Maceral Association in Coal-bearing Formation of Mae Than Coal Mine in Lampang, Thailand - Implication for Depositional Environment

Thunyapat Sattraburut[1*] and Benjavun Ratanasthien[2]

[1]Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170, Thailand
[2]Department of Geological Sciences, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand

ARTICLE INFO

Received: 30 Aug 2021
Received in revised: 29 Oct 2021
Accepted: 9 Nov 2021
Published online: 23 Nov 2021
DOI: 10.32526/ennrj/20/202100166

Keywords:
Maceral/ Coal petrography/ Mae Than/ Miocene/ Lignite/ Paleoclimate

*** Corresponding author:**
E-mail: thunyapat.sat@mahidol.ac.th

ABSTRACT

The Mae Than Basin in Lampang Province contains low-ranked coal reserves of northern Thailand. Coal seams and ball clays were mined in the southern part of the basin. This study focuses on the coal petrography of coal samples collected from the upper coal seam in the Mae Than Coal Mine. Both the organic and inorganic constituents provide information on the nature and characteristics of the coal, reflecting the physical and chemical behaviors of coal. Petrological analysis reveals that the Mae Than coals contain more huminite than liptinite macerals, while inertinite is negligible. Huminite occurs mainly in the form of texto-ulminite, textinite, densinite, and gelinite. Liptinite consists of sporinite, cutinite, resinite, suberinite, liptodetrinite, and terpenite. The morphology of cutinite, sporinite, and the presence of terpenite indicate that the peat-forming vegetation may consist of conifers. In addition to the macerals, the coal samples contain a small to moderate amount of mineral matter. Silica and clay minerals are the main minerals found in the cavities and between the cracks of the coals. The assemblage of macerals and mineral matter indicates that the Mae Than coals were formed mainly from common peat-forming vegetation, possibly conifers, in a freshwater forest swamp or mire in a warm temperate climate. In addition, the high degree of preservation of the macerals indicates a high water table and suggests rheotrophic, anoxic, limnotelmatic to telmatic conditions during deposition.

1. INTRODUCTION

Coal is typically used to generate very high temperatures through combustion to provide electricity to small households, as well as large manufacturing facilities such as factories and transportation. The Mae Than coal mine in Lampang Province (Figure 1) was one of the most important coal resources in northern Thailand and had been operated by Siam Cement Public Company Limited (SCG) since 1993. It was economically exploited for sub-bituminous coals and ball clays. Open-pit coal mining (Figures 2(a) and 2(b)) was conducted in the near-surface deposits, particularly in the southern part of the basin.

Fossil fuels were deposited in intermontane basins during the Late Paleogene to Middle Miocene (commonly referred to as Tertiary) in Northern Thailand as a result of the movement of the Indian and Eurasian plates. These basins are generally composed of coal and oil shale. Coal deposits exist in many of the Tertiary Basins in Northern Thailand, such as Mae Moh Basin, Mae Than Basin, Li Basin, and Na Hong Basin. Series of faulted grabens were formed, which were later occupied by lakes during the Oligocene to early Miocene (Ratanasthien et al., 1999). This led to the deposition of fluvial and fluviolacustrine sediments and the accumulation of peat and oil shale. The quality of coal varied depending on the depositional environment. According to palynological studies, the climate during the Oligocene to late Miocene in Thailand was far from stable (Sepulchre et al., 2009; Songtham et al., 2005).

Citation: Sattraburut T, Ratanasthien B. Maceral association in coal-bearing formations of Mae Than Coal Mine in Lampang, Thailand - Implication for depositional environment. Environ. Nat. Resour. J. 2022;20(1):96-109. (https://doi.org/10.32526/ennrj/20/202100166)

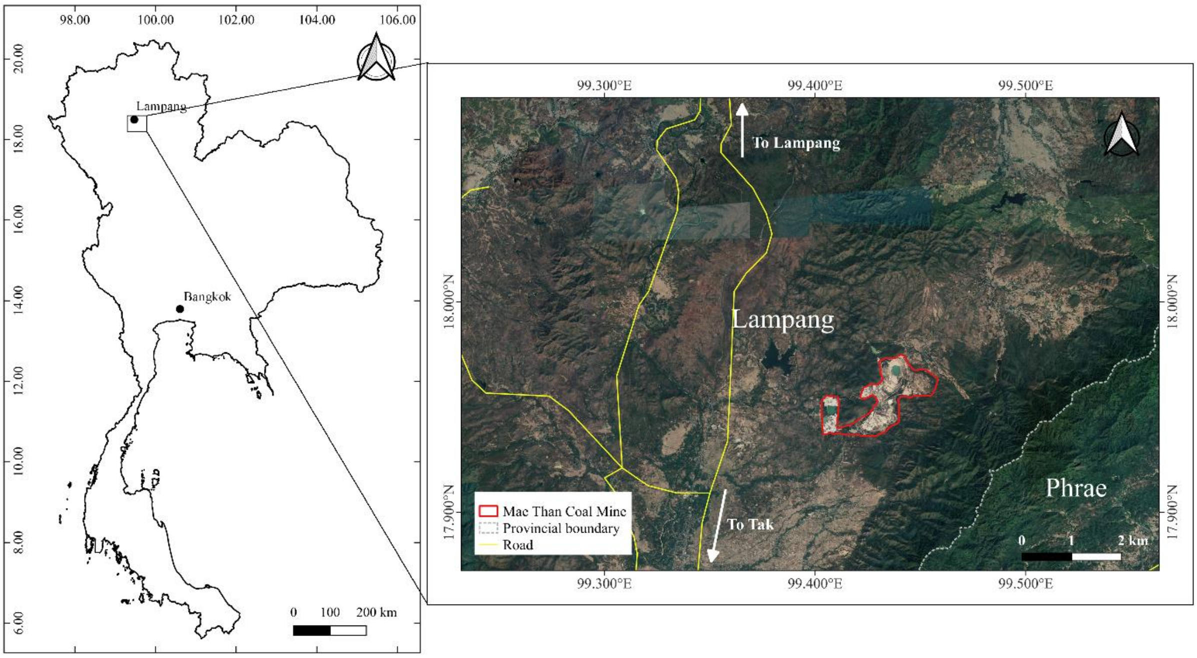

Figure 1. Location of the Mae Than Coal Mine, Mae Tha District, Lampang Province

Figure 2. (a) Mae Than open-pit coal mine (looking west), (b) coal seams and Inter Burden sediments (looking north), (c) woody texture coal, and (d) hard bright coal

Maceral, the organic component of coal and oil shale, can be observed under the petrographic microscope. The association of macerals with inorganic minerals is used to interpret the depositional environment of coal or oil shale based on the relationship of specific maceral compositions (Diessel, 1986; Sahay, 2011). The petrographic study of coal is important because maceral compositions reflect both the physical and chemical behaviors of coals, especially during their thermochemical reactions. However, limited number of studies have been conducted about coal in the Mae Than Basin and are outdated, whereas only one study (Kasetsomboon, 2012) dealt with coal petrography and the depositional environment reconstruct of coals. Therefore, the main focus of this study is to examine the maceral association exposed in the Mae Than Coal Mine by the petrographic method and to discuss the depositional conditions during accumulation. A comparison with other nearby Tertiary basins is also made.

2. METHODOLOGY

2.1 Geological setting

As the influence of collision between the Indian and Eurasian plates, the Mae Than Basin was subjected to tectonic deformation during the Miocene to Quaternary (Muenlek, 1992), while Morley et al. (2011) proposed that small basins in northern Thailand may either had a very short history of the activity or were only episodically active. The approximate time of deposition in the Mae Than Basin is 17-7 Ma (Morley and Racey, 2011).

The Mae Than Basin is a small Tertiary Basin located between the Mae Tha and Sop Prap Districts and is about 58 km south-southeast of Lampang Province. The coal mine is situated in the southern part of the basin. The concession covers an area of approximately 9.4 km^2 and is bounded by latitudes 17°57´N and 17°59´N, and longitudes 99°26´E and 99°28´E. Coal qualities based on an air-dried basis in the Mae Than Coal Mine were reported that the volatile matter varied between 38.6 and 40.5%, ash content ranged from 10.5-12.0%, fixed-carbon content varied between 31.9 and 37.7%, heating value ranged from 4,700-5,022 Kcal/kg, and total sulfur content varied between 0.55-1.22% (Muenlek, 1992; Kasetsomboon, 2012). The coal from Mae Than coal mine was classified as sub-bituminous C.

The Mae Than Basin is an intermontane basin composed of Tertiary clastic sediments, particularly an economically important ball clay and coal seams of sub-bituminous rank. The basin has a half-graben geometry, generally dipping 10-15° to the east and thickening to the east (Morley and Racey, 2011). It is elongated towards NE-SW, 4-5 km wide and 10-12 km long (Muenlek, 1992). The basin is divided into two sub-basins: the southern and northern sub-basins. The Mae Than Coal Mine was operated in the southern sub-basin, which occupied an area of about 1.5-2.0 km^2. The southern sub-basin is controlled by the NNE-SSW and N-S trending faults. It is a flat terrain bounded by a high mountainous area with an elevation of 400-500 m. Permo-Triassic volcanic basement rocks bound the basin to the east and north (Figure 3).

The Tertiary succession can be divided into three units (Figure 4). The lower unit unconformably overlies the Permo-Triassic volcanic rocks. It is about 25-70 m thick and consists of gravelly sand, reddish-brown conglomeratic sandstone, clayey sandstone, siltstone, and conglomerate. The middle unit is about 70-200 m thick and consists of fluvial-lacustrine mudstone, sandstone, ball clay, and sub-bituminous coal. Two coal seams have been identified: the upper coal seam and the lower coal seam. The upper coal seam has a thickness of 3-16 m, while the lower coal seam with some associated oil shale has a thickness of 0.5-27.0 m. Fossils, including mastodon teeth, have been found in fluvial sediments in the upper part of this unit, indicating a Mid-Miocene age. The upper unit is about 30-80 m thick and consists of light-brown to reddish-brown sandstone, tuffaceous sandstone, siltstone, mudstone, and some conglomerates of alluvial deposits (Muenlek, 1992; Ratanasthien, 2011).

2.2 Material and methods

Twelve coal samples were collected from the upper coal seam of the Mae Than Coal Mine in Lampang, Northern Thailand. The sampling interval is approximately 0.5 m from the top to the bottom of the coal seam. The coals are black, dull to bright, hard, massive, and have a woody texture (Figures 2(c) and 2(d)). Firstly, the coal samples were air-dried for a day to remove surface moisture. Then, the samples were crushed into loose fragments and embedded in epoxy resin before polishing. The polished blocks were polished on a glass plate with aluminum oxide powder. They were then polished with chromium oxide followed by periclase powder on a high-speed polishing machine covered with chamois leather. Finally, the polished sections were examined with a coal petrographic microscope under white light, polarized light, and UV excitation in the Department of Geological Sciences, Faculty of Science, Chiang Mai University. The macerals were examined and identified. Macerals of coal are classified into three different groups based on their differences in reflectivity and chemical composition: the huminite or vitrinite group, the exinite or liptinite group, and the inertinite group. The methods for maceral identification are given in the works of Pickel et al. (2017), Sýkorová et al. (2005), International Committee for Coal and Organic Petrology (2001), Standard Association of Australia (1998), and Stach et al. (1982).

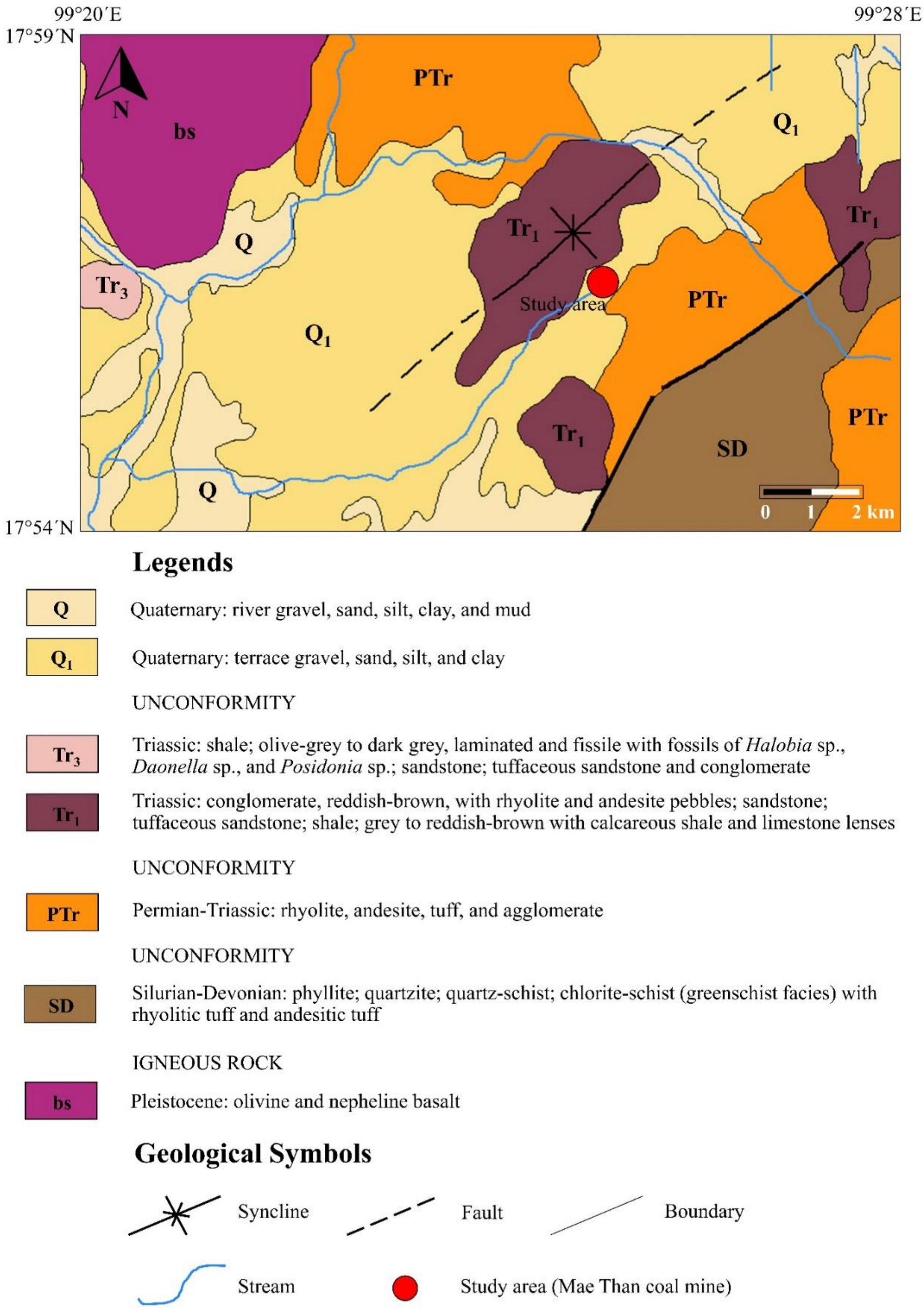

Figure 3. Geologic map of Mae Than Basin [modified from Geological Survey Division (1974)].

Coals always contain inorganic constituents. These minerals can occur as crystalline and/or non-crystalline particles. More than 150 types of minerals are present in coal. However, they are usually clays, pyrite, quartz, calcite, and lesser amounts of other minerals (Vorres, 1986). Mineral matter can be identified by petrographic examination of polished sections of coal in transmitted and reflected light. Several optical properties must be observed to identify minerals, such as color, morphology, reflectance, and anisotropy (Jenkins and Walker, 1978). Detailed methods for mineral matter identification are given in the works of Stach et al. (1982), Ward (2002), Xiuyi (2011), and Susilawati (2015).

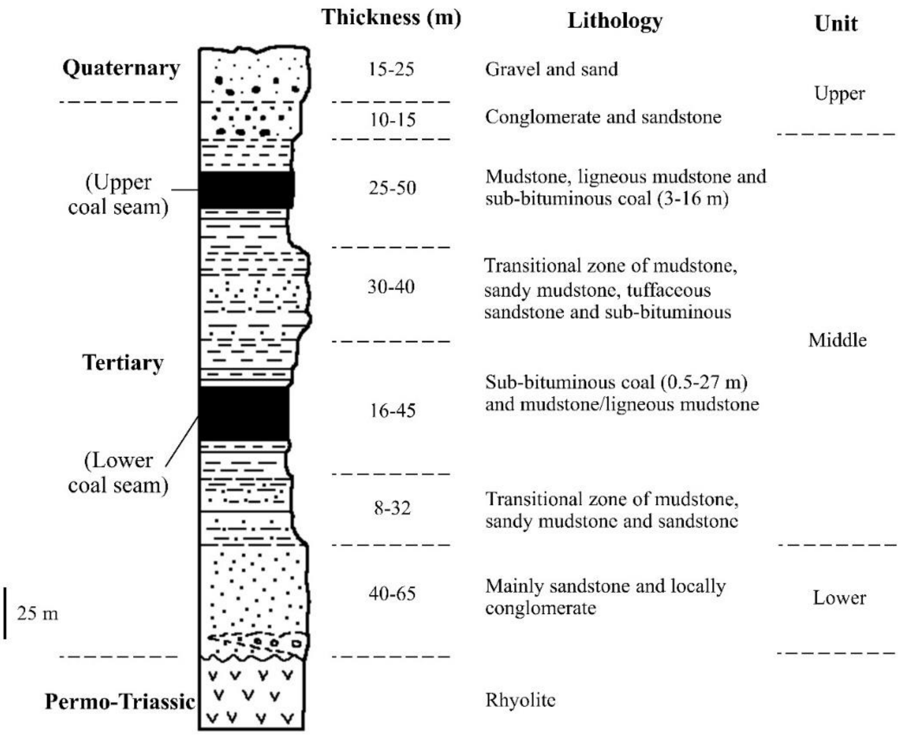

Figure 4. General stratigraphy of the Mae Than coal deposit [modified from Muenlek (1992)]

3. RESULTS

Coals from the Mae Than Coal Mine were examined. They show a variety of macerals in each maceral group. Overall, the dominant macerals are the huminite (vitrinite) groups (42-70%). The second prominent facies is dominated by the liptinite group (5-46%). A small amount of funginite from the inertinite group is also found (typically less than 3% of the total macerals). The maceral composition of the coals is shown in Table 1.

Table 1. The maceral composition (%) of the coals from the upper coal seam of the Mae Than Coal Mine

Sample	Tot Hum	Tot Lip	Tot Inert	Tot MM	Huminite			Liptinite					
					Tel	Gel	Det	Sp	Cu	Re	Lip	Su	Ter
MT01	56	5	0	39	37	16	3	2	0	2	1	0	0
MT02	69	21	0	10	26	32	11	3	14	1	2	0	1
MT03	61	34	0	5	34	27	0	6	0	3	1	0	24
MT04	55	28	1	16	14	12	29	9	5	10	4	0	0
MT05	63	11	1	25	41	14	8	3	4	2	2	0	0
MT06	70	22	0	8	4	54	12	7	1	9	5	0	0
MT07	67	13	1	19	46	21	0	3	2	0	4	0	4
MT08	42	14	0	44	8	11	23	2	2	5	4	0	1
MT09	69	11	3	17	45	16	8	3	3	3	0	0	2
MT10	48	46	0	6	1	43	4	9	13	6	16	2	0
MT11	56	13	1	30	45	11	0	1	8	1	3	0	0
MT12	54	36	0	10	15	31	8	12	2	6	2	0	14
Min	42	5	0	5	1	11	0	1	0	0	0	0	0
Max	70	46	3	44	46	54	29	12	14	10	16	2	24
Avg	59.2	21.2	0.6	19.1	26.3	24.0	8.8	5.0	4.5	4.0	3.7	0.2	3.8

Tot=total; Hum=huminite; Lip=liptinite; Inert=inertinite; MM=mineral matter; Tel=telohuminite; Gel=gelohuminite; Det=detrohuminite; Sp=sporinite; Cu=cutinite; Re=resinite; Lip=liptodetrinite; Su=suberinite; Ter=terpenite; Min=minimum; Max=maximum; Avg=average

3.1 Huminite

Two major maceral subgroups in the huminite group are telohumnite, in the form of textinite (Figures 5(e) and 5(f)) and texto-ulminite (Figures 5(a)-5(d), 5(g), and 5(h)), and gelohuminite, in the form of corpohuminite and a groundmass of gelinite (Figures 6(a), 6(b), and 6(f)). Detrohuminite is also found in the form of densinite (Figures 5(e) and 5(f)).

3.2 Liptinite

The liptinite macerals consist mainly of sporinite, cutinite, resinite, liptodetrinite, suberinite, and terpenite. The sporinite, which has the highest content and well-preserved forms, is usually bright yellow. Some of them have a circular body with an irregular rim, while the others have a saccate form of the pollen (Figures 6(a) and 6(b)). Sporinite is embedded in the groundmass of gelinite and densinite. Cutinite is found in moderate quantity with whole structures, and the margins are recognizable (Figure 6(a)). Resinite is roundish in shape and bright yellowish-orange under UV excitation (Figure 6(a)). Liptodetrinite (Figures 6(a) and 6(b)) is common in the groundmass. It occurs as small fragments derived from other liptinitic material, e.g., spores, pollen grains, cutin, algae, resin, and pigments. Suberinite shows layers of greenish-yellow cell walls under UV excitation. It associates with texto-ulminite. Terpenite (Figures 6(c) and 6(d)) generally occurs as a filling of woody cell structures and cavities. It is usually pale greenish-yellow under UV excitation.

3.3 Inertinite

Funginite (Figures 5(g) and 5(h)) is the only inertinite in this study. It accounts for less than 3% of the total macerals and is usually associated with huminite. It is characterized by a round to oval shape with varying sizes. Funginite is mainly composed of moderately to high reflecting multi-celled fungal spores or fungal remains. The cellular cavities are filled with mineral matter, especially silica.

3.4 Mineral matter

Mineral matter in coals (between 5 and 44%) consists mainly of silica (Figures 5(b) and 5(f)), and clay minerals (Figures 5(d) and 6(f)). It is dominated and commonly found in cracks, cavities, and fissures of the woody texture. Siderite, pyrite, goethite, and some carbonate minerals (Figure 6(e)) are present in low to moderate abundance.

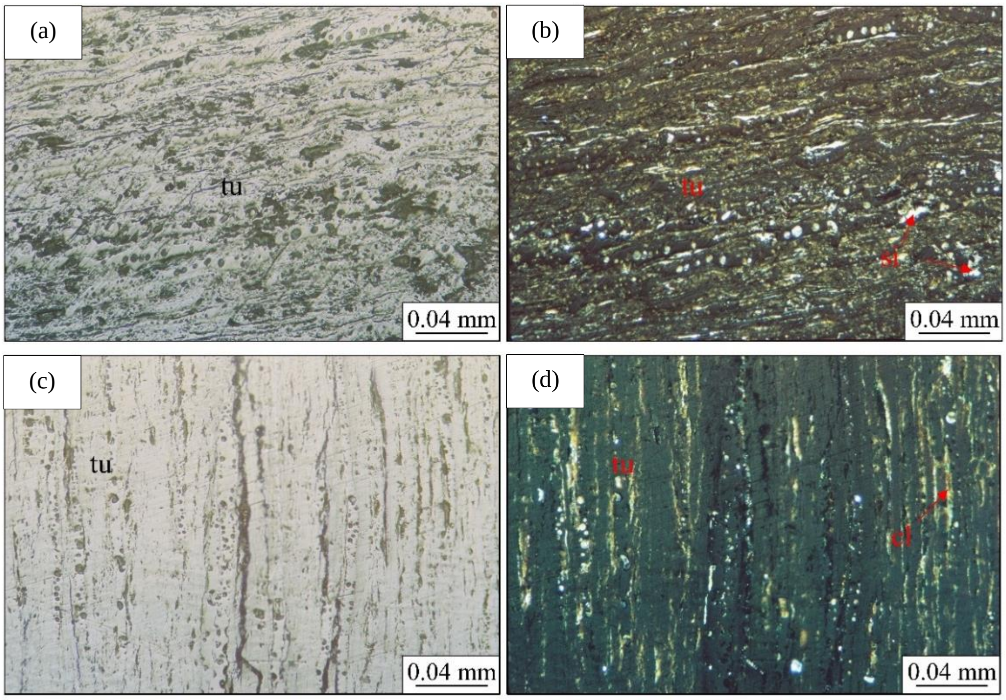

Figure 5. (a) and (b) texto-ulminite and silica in cavities and cracks; (c) and (d) texto-ulminite and clay minerals filled in cracks of wood structure; (e) and (f) textinite and densinite as groundmass. Weathering crack or desiccation crack is shown as a result of water loss. (g) and (h) funginite associated with texto-ulminite. tu=texto-ulminite; si=silica; cl=clay minerals; t=textinite; d=densinite; wc=weathering crack; fg=funginite. (a), (c), (e), and (g) are shown under white light; (b), (d), (f), and (h) are shown under polarized light.

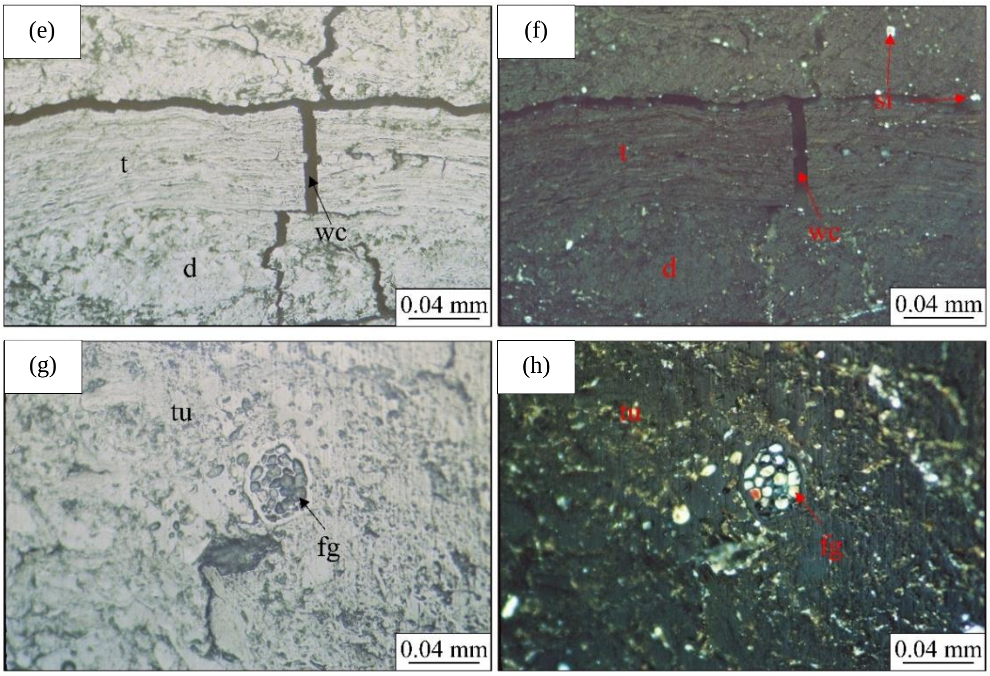

Figure 5. (a) and (b) texto-ulminite and silica in cavities and cracks; (c) and (d) texto-ulminite and clay minerals filled in cracks of wood structure; (e) and (f) textinite and densinite as groundmass. Weathering crack or desiccation crack is shown as a result of water loss. (g) and (h) funginite associated with texto-ulminite. tu=texto-ulminite; si=silica; cl=clay minerals; t=textinite; d=densinite; wc=weathering crack; fg=funginite. (a), (c), (e), and (g) are shown under white light; (b), (d), (f), and (h) are shown under polarized light (cont.).

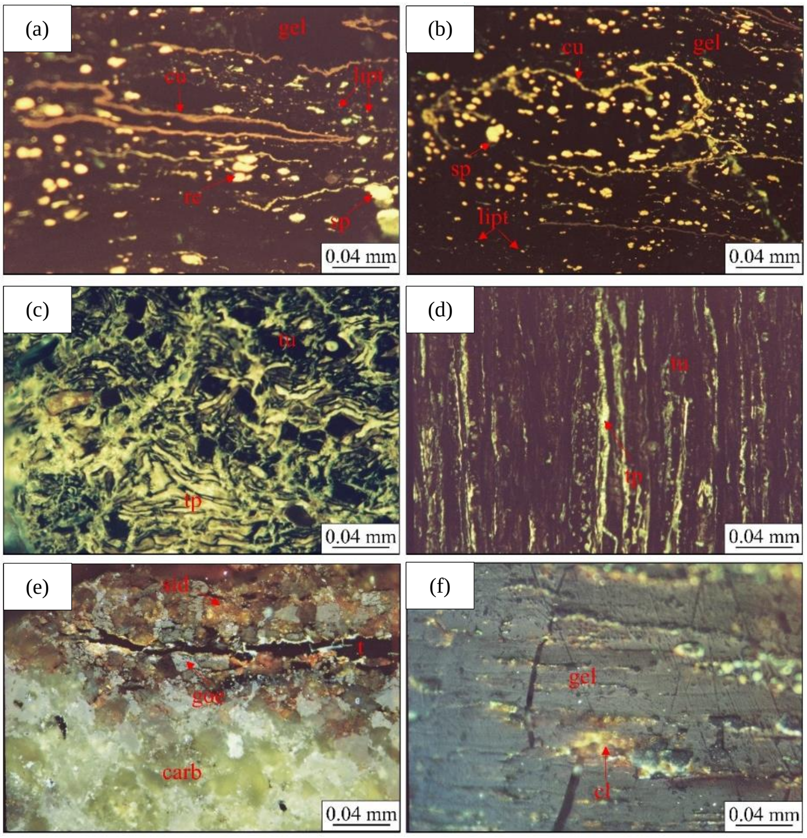

Figure 6. (a) long cutinite with needle-like morphology, with resinite, saccate sporinite, and small fragments of liptodetrinite embedded in a groundmass of densinite and gelinite; (b) bright yellow sporinite with convolute cutinite and liptodetrinite embedded in a groundmass of densinite and gelinite; (c-d) greenish yellow terpenite embedded between woody cell structures of texto-ulminite; (e) textinite and mineral matter in coals, including siderite, goethite, and carbonate minerals; (f) Gelinite with clay minerals filling the cavity. Cu=cutinite; re=resinite; sp=sporinite; lipt=liptodetrinite; gel=gelinite; tu=texto-ulminite; tp=terpenite; t=textinite; sid=siderite; goe=goethite; carb=carbonate minerals; cl=clay minerals. (a), (b), (c), and (d) are shown under UV excitation. (e) and (f) are shown under polarized light.

4. DISCUSSION

4.1 Petrographic compositions

The low-ranked Mae Than coal, classified as sub-bituminous, contains all three maceral groups in varying amounts. The most abundant maceral is huminite. Texto-ulminite and textinite of telohuminite are the most abundant macerals, followed by corpohuminite and gelinite of gelohuminite. Detrohuminite in the form of densinite is also found as a groundmass. The conspicuous telohuminite macerals are derived from the parenchymatous and woody tissues of roots, stems, barks, and leaves. In this study, large amounts of telohuminite and gelohuminite were found. This indicates preservation in a weakly oxidizing environment. This suggests the preservation of cell tissue under moist, possibly low pH conditions in forested peatlands (Ratanasthien, 2011). The presence of telohuminite in Tertiary coals usually indicates coniferous origin, as angiosperm wood and herbaceous plants are generally structurally decomposed (Diessel, 1992). However, in this study, gelohuminite is also present in significant amounts. It could be derived from intensely gelified plant tissues and other humic substances, which are enriched in limnotelmatic deposited peat. In addition, the assemblage of huminite and mineral matter in coals is commonly used as an indication of the depositional environment of ancient mires or peatlands (Wang et al., 2020; Wang et al., 2021).

Liptinite is considered the most important indicator for interpreting the depositional environment. In this study, cutinite exhibits clear cuticular ledges and shows well-preserved morphology. A needle-like cutinite (Figure 6 (a)) indicates a leaf of a conifer (Del Fueyo et al., 2019). These indicate a slightly reducing to strongly reducing condition of the deposit (Pophare et al., 2014; Stach et al., 1982). Leaf morphology is also useful in determining whether the climate in northern Thailand was seasonally tropical or temperate. In addition, sporinite as a saccate form of pollen in this study (Figures 6 (a) and 6 (b)) is restricted to members of Podocarpaceae and Pinaceae (Leslie, 2008), which are considered conifers. This suggests that the climate was temperate during the deposition of the Mae Than coal and conifers were the dominant vegetation (Wagner et al., 2019). Terpenite (Figures 6(c) and 6(d)) occurs only in low- to medium-rank coals where vitrinite reflectance was fixed at less than 1% Ro. This is consistent with the Mae Than sub-bituminous coal (0.40-0.44 %Ro). Terpenite is commonly represented as droplets or streaks derived from the essential oil of plants. Conifers are considered a source of highly aromatic hydrocarbons and *n*-alkanes (Qin et al., 2012; Schlanser et al., 2020), which generally yield a large amount of oil. This suggests that terpenite may be derived from conifer leaves. Evidence from the macroflora and palynology also supports a warm temperate climate during peat formation (Morley and Racey, 2011; Ratanasthien, 2011). The associations of sporinite, cutinite, resinite, liptodetrinite, and suberinite indicate deposition in a freshwater forest swamp or mire.

Funginite of the inertinite group is widespread in low-ranked Tertiary coals (Stach et al., 1982). It indicates the occurrence of recent weathering of peat under inhospitable conditions (International Committee for Coal and Organic Petrology, 2001). It also indicates aerobic conditions and microbial involvement during peat accumulation (Xie et al., 2019). In addition, inertinite could be formed by forest fires ignited by volcanic eruptions or lighting (Sun et al., 2017). The amount of inertinite in coal probably indicates how intense and/or widespread the wildfires may be (Xu et al., 2020). The absence of other inertinite macerals suggests that the Mae Than Basin has not experienced a particularly fire-prone period.

Mineral matter in coal is formed by various processes, such as detrital input from source rocks, diagenetic and epigenetic alteration, and precipitation from solutions. In this study, mineral matter consists mainly of silica and clay minerals. Silica is commonly found as pore or cell fillings in other coal macerals. This type of occurrence suggests an authigenic origin through epigenetic precipitation during the early stage of peat development (Sykes and Lindqvist, 1993; Dai et al., 2018). Quartz formed from solution and mostly of finely-crystalline structure. The dissolved silica could be originated from the leaching of the nearby silica-rich bedrock, which is volcanic rocks such as rhyolite, andesite, and tuff. Clay minerals dominate in cracks, cavities, and fissures between woody cell structures as finely distributed inclusions. This indicates that organic materials were impregnated with muddy water during deposition. Pyrite, along with siderite, is commonly found in woody cell cavities and fissures in coals. Siderite was initially formed by precipitation from solutions during syngenetic or diagenetic formation and then replaced by pyrite after coal consolidation (Smyth, 1966; Stach et al., 1982). Primary siderite can be converted to pyrite by descending or ascending H_2S-containing solutions

(Smyth, 1966). Siderite is usually found as an authigenic mineral in nonmarine, organic-rich environments under strongly reducing conditions (Passey, 2014). Other carbonate minerals were usually deposited during the second stage of the coalification process (Stach et al., 1982). They could be precipitated from leached carbonate solutions derived from Triassic limestone near the coal mine or they could be the result of organic matter degradation during coalification.

Several coal facies diagrams have been developed to reconstruct the paleoenvironment (Diessel, 1982; Mukhopadhyay, 1989; Calder et al., 1991; Diessel, 1992). The tissue preservation index (TPI) vs. gelification index (GI) diagram (Figure 7) and the vegetation index (VI) vs. groundwater index (GWI) diagram (Figure 8) are used to reconstruct conditions during organic matter accumulation. The TPI vs. GI diagram was originally proposed by Diessel (1992), while the VI vs. GWI diagram was first proposed by Calder et al. (1991). Later, these diagrams were modified by Kalaitzidis et al. (2004) for Tertiary low-rank coals. In this study, the TPI values vary between 0.02 and 4.09 (almost below 2.50), indicating moderate to strong organic matter preservation. The values of GI range from 11.00 to 57.63, indicating that the organic matter was gelified under very low oxygen content and wet conditions. The values of VI vary from 0.60 to 18.33. A high value of VI (>1) indicates that the preservation of plant tissues occurred under comparatively more reducing and acidic conditions (Oskay et al., 2019). The GWI values range from 0.87 to 53, indicating that the accumulation of organic matter developed under a rheotrophic hydrological regime (Oskay et al., 2019).

In addition, the TDF coal facies diagram along with the ABC coal facies diagram are applied to determine the paleoenvironment during peat accumulation based on coal composition. The TDF and ABC diagrams were originally proposed by Diessel (1982) and Mukhopadhyay (1989), respectively. In a TDF coal facies diagram, coals are on the left line of a triangle between limnotelmatic and telmatic conditions (Figure 9). This means the depositional environment developed in a flooded environment that is constantly covered with shallow water (Diessel, 1982). In the ABC coal facies diagram (Figure 10), all Mae Than coals fall within an area of anoxic conditions. It also shows that the water table is permanently above the depositional surface (Diessel, 1982).

All coal facies diagrams indicate that the swamp or mire was under anoxic conditions, which can be attributed to a permanently high water table under limnotelmatic to telmatic conditions (Oskay et al., 2019). Maceral compositions also suggest that peat was deposited in the mire to forest swamp.

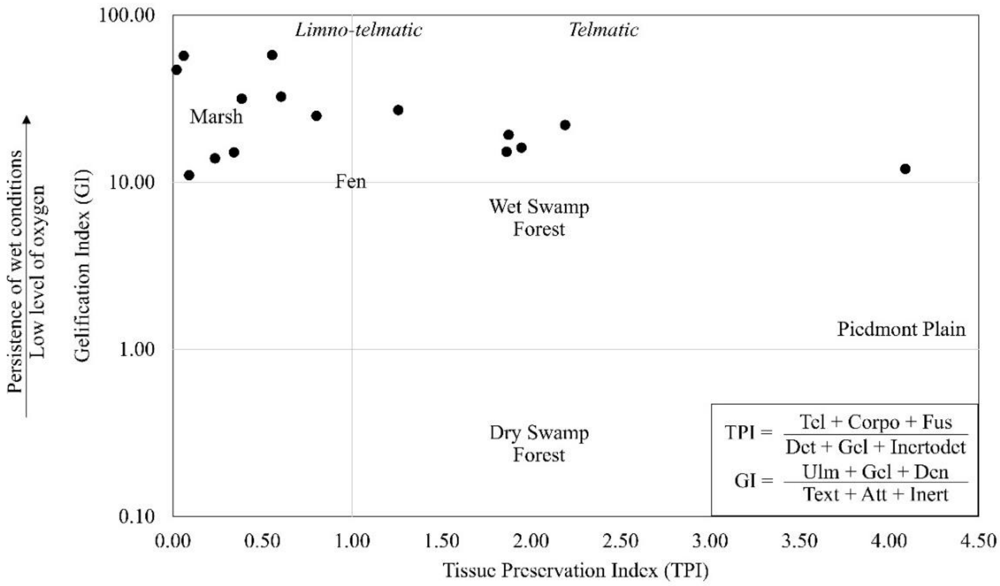

Figure 7. The tissue preservation index (TPI) vs. gelification index (GI) plot of coal samples from the Mae Than Coal Mine [after Diessel (1992), as modified from Kalaitzidis et al. (2004)]. Tel=telohuminite; Corpo=corpohuminite; Fus=fusinite; Det=detrohuminite; Gel=gelohuminite; Inertodet=inertodetrinite; Ulm=ulminite; Den=densinite; Text=textinite; Att=attrinite; Inert=inertinite

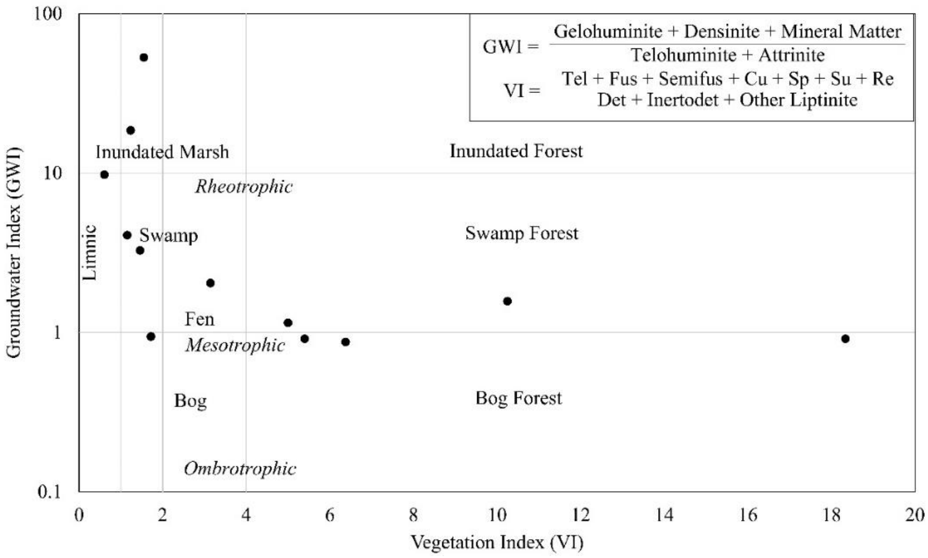

Figure 8. The vegetation index (VI) vs. ground water plot of coal samples from the Mae Than coal mine [after Calder et al. (1991), as modified from Kalaitzidis et al. (2004)]. Tel=telohuminite; Fus=fusinite; Semifus=semifusinite; Cu=cutinite; Sp=sporinite; Su=suberinite; Re=resinite; Det=detrohuminite; Inertodet=inertodetrinite

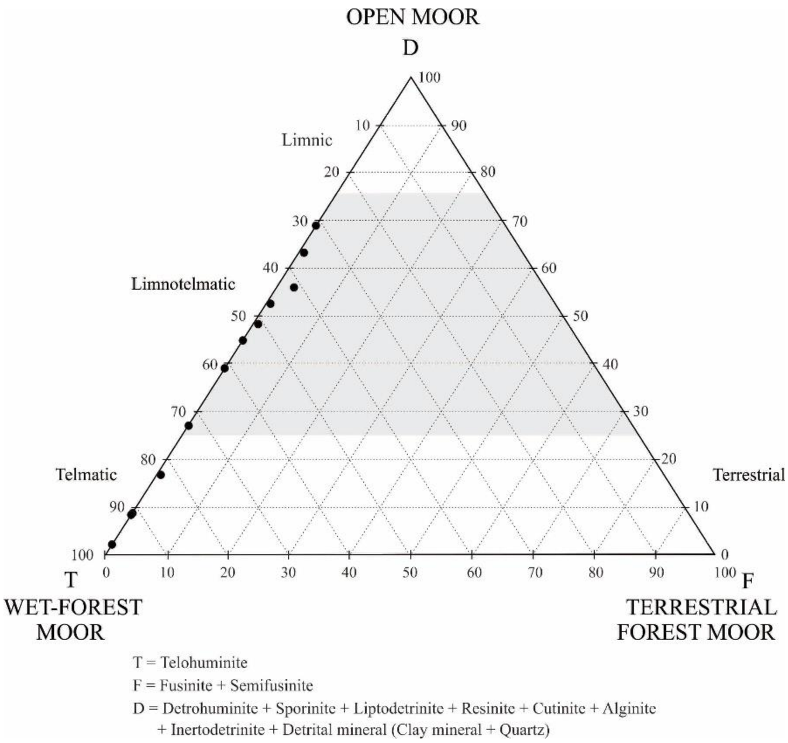

Figure 9. TDF coal facies diagram of the Mae Than coals based on maceral composition [after Diessel (1982), as modified from Edress et al. (2018)].

4.2 Comparison with other works

The petrography of the coal in this work is comparable to others. Kasetsomboon (2012) reported that the two major maceral groups found in the Mae Than Basin are huminite and liptinite. Humotelinite (or telohumnite) and humodetrinite (or detrohuminite) are two of the predominant huminites, commonly found in the form of texto-ulminite, humodetrinite, or densinite, and in a groundmass of gelinite and gelocollinite. Liptinite macerals consist mainly of alginate, cutinite, resinite, sporinite, liptodetrinite, suberinite, terpenite, exudatinite, and fluorinite. Alginite is commonly found as telaginite, including *Pila* sp. and *Botryococcus* sp. The inertinite group is present in small amounts and consists of sclerotinite and fusinite. The maceral associations indicate that the Mae Than Basin was a forest or forest swamp with fluctuating water levels. The basin also yielded plants indicative of a temperate climate (Ratanasthien, 2011). Our results are consistent with other studies in which huminite and liptinite are the predominant maceral groups, suggesting a freshwater forest swamp or mire.

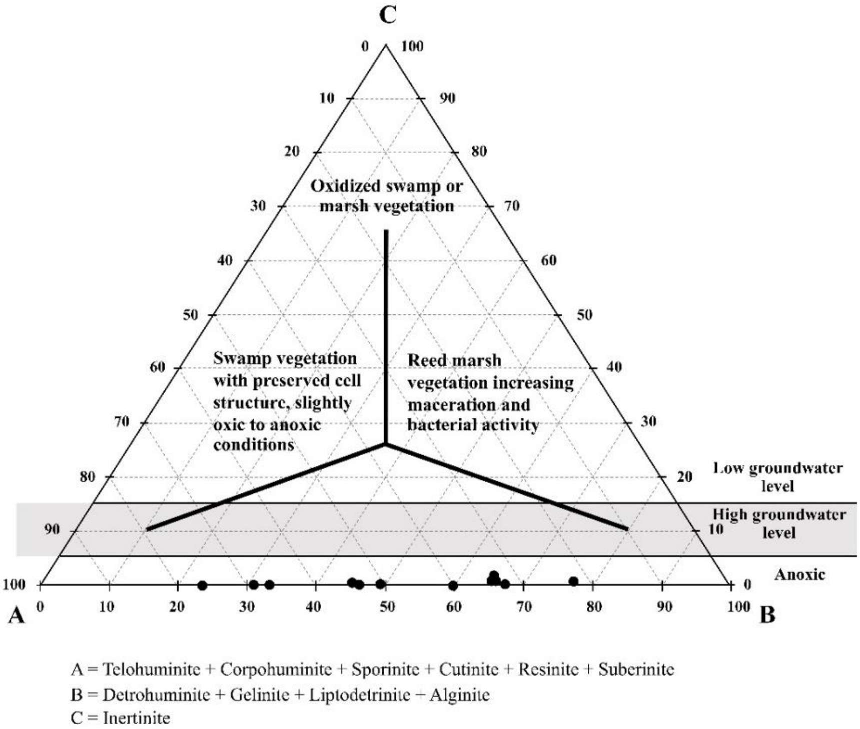

Figure 10. ABC coal facies diagram of the Mae Than coals based on maceral composition [after Mukhopadhyay et al. (1989), as modified from Edress et al. (2018)].

4.3 Comparison with nearby areas

Since there are not many detailed studies in the Mae Than Basin, we compare our work with the petrography of other coals and some macrofloral and palynological research studies from some nearby areas with Miocene coal-bearing basins in northern Thailand (Figure 11). Endo (1963) and Endo (1966) indicated from macrofossils that northern Thailand had a warm temperate climate during the Paleogene. Watanasak (1989) and Watanasak (1990) reported an extensive palynological assemblage from the Oligocene to Pliocene, consisting of various spore and pollen assemblages together with freshwater algae (*Pediastrum*) and some dinoflagellate cryst.

The Mae Moh Basin in Lampang is located to the Northeast of the Mae Than Basin and consists mainly of finely detritic humic components with small amounts of pollen grains and fungal spores, and rare sclerotinite and resinite. The coals have been identified as the decomposed product of leaves, stems, and roots of the herbaceous plant (Gibling and Ratanasthien, 1980). This is consistent with palynological studies showing that the Middle Miocene deposits of the Mae Moh Basin occurred in ponds surrounded by tropical vegetation at low to mid-elevations (Sepulchre et al., 2009).

The Mae Teep Basin in Lampang is a small Tertiary Basin Northeast of the Mae Than Basin. The petrography of the coal shows that the predominant macerals are the huminite group, mainly densitnite and texto-ulminite, while the liptinite group yields only minor amounts (Silaratana, 2005). The maceral associations suggest forest swamp and freshwater lacustrine during coal and oil shale deposition (Silaratana, 2005; Sangtong et al., 2021). Initially, it was a marsh or lake surrounded by saltwater covered by aquatic vegetation such as reeds and grass, followed by a forest swamp with forests and ferns (Sangtong, 2018).

The palynological study was conducted in the Tertiary Li Basin in Lamphun (Songtham et al., 2003). Assemblages of warm temperate and tropical vegetation were recognized. During the Oligocene to Miocene, the climate changed from warm temperate to tropical, probably due to the shift of the Southeast Asian landmass from temperate to tropical latitudes.

This may have led to a transition in vegetation types later on. The depositional environment of the Li Basin is interpreted as lacustrine and swamp deposits (Songtham, 2003). In addition, the relationship between coal quality and palynological assemblages was determined. It was found that coals from warm temperate zones are likely to be of better quality than those from the tropical zone. In addition, a seed wing of *Pinus* was recovered from the Li Basin (Grote and Srisuk, 2021). Based on the palynology and macrofossils, the climate of Northern Thailand was cooler than today in the late Oligocene and Miocene, while it became tropical in the middle Miocene (Grote and Srisuk, 2021; Songtham et al., 2003).

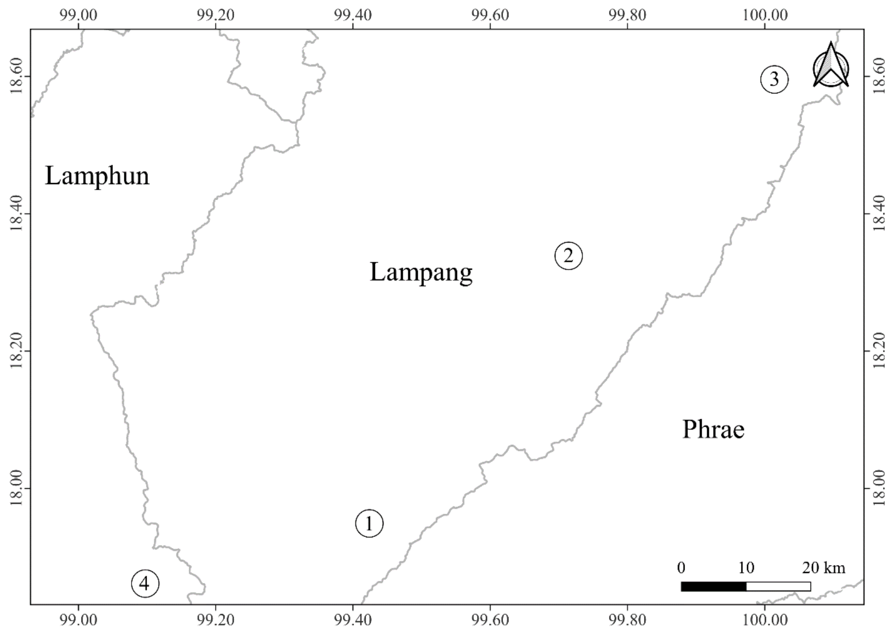

Figure 11. Regional map showing locations of some Tertiary Basins in Northern Thailand. 1=Mae Than Basin; 2=Mae Moh Basin; 3=Mae Teep Basin; 4=Li Basin

Most of the coals in the basins in northern Thailand are dominated by huminite and liptinite, indicating depositional conditions of forest swamps, mire, and lakes. They formed in intermontane pull-apart basins during extensional movements of the Himalayan orogeny in the Late Neogene. Of the other nearby basins, both the paleoclimate and depositional environment in the Mae Than Basin are comparable to those of the Li and Mae Teep Basins, probably due to similarity in topography, elevation, and tectonic evolution.

Overall, most of the intermontane basins in Northern Thailand, including the Mae Than Basin, consisted of coal seams of varying thickness deposited in peat swamps or lacustrine environments. The paleoclimate during deposition was warm temperate to tropical. Regarding the petrography of the coal, our work is consistent with other work. In addition, our study suggests that a dominant Mae Than coal probably originated from coniferous tree trunks.

5. CONCLUSION

The maceral assemblages in the Mae Than coal show an abundance of telohumnite, gelohuminite, and a small amount of detrohuminite. This suggests that the predominant maceral was derived from woody tissue of tree trunks, which was more or less gelified. Liptinite includes sporinite, cutinite, resinite, liptodetrinite, suberinite, and terpenite. The presence of needle-like cutinite, a saccate form of sporinite, and terpenite suggests that the source material of the coal may have come from coniferous trees, and also indicates a warm temperate climate. Dispersed mineral matter filled in cracks or cavities in the coals indicates that peat was impregnated with muddy water. The Mae Than coals were deposited in a freshwater forest swamp or mire and the water table was constantly above the depositional surface. Peat accumulated under rheotrophic, anoxic, limnotelmatic to telmatic conditions.

ACKNOWLEDGEMENTS

The authors would like to thank the Mae Than Coal Mine for permitting sampling and field study. Our thanks also go to the Department of Geological Sciences, Faculty of Science, Chiang Mai University for technical supports in the laboratory. We also acknowledge the critical comments and suggestions of anonymous reviewers, which significantly improved the manuscript.

REFERENCES

Calder J, Gibling M, Mukhopadhyay P. Peat formation in a Westphalian B piedmont setting, Cumberland Basin, Nova Scotia. Bulletin de la Société Géologique de France 1991;162:283-98.

Dai S, Guo W, Nechaev VP, French D, Ward CR, Spiro BF, et al. Modes of occurrence and origin of mineral matter in the Palaeogene coal (No. 19-2) from the Hunchun Coalfield, Jilin Province, China. International Journal of Coal Geology 2018;189:94-110.

Del Fueyo GM, Gnaedinger SC, Diaz MAL, Carrizo MA. Permineralized conifer-like leaves from the Jurassic of Patagonia (Argentina) and its paleoenvironmental implications. Earth Sciences 2019;91:e20180363.

Diessel CFK. An appraisal of coal facies based on maceral characteristics. Asurealian Coal Geology 1982;4(2):2-8.

Diessel CFK. The correlation between coal facies and depositional environment. Proceedings of the 20th Symposium of the Advances in the Study of the Sydney Basin. New South Wales: University of Newcastle; 1986. p. 19-22.

Diessel CFK. Coal-Bearing Depositional Systems. Berlin-Heidelberg, Germany: Springer-Verlag; 1992.

Edress NAA, Opluštil S, Sýkorová I. Depositional environments of the Jurassic Maghara main coal seam in north central Sinai, Egypt. Journal of Asian Earth Science 2018;140:241-55.

Endo S. Some older Tertiary plants from northern Thailand. Japanese Journal of Geology and Geography 1963;34(2-4):177-80.

Endo S. A supplementary note on the Paleogene Li flora in northern Thailand. In: Kobayashi T, Toriyama R, editors. Geology and Palaeontology of Southeast Asia. Tokyo, Japan: The University of Tokyo Press; 1966. p. 165-9.

Geological Survey Division. Geological Map of Thailand 1:250,000 Changwat Uttaradit NE47-11. Bangkok, Thailand: Geological Survey Division, Department of Mineral Resources; 1974.

Gibling M, Ratanasthien B. Cenozoic basins of Thailand and their coal deposits: A preliminary report. Geological Society of Malaysia, Bulletin 1980;13:27-42.

Grote PJ, Srisuk P. Fossil *Pinus* from the Cenozoic of Thailand. Review of Palaeobotany and Palynology 2021;295:Article No. 104501.

International Committee for Coal and Organic Petrology. The new inertinite classification (ICCP System 1994). Fuel 2001; 80:459-471.

Jenkins RG, Walker PL. Analysis of mineral matter in coal. In: Karr C, editor. Analytical Methods for Coal and Coal Products. New York: Academic Press; 1978. p. 265-92.

Kalaitzidis S, Bouzinos A, Papazisimou S, Christanis K. A short-term establishment of forest fen habitat during Pliocene lignite formation in the Ptolemis Basin, NW Macedonia, Greece. International Journal of Coal Geology 2004;57:243-63.

Kasetsomboon N. Petroleum Source Rock Potential in Mae Than Basin, Lampang Province [dissertation]. Chiang Mai, Thailand: Chiang Mai University; 2012.

Leslie AB. Interpreting the function of saccate pollen in ancient conifers and other seed plants. International Journal of Plant Sciences 2008;169(8):1038-45.

Morley C, Charusiri P, Watkinson IM. Structural geology of Thailand during the Cenozoic. In: Ridd MF, Barber AJ, Crow MJ, editors. The Geology of Thailand. London, United Kingdom: Geological Society; 2011. p. 273-334.

Morley C, Racey A. Tertiary stratigraphy. In: Ridd MF, Barber AJ, Crow MJ, editors. The Geology of Thailand. London, United Kingdom: Geological Society; 2011. p. 223-71.

Muenlek S. Coal geology of Mae Than Basin, Amphoe Mae Tha, Lampang. In: Piancharoen C, editor. A National Conference on Geologic Resources of Thailand: Potential for Future Development. Bangkok: Department of Mineral Resources; 1992. p. 112-21.

Mukhopadhyay P. Organic Petrography and Organic Geochemistry of Tertiary Coals from Texas in Relation to Depositional Environment and Hydrocarbon Generation. Taxas, USA: Bureau of Economic Geology; 1989.

Oskay RG, Christanis K, Salman M. Coal features and depositional environment of the Northern Karapinar-Ayranci coal deposit (Konya, Central Turkey). Turkish Journal of Earth Sciences 2019;28:1-15.

Passey SR. The habit and origin of siderite spherules in the Eocene coal-bearing Prestfjall Formation, Faroe Islands. International Journal of Coal Geology 2014;122:76-90.

Pickel W, Kus J, Flores D, Kalaitzidis S, Christanis K, Cardott BJ, et al. Classification of liptinite - ICCP System 1994. International Journal of Coal Geology 2017;169:40-61.

Pophare AM, Ramteke CP, Prasad ALV. Petrographic characteristics of coal seams of Kamptee Coalfield, Central India. In: Shrivastava KL, Kumar A, editors. Geo-Resources. Jodhpur, India: Scientific Publishers (India); 2014. p. 321-38.

Qin S, Sun Y, Tang Y, Jin K. Early diagenetic transformation of terpenoids from conifers in the aromatic hydrocarbon fraction: A long term, low temperature maturation experiment. Organic Geochemistry 2012;53:99-108.

Ratanasthien B, Kandharosa W, Chompusri S, Chartprasert S. Liptinite in coal and oil source rocks in Northern Thailand. Journal of Asian Earth Science 1999;17:301-6.

Ratanasthien B. Coal deposits. In: Ridd MF, Barber AJ, Crow MJ, editors. The Geology of Thailand. London, United Kingdom: Geological Society; 2011. p. 393-414.

Sahay VK. Limitation of petrographic indies in depositional environment interpretation of coal deposits. Central European Journal of Geosciences 2011;3(3):287-90.

Sangtong P, Wannakomol A, Terakulsatit B. Petroleum potential of Mae Teep organic sediments, northern Thailand. International Journal of GEOMATE 2021;20(80):128-34.

Sangtong P. Depositional Environment and Petroleum Source Rock Potential in Mae Teep Basin, Lampang Province [dissertation]. Nakhon Ratchasima, Thailand: Suranaree University of Technology; 2018.

Schlanser KM, Diefendorf AF, West CK, Greenwood DR, Basinger JF, Meyer HW, et al. Conifers are a major source of sedimentary leaf wax *n*-alkanes when dominant in the landscape: Case studies from the Paleogene. Organic Geochemistry 2020;147:Article No. 104069.

Sepulchre P, Jolly D, Ducrocq S, Chaimanee Y, Jaeger JJ. Mid-Tertiary palaeoenvironment in Thailand: Pollen evidences. Climate of the Past Discussions 2009;5:709-34.

Silaratana T. Effects of Environmental Factors on Accumulation of Fossil Fuel Deposits in Northern Thailand [dissertation]. Chiang Mai, Thailand: Chiang Mai University; 2005.

Smyth, M. A siderite-pyrite association in Australian coals. Fuel 1966;45:221-31.

Songtham W, Ratanasthien B, Midenhall DC, Singharajwarapan S, Kandharosa W. Oligocene-miocene climatic changes in Northern Thailand resulting from extrusion tectonics of Southeast Asian Landmass. Science Asia 2003;29:221-33.

Songtham W, Ratanasthien B, Watanasak M, Midenhall DC, Singharajwarapan S, Kandharosa W. Tertiary basin evolution in Northern Thailand: A palynological point of view. Natural History Bulletin of the Siam Society 2005;53(1):17-32.

Songtham W. Stratigraphic Correlation of Tertiary Basins in Northern Thailand Using Algae Pollen and Spore [dissertation]. Chiang Mai, Thailand: Chiang Mai University; 2003.

Stach E, Mackowsky MT, Teichmüller M, Taylor GH, Chandra G, Teichmüller R. Stach’s Textbook of Coal Petrography. Berlin, Germany: Gebrüder Bornstaeger; 1982.

Standard Association of Australia. Australian Standard AS2856.2 Coal petrography Part 2: Maceral analysis. New South Wales, Australia: Standards Australia; 1998.

Sun Y, Zhao C, Püttmann W, Kalkreuth W, Qin S. Evidence of widespread wildfires in a coal seam from the middle Permian of the North China Basin. Lithosphere 2017;9(4):595-608.

Susilawati R. Mineral matter in coal. Buletin Sumber Daya Geologi 2015;10(1):1-14.

Sykes R, Lindqvist JK. Diagenetic quartz and amorphous silica in New Zealand coals. Organic Geochemistry 1993;20:855-66.

Sýkorová I, Pickel W, Christanis K, Wolf M, Taylor GH, Flores D. Classification of huminite: ICCP System 1994. International Journal of Coal Geology 2005;62:85-106.

Vorres KS. Chemistry of Mineral Matter and Ash in Coal: An Overview. Washington, DC, USA: American Chemistry Society; 1986.

Wagner N, Eble C, Hower J, Falcon R. Petrology and palynology of select coal samples from the Permian Waterberg Coalfield, South Africa. International Journal of Coal Geology 2019;204:85-101.

Wang S, Shao L, Wang D, Hilton J, Guo B, Lu J. Controls on accumulation of anomalously thick coals: Implications for sequence stratigraphic analysis. Sedimentology 2020;67: 991-1013.

Wang S, Shao L, Li J, Li J, Jones T, Zhu M, et al. Coal petrology of the Yimin formation (Albian) in the Hailar Basin, NE China: Paleoenvironments and wildfires during peat formation. Cretaceous Research 2021;124:Article No. 104815.

Ward CR. Analysis and significance of mineral matter in coal seams. International Journal of Coal Geology 2002;50:135-68.

Watanasak M. Palynological zonation of Mid-Tertiary intermontane basins in Northern Thailand. Proceedings of the International Symposium on Intermontane Basins: Geology and Resources; 1989 Jan 30 - Feb 2; Chiang Mai: Thailand; 1989.

Watanasak M. Mid Tertiary palynostratigraphy of Thailand. Journal of Southeast Asian Earth Sciences 1990;4:203-18.

Xie P, Hower JC, Liu X. Petrographic characteristics of the brecciated coals from Panxian county, Guizhou, Southwestern China. Fuel 2019;243:1-9.

Xiuyi T. Mineral matter in coal. In: Gao J, editor. Coal, Oil Shale, Natural Bitumen, Heavy Oil, and Peat - Volume 1. Oxford, USA: EOLSS Publication; 2011.

Xu Y, Uhl D, Zhang N, Zhao C, Qin S, Liang H. Evidence of widespread wildfires in coal seams from the Middle Jurassic of Northwest China and its impact on paleoclimate. Palaeogeography, Palaeoclimatology, Palaeoecology 2020; 559:Article No. 109819.