. europaeus* points to wet and warm climatic conditions. Peat accumulation was mainly autochthonous and plant-litter degradation was low to moderate; at some places, reworked peat was also deposited (hypoautochthonous material).

Recent attempts to describe the ecohydrological conditions of the Ptolemais Lignite-bearing Sequence (Mulder et al., 2000) suggested ombrogenous mire, which is in contrast to the widespread view of a topogenous model of lignite formation. If the developed peat mires were ombrogenous, this would imply that the local hydrological regime was controlled by precipitation. However, the overall features of the

lignite deposits, as described during the last decades (Anastopoulos and Koukoulzas, 1972; Cameron et al., 1984; Gregor and Velitzelos, 1995; Kalaitzidis et al., 2000; Koukoulzas et al., 2000; Papanicolaou et al., 2000), but also as became evident from this study, do not support this assessment. The main features of the Ptolemais lignite that point to the topogenous model can be summarized as: (a) high ash values dominated either by detrital silicates and/or authigenic calcite, (b) growth of wetland and aquatic plants such as *C. mariscus* and *Potamogeton* spp. respectively, as well as of *G. europaeus*, (c) low preservation of organic matter, and (d) intercalation of lignite seams with limnic sediments.

5.3. Palaeoenvironmental evolution

Stratigraphic, sedimentologic and lithological features of the UXL have led to a reconstruction of the depositional palaeoenvironment (Fig. 9). Moreover, palaeobotanical, coal-petrographic and mineralogical data have helped to assess the ecological conditions that affected peat at the time of accumulation. During the formation of the Upper Lignite-bearing Sequence, the area, which nowadays occupies the open pits of the Notio Field and Tomeas Eksi, was an extensive limnotelmatic environment. Climatic conditions significantly affected the establishment of either fens or forest swamps, and controlled the sediment characteristics (calcareous vs. siliceous) in the study area. By contrast, the tectonic activity controlled the lateral, as well as the vertical expansion of the facies, during the whole period of sedimentation. Normal faults controlled the subsidence of the Ptolemais Basin and provided the required accommodation space for peat accumulation.

Due to the lack of coring data for Tomeas Eksi, the detailed reconstruction of the UXL is restricted to the area of Notio Field (Fig. 9). Regarding the period before the UXL deposition, herbaceous plants, i.e. wetland and aquatic elements, grew in the wet areas (northern parts of Notio Field) forming the matrix lignite that underlies the UXL (Fig. 9a). During this period, carbonate influx was intense and thus, peat was enriched in calcite. However, in the southwestern–southern area, where subsidence was greatest, the groundwater table was too high for peat-forming plants to grow and, hence, inorganic, mainly marly

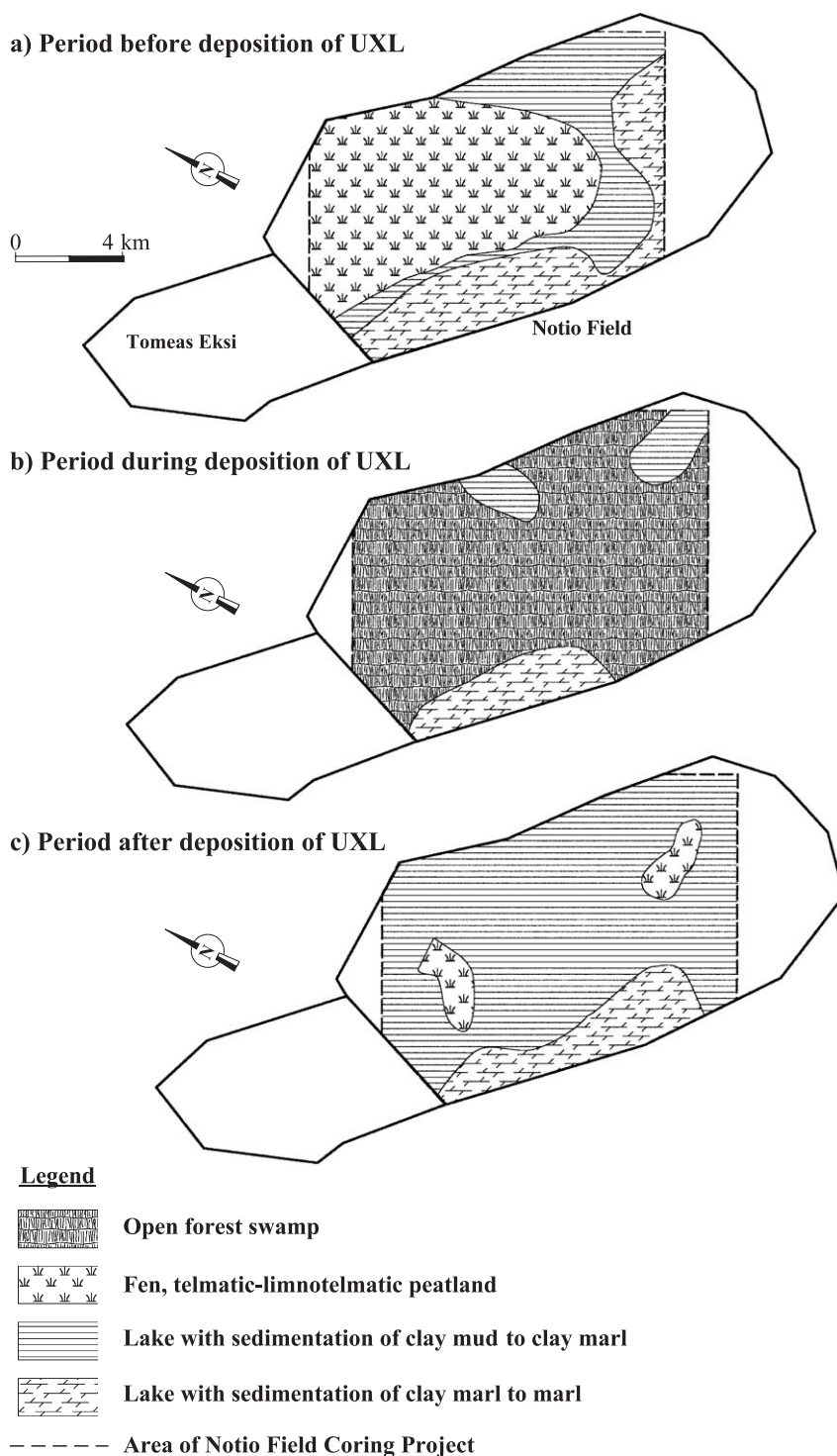


Fig. 9. Schematic reconstruction of the palaeoenvironment in the Notio Field of the Ptolemais Basin: (a) before, (b) during and (c) after the deposition of the Upper Xylite Layer.

sedimentation prevailed in an open-lake environment. The subsidence of the basin was controlled by normal faults that were active during the peat accumulation. Because of the activity of small streams, fine silt and clay layers were deposited within the palaeomire. Moreover, the input of clay material into the lake resulted in sedimentation of facies that were transitional between clay and marl. Clayey and calcareous muds were accumulated in areas between the mire and the open lake (Figs. 9a and 10).

During a subsequent stage, the open lake retreated to the W–SW area, and the areas of the Notio Field and, obviously the Tomeas Eksi, were covered by arboreal vegetation (Figs. 9b and 10). The reason for the expansion of the arboreal vegetation is not known; however, it may be inferred that the climatic conditions were more humid and warm than during the deposition of the underlying matrix lignite. During

this period, the study area represented a mire that developed in a telmatic to limnotelmatic regime, where herbaceous helophytic vegetation (sedges and reeds) and trees (*G. europaeus*) grew under relatively high groundwater table. Periodically short-term flood events, either as a result of the rise of lake level or because of the activity of streams that flowed through the mire, caused increased inorganic influx. In the first case, the mire was supplied with carbonates, whereas in the second case with silicates (quartz, clay minerals, feldspars). The streams that flowed through previously exposed peat surfaces of the marginal areas brought SO_4^{2-} into the mire system; the simultaneous input of Ca^{2+} -rich waters caused the precipitation of gypsum. Intermediate layers of calcareous mud and marl were deposited during high lake-level stages, whereas clayey mud and clay were deposited during high flow of the streams. Short-term transportation of

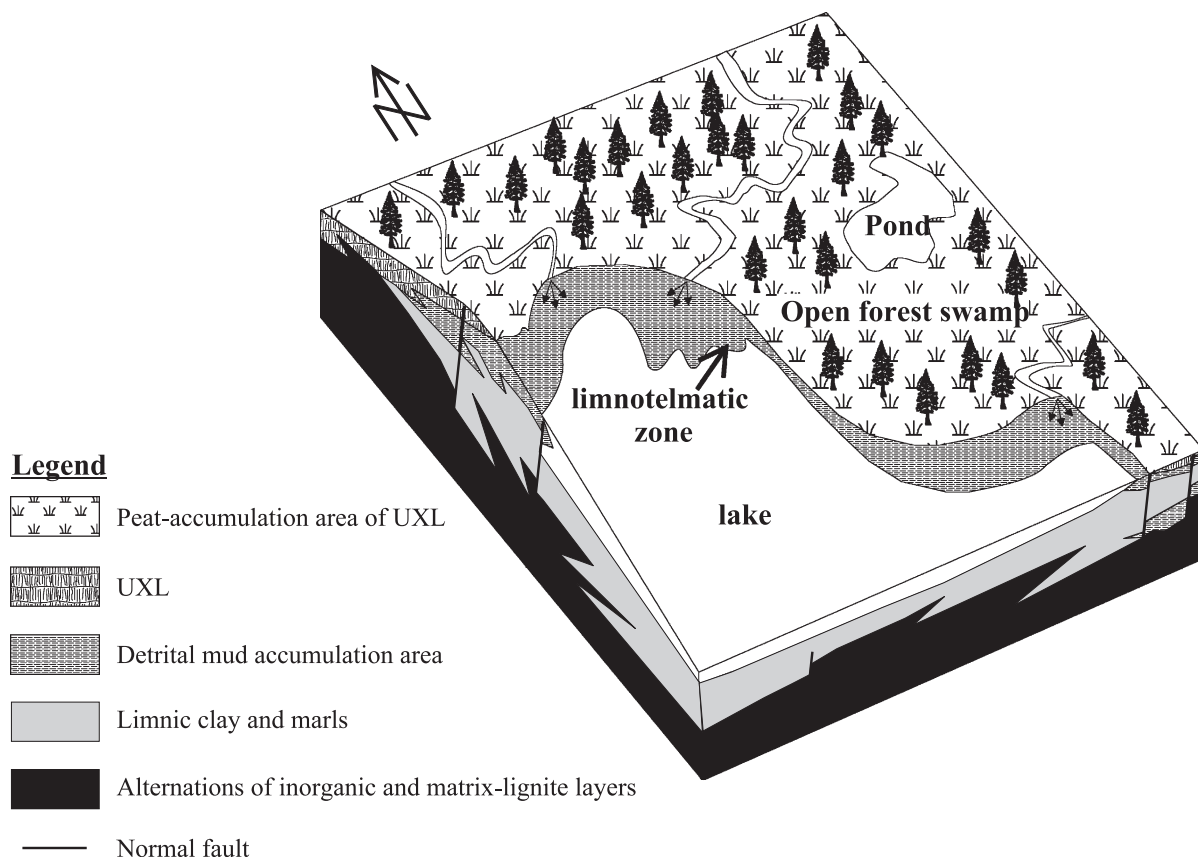


Fig. 10. Schematic reconstruction of the peat accumulation environment in the Ptolemais Basin, during the deposition of the Upper Xylite Layer.

the organic matter from the telmatic to limnotelmatic area took place during flooding events, providing intermediate to peat and mud facies. These facies represent the hypo-autochthonous part of the UXL.

After this stage it seems that the whole area subsided and the groundwater table rose resulting in the interruption of peat accumulation, and the subsequent sedimentation of inorganic layers. Silicate (clay) deposition predominated over most of the area, whereas carbonates (marl) formed in the west–southwestern area. Peat accumulation recovered initially at several small sites and, later on, over the entire study area. However, the arboreal vegetation could no longer prevail, thus the uppermost benches consist of matrix lignite (Figs. 3 and 9c).

6. Conclusions

In Greece lignites that derived from Taxodiaceae occur in several Miocene coal basins. Due to the fact that xylite-rich lignites formed only during Miocene, it has been adopted (Riegel et al., 1995) that in Northern Greece during Pliocene the conditions that prevailed prevented the growth and contribution of arboreal vegetation to peat formation.

However, in the upper part of the Ptolemais Lignite-bearing Sequence being of Pliocene age, a xylite-rich lignite layer, namely the Upper Xylite Layer, occurs that laterally expands in the open pits of Notio Field and Tomeas Eksi. This layer is up to 6 m thick and consists of xylite-rich and matrix lignite intercalated with clay and marl layers. The ash contents reach 42.2% reflecting intense inorganic influx, and the gross calorific values are up to 13.4 MJ/kg on a moist, ash-free basis. The stratigraphic, sedimentological, coal-petrographic and mineralogical features suggest an autochthonous to hypo-autochthonous peat formation during the Early Pliocene. Peat-forming vegetation consisted of herbaceous and woody (*G. europaeus*) vegetation that grew under wet and warm climatic conditions. Peat accumulated in an open-forest swamp under telmatic to limnotelmatic conditions, and under conditions of increased inorganic influx, depending on local tectonic events, the intensity of streams and the influence of the neighboring lake.

Although from Pliocene and up today Cyperaceae species constitute the main peat-forming helophytes in

the Greek palaeomires, forest-swamp habitats were established for short time in Early/Middle Pliocene at some places of Ptolemais Basin due to local (?) climatic conditions.

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