

# DEPOSITION ENVIRONMENT OF ORGANIC SEQUENCES IN MAE TEEP COAL MINE IMPLIED BY MACERAL CHARACTERISTICS

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## Abstract

This study is to assesses the depositional environment and characteristics of petroleum source rocks of Mae Teep basin in Lampang province, Thailand. The stratigraphic units included leonardite, coals, and oil shale units. A total of 44 samples were collected and subjected to petrological analysis for their maceral types. Additionally, the proximate and ultimate chemical analyses were performed. All results were used to interpret their deposition environments. The leonardite contains a high concentration of ash but low concentrations of organic matters, <15.00 wt%. The coal sub-units contain 10.40-68.48 wt% ash, 27.43-45.78 wt% volatile matter, and 3.16–46.31 wt% fixed carbon. The coals are classified as vitrinite (67.4-75.3%) and liptinite (11.9-23.2%). The liptinite is dominated by liptodetrinite, sporinite, cutinite, and fluorinite. The oil shale contains 49.59–83.85 wt% ash, 14.55-37.67 wt% volatile matter, and 0.55-12.74 wt% fixed carbon and short- and long-bodied lamalginite maceral dominated. The results indicated that fluctuation of the water levels had caused the depositional environment changes from a shallow swamp to reed-sedge peat, and from forest swamp to deep, stagnant, lacustrine deposits. The organic deposits settled in the basin through catastrophic fluvial flood events.

**Keywords:** Mae Teep coal mine, lamalginite, maceral type, swamp, lacustrine

## Introduction

Mae Teep basin is the location of 1 of the Tertiary coal deposits in northern Thailand (Figure 1). It was proposed that the basin was formed as a result of the collision between the

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**Figure 1.** Map of northern Thailand shows the Tertiary basins and the study area (black) of the Mae Teep basin in northern Thailand (Modified from Gibling *et al.*, 1988)

Indian-Australian plate and the Eurasian plate. This collision further activated strike-slip fault zones e.g. the Red River, Mae Ping, and Three Pagoda fault zones. Associated with the tectonic event, several intermontane basins were created and they produced fossil fuel deposits which can be seen throughout Thailand and the Andaman Sea (Lacassin *et al.*, 1997; Morley and Racey, 2011). Mae Teep basin is located about 80 kilometers northeast of Lampang city (Sundharovat, 1964) and it has good petroleum source rocks (Gibling *et al.*, 1985). The stratigraphic organic sequences in Mae Teep coal mine were associated with fine- to very fine-grained sediments, generally clays and silt (Petersen *et al.*, 2006). Mae Teep valley displays a flat, rolling topography with elevations of 220-280 m above mean sea level and is surrounded by mountains with elevations around 1,200 m above mean sea level. The basin trends in a north-northeast to south-southwest direction and is located between the Ngao and Phrae basins. The strata on the western margin of the Mae Teep basin have strikes between N10°-30°E with a monocline dipping eastwards at 40° for lower sequences and at less than 20° for the upper sequences (Gibling *et al.*, 1988;

Ratanasthien, 1992; Ratanasthien *et al.*, 2000; Ratanasthien, 2011). The basin is bounded by Permian, Permo-Triassic, and Jurassic age rocks (Songtham, 2003; Morley and Racey, 2011) and more importantly by the shale of the Triassic Pha Daeng Formation (Piyasin, 1975; Chaodumrong and Chaimanee, 2002). The age of the Mae Teep deposit was estimated between circa 18 and 14 Ma (Buffetaut *et al.*, 1988), around the Early Miocene – Mid-Miocene boundary, from the presence of a primitive species of the *Stegologphodon* sp. in the sediments lying under the main coal seam.

The purpose of this study is to interpret the depositional environments of the organic-bearing sedimentary successions associated at Mae Teep coal mine by using organic petrography, geochemical proximate, and ultimate analyses.

## Materials and Methods

The organic successions of Mae Teep coal mine exposed at the mine-front bottom to the top include a leonardite unit, a coal unit, and an oil shale unit. A total of 44 organic matter samples were collected by the channel sampling method according to D4596-09 of the American Standards for Testing of Materials (ASTM) (ASTM, 2011a) from these units. We further divided these 3 units into 7 sub-units: (i) leonardite, (ii) coal C, (iii) coal B, (iv) coal A, (v) oil shale in coal A, (vi) lower oil shale, and (vii) upper oil shale. Approximately 5 kg of each sample was collected and sealed in a plastic bag with appropriate labels identifying the thickness, rock type, and other notes according to the ASTM D2013 (ASTM, 2011b). There were 4 samples from the leonardite, 26 samples from coal C, coal B, and coal A, 4 samples from the upper oil shale, 6 samples from the lower oil shale, and 4 samples from the oil shale in coal A.

All samples were prepared following ASTM D2013M- 1 and D346-04 (ASTM, 2011c) for geochemical analysis. The proximate analyses were conducted based on ASTM D3302-M (ASTM, 2011d) by using a LECO Model TGA- 701, whereas the total

moisture measurement and instrumental procedures were conducted based on ASTM D7582 (ASTM, 2011e). The ultimate analyses were conducted based on ASTM D5373–08 (ASTM, 2011f) by using a LECO Model Tru Spec CHN. Total sulphur was also measured based on ASTM D4239 (ASTM, 2011g). Oxygen was determined by subtracting the sum of the percentage of C, H, N, and S, and ash from 100.

Maceral analyses were carried out on all 7 sub-units as follows. Polished pellet samples were prepared under a microscope and crushed samples were molded in epoxy resin based on ASTM D2797-11a (ASTM, 2011h). The polishing methods were followed as described by Hutton (1987) and point counting (400 counts of macerals and minerals per sample) was performed. Analytical procedures and maceral identification, conducted by using a reflected light microscope equipped with a polarizer and UV-excitation, followed the maceral standards outlined by ASTM D2799 (ASTM, 2011i; International Committee for Coal and Organic Petrology, 1998, 2001; Sykorova *et al.*, 2005).

## Results and Discussion

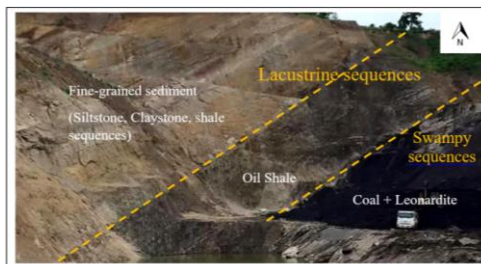
### Sedimentary Successions of Mae Teep Coal Mine

From field investigations and petrographic analyses of all samples, it was found that the stratigraphic sequences of the organic deposits were divided into the swampy and lacustrine environments. For the swampy environment, 4 sub-units starting from the bottom to the top were leonardite, coal C, coal B, and coal A, respectively (Figure 2).

The leonardites are visually characterized by a brown to black colour. At closer examination, they are also stiff and sticky when they are wet, due to the high carbonaceous clay contents. The coal C sub-unit consists of impure coal of sapropelic origins with fine- to very fine-grained sediments present in this stratum. The coal C sub-unit varies in colour from dark brown to black. It has a moderate to dull luster, brittle and highly clay contents, and crumbles easily with an uneven fracture. There are also small

layers in this unit and the total thickness of coal C including the leonardite layers is 6.80 m. The coal B sub-unit is characterized by layers of 10-30 cm thick material with a moderate vitreous to dull luster. Some places show thin layers with a brighter luster that are sub-conchoidal and moderately hard. The total thickness of the coal B sub-unit is 2.43 m. The coal A sub-unit, the uppermost stratum of the swampy environment, is characterized by massive layers of forest-derived detritus. They display a black, vitreous luster, are brittle and have conchoidal fractures with orthogonal cracks on the dry surface. The thicknesses of the coal layers embedded in this unit are 2.53, 3.37, and 2.23 m, respectively. The combined thicknesses of the swampy unit, the leonardite, and the coal C-A sub-units is 10.73 m (Figure 3).

The lacustrine environment can be divided into 3 sub-units which are the oil shale in coal A sub-unit, the lower oil shale sub-unit, and the upper oil shale sub-unit. They are made up of fine- to very fine-grained sediments deposited together with algae and cemented by organic material. In the oil shale in the coal A sub-unit, we observed an oil shale layer interbedded with the coal A sub-unit comprising 2 layers with thicknesses of 0.60 and 0.53 m, respectively. The lower and the upper oil shale sub-units are classified based on variations in thickness and colour. The lower oil shale sub-unit shows a non-uniform thickness of sedimentary sequences, gray to greenish black and with the odor of oil



**Figure 2. The Mae Teep mine front showing contract boundaries between the swampy and lacustrine units and the contrast colour of the oil shale and the fine-grained sediment unit**

in the fresh rock. The upper oil shale sub-unit has more uniform thinner beds 1-5 cm thick, some of which have fossil and shell fragments. The thicknesses of the lower and upper oil shale sub-unit are 2.16 and 3.14 m, respectively (Figure 3).

Both of the lacustrine environment units are overlaid by a fine-grained sedimentary sequences unit. The sediments consist of siltstone, claystone, and mudstone with an absence of organic materials such as algae. The total thickness of these sequences is 5.50 m. The fine-grained sedimentary sequence unit is overlaid unconformably by a series of unconsolidated Quaternary sediments including gravel, sand, silt, clays, mud, and lateritic soil with local calcite cement about 69.50 m thick (Table 1).

### The Geochemistry of the Coal, Leonardite and Oil Shale

The geochemical compositions illustrate the differences between the organic materials

in the proximate and ultimate analyses. The proximate and ultimate results were reported in an air-dried basis, but the moisture condition might include inherent moisture.

The proximate results refer to the percentage of moisture, ash, volatile matter, and fixed carbon. The moisture contents on an as-received basis vary from 1.21-20.38 wt%. On a dry basis, the volatile matter averages 10.90 wt% in the leonardite, 37.79, 39.30, and 36.82 wt in coal C, coal B, and coal A, respectively, 36.59 wt% in the oil shale in coal A, 18.29 wt% in the lower oil shale, and 22.46 wt% in the upper oil shale. Of the ash contents, the highest value is in the leonardite (avg. 84.79 wt%) and the oil shales also have high ash contents with an average of 72.39 wt%, while the ash contents in the coals are low, varying from 13.49-48.72 wt% with the content of coal B being the lowest. The fixed carbon value is high in the coals with an average of 25.71 wt% and low in the leonardite and oil shales, varying from 0.55-12.74 wt%, with average values of 4.32 wt% in the leonardite and 4.09 wt% in the oil shale units (Table 2).

The ultimate analysis refers to the percentage of carbon, hydrogen, nitrogen, sulfur, and oxygen. The carbon contents range from 6.86-50.48 wt% with an average of 23.63 wt%. It is high in the coal unit but low in the leonardite and oil shale units, with an average of 34.72 wt% in the coal, 7.25 wt% in the leonardite, and 17.99 wt% in the oil shale. Hydrogen contents vary from 1.43-5.56 wt% with an average of 3.17 wt%. The nitrogen and sulfur contents are very low, less than 4.00 wt% with an average of 0.19 wt% in the leonardite, 1.05 wt% in the coal, and 0.43 wt% in the oil shale. Sulfur averages 1.45 wt% in the coal, 0.77 wt% in the oil shale, and 0.30 wt% in the leonardite (Table 2).

### Petrography of the Coal, Leonardite and Oil Shale

The petrographic microscope showed that the macerals consist of vitrinite, liptinite, and a little inertinite (Table 3). This easily illustrates the difference for the coal formations and the organic-rich sediments such as the leonardite and oil shale sequences.

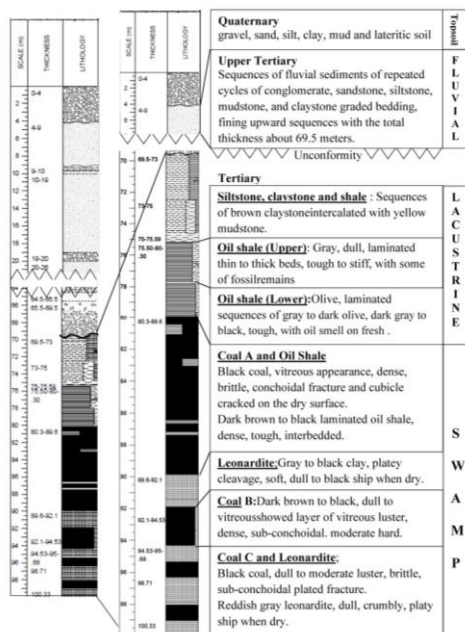


Figure 3. The stratigraphic unit and sample descriptions from samples collected in vertical succession at the Mae Teep Coal Mine open pit

**Table 1. Rock units according to the depositional environments of the Mae Teep deposit**

| Environments | Units                                 | Sub-units                                                      | Geochemical content**                                                    | Maceral Types***                                                                               |                       |
|--------------|---------------------------------------|----------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------------------|
| Fluvial      | Fluvial sequences (semi-consolidated) |                                                                | -                                                                        | -                                                                                              | -                     |
| Lacustrine   | Fine-grained sedimentary sequences    |                                                                | - High ash<br>- Low volatile matter<br>- Low carbon                      | -                                                                                              | -                     |
|              |                                       | Oil Shale                                                      | - High Ash<br>- High volatile matter<br>- High carbon<br>- High hydrogen | Alginite<br>(Lamalginites and Telalginites)<br>Alginite; Lamalginites<br>(Short and long body) | Liptinite             |
|              |                                       | Upper Oil Shale *<br>Lower Oil Shale *<br>Oil Shale in Coal A* |                                                                          |                                                                                                |                       |
|              | Coal                                  | Coal A *                                                       | - Low ash<br>- High volatile matter<br>- High carbon                     | Texto-ulminite + Telocollinite<br>Exsudatinite, Cutinite, Fluorinite                           | Vitrinite & Liptinite |
| Swamp        | Coal                                  | Coal B *                                                       | - High carbon                                                            | Texto-ulminite + Telocollinite<br>Sporinite, Resinite                                          |                       |
|              | Coal                                  | Coal C *<br>(Sapropelic coal)                                  |                                                                          | Gelovitrinite<br>Cutinite, Liptodetrinite, Resinite, Sporinite                                 |                       |
|              | Leonardite                            | Leonardite*                                                    | - High ash<br>- High volatile matter<br>- High carbon                    | Gelovitrinite<br>Liptodetrinite, Resinite                                                      |                       |
|              |                                       |                                                                |                                                                          |                                                                                                |                       |

\*Organic sub-units in this study; \*\*refer to results of proximate and ultimate analysis from Table 2; \*\*\* refer to results of petrography from Table 3.

**Table 2. Average results of proximate and ultimate analyses of samples from the Mae Teep deposits divided by sub-units from the bottom to the top of the sequences**

| Units             | Value (wt%) | Proximate analysis |                 |       |              | Ultimate analysis |      |      |      |       |
|-------------------|-------------|--------------------|-----------------|-------|--------------|-------------------|------|------|------|-------|
|                   |             | Moisture           | Volatile Matter | Ash   | Fixed Carbon | C                 | H    | N    | S    | O     |
| Leonardite        | Avg.        | 7.22               | 10.90           | 84.79 | 4.32         | 7.25              | 1.95 | 0.19 | 0.30 | 5.53  |
|                   | Min.        | 5.14               | 8.94            | 83.62 | 3.43         | 6.86              | 1.43 | 0.13 | 0.30 | 5.27  |
|                   | Max.        | 8.23               | 12.95           | 85.68 | 5.38         | 7.88              | 2.22 | 0.24 | 0.31 | 5.85  |
| Coal C            | Avg.        | 14.14              | 37.79           | 37.32 | 24.89        | 35.01             | 4.54 | 1.08 | 1.87 | 16.61 |
|                   | Min.        | 10.48              | 29.03           | 20.59 | 11.35        | 27.87             | 3.53 | 0.92 | 0.38 | 11.40 |
|                   | Max.        | 17.97              | 45.78           | 59.62 | 36.27        | 44.72             | 5.09 | 1.26 | 3.31 | 25.75 |
| Coal B            | Avg.        | 14.74              | 39.30           | 33.04 | 27.66        | 31.73             | 4.43 | 0.96 | 2.09 | 15.60 |
|                   | Min.        | 10.42              | 36.79           | 10.40 | 14.49        | 28.19             | 4.01 | 0.75 | 0.64 | 14.80 |
|                   | Max.        | 20.38              | 43.67           | 48.72 | 45.93        | 35.27             | 4.84 | 1.17 | 3.53 | 16.40 |
| Coal A            | Avg.        | 9.62               | 36.82           | 38.60 | 24.58        | 37.41             | 4.29 | 1.10 | 0.39 | 21.86 |
|                   | Min.        | 3.32               | 27.43           | 12.37 | 3.16         | 18.29             | 2.10 | 0.30 | 0.30 | 8.018 |
|                   | Max.        | 17.86              | 45.19           | 68.48 | 46.31        | 50.48             | 5.56 | 1.72 | 0.58 | 30.96 |
| Oil Sh. In Coal A | Avg.        | 6.76               | 36.59           | 54.44 | 8.99         |                   |      |      |      |       |
|                   | Min.        | 6.25               | 35.07           | 49.59 | 2.69         |                   |      |      |      |       |
|                   | Max.        | 7.65               | 37.67           | 62.24 | 12.74        | 29.75             | 4.16 | 0.94 | 1.06 | 11.81 |
| Oil Sh. (Lower)   | Avg.        | 3.90               | 18.29           | 80.08 | 1.64         |                   |      |      |      |       |
|                   | Min.        | 1.98               | 14.55           | 69.14 | 1.31         |                   |      |      |      |       |
|                   | Max.        | 4.97               | 28.34           | 83.85 | 2.52         | 11.73             | 2.13 | 0.17 | 0.94 | 4.96  |
| Oil Sh. (Upper)   | Avg.        | 2.80               | 22.46           | 75.90 | 1.64         |                   |      |      |      |       |
|                   | Min.        | 1.21               | 19.13           | 71.01 | 0.55         |                   |      |      |      |       |
|                   | Max.        | 3.86               | 28.44           | 78.97 | 3.15         | 12.50             | 2.30 | 0.19 | 0.30 | 7.00  |

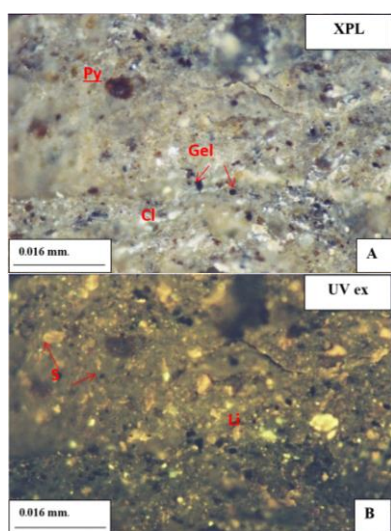
**Table 3. Average percentage results of maceral, sub-maceral types, and mineral matter in each sub-unit under microscopy**

| Maceral   | Sub-maceral (%) | Sub-Units  |        |        |        |                 |                 |                 |
|-----------|-----------------|------------|--------|--------|--------|-----------------|-----------------|-----------------|
|           |                 | Leonardite | Coal C | Coal B | Coal A | Oil Sh. (Inter) | Oil Sh. (Lower) | Oil Sh. (Upper) |
| Vitrinite | Tel             | 0.6        | 2.8    | 38.5   | 48.3   | 0               | 0               | 0               |
|           | Det             | 2.9        | 42.3   | 0      | 0.6    | 0               | 0               | 0               |
|           | Gel             | 17.1       | 22.3   | 36.8   | 21.6   | 26.4            | 4.0             | 5.54            |
|           | Sum             | 20.6       | 67.4   | 75.3   | 70.5   | 26.4            | 4.0             | 5.54            |
| Liptinite | Sp              | 1.9        | 4.7    | 1.8    | 1.7    | 0.8             | 0.05            | 0               |
|           | Re              | 2.0        | 0.6    | 1.9    | 0.6    | 1.1             | 0               | 0               |
|           | Li              | 11.6       | 4.6    | 5.9    | 5.5    | 7.9             | 4.80            | 3.62            |
|           | Cu              | 0          | 2.1    | 2.3    | 3.4    | 0               | 0               | 0               |
|           | Fl              | 0          | 0      | 0      | 3.4    | 0               | 0               | 0               |
|           | Su              | 0          | 1.0    | 0      | 0      | 0               | 0               | 0               |
|           | Al La           | 1.6        | 0      | 0      | 8.3    | 43.5            | 10.54           | 18.46           |
|           | Te              | 0          | 0      | 0      | 0.1    | 3.1             | 4.15            | 4.15            |
|           | Sum             | 17.3       | 13.0   | 11.9   | 23.2   | 56.4            | 19.54           | 26.23           |
|           | Inertinite      | 0          | 0.7    | 0.1    | 0.3    | 0               | 0               | 0               |
|           | Mineral Matter  | 62.1       | 19.0   | 12.7   | 6.1    | 17.2            | 76.46           | 68.23           |

Tel = Telovitrinite, Det= Detrovitrinite, Gel = Gelovitrinite;

Sp= Sporinite, Re = Resinite, Li = Liptodetrinite, Cu = Cutinite, Fl= Fluorinite, Su = Suberinite;

Al = Alginite; La = Lamalginite, and Te= Telalginite.

**Figure 4. Petrographic micrograph of leonardite showing the organic and inorganic association**

XPL = Cross polarized light, UV ex = UV-excitation

Gel = Gelinite, Py = Pyrite, Cl = Clay, S = Sporinite, Li = Liptodetrinite

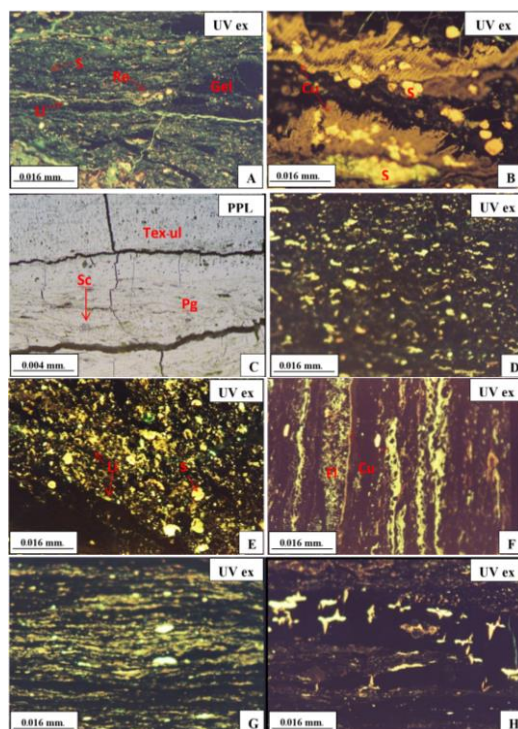
(A) Association of organic, inorganic sediments (black and white) and gelinite lumps (brown) in XPL.

(B) Under UV-excitation, liptodetrinite and sporinite displays yellowish brown in the dark brown organic gel matrix.

The leonardite has 26.0% of vitrinite, made up of decomposed organic matter in the form of gel (gelovitrinite) and minor organic fragments. The liptinite content is 17.3%, consisting mainly of liptodetrinite; those contents resistant to oxidation such as liptodetrinite are the oxidation products of other liptinite macerals, together with resinite and sporinite. The liptodetrinite displayed a gray to dark gray colour in plane polarized light (PPL) and yellow to dark brown in cross polarized light (XPL). Under UV-excitation, it showed a structureless form of small yellow globules dispersed in gelinite (Figure 4).

Coal C which shows sapropelic deposits, is composed of 67.4% vitrinite, 13.0% liptinite, and 0.7% inertinite; the liptinite which can withstand various oxidation levels, consists of 4.6% liptodetrinite, 4.7% sporinite, 2.1% cutinite, 0.6% resinite, and 1.0% suberinite (Table 3). They appeared in pale gray with high relief in the PPL and dark in the XPL. Under UV-excitation they showed a cuticle structure and cell walls and they fluoresced yellow to dark brown (Figure 5(a) and 5(b)).

Coal B consists mainly of 75.3% vitrinite and 11.9% liptinite with a small amount, 0.1%, of inertinite. The vitrinite is composed of 38.5% telovitrinite and 36.8% gelovitrinite.



**Figure 5.** Petrographic micrograph of coal sample., Coal C (A and B) shows well preserved plant tissue. Coal B (C and D) is mostly composed of gelovitrinite in clarite with sporinite and liptodetrinite. Coal A (E, F, G, and H) shows cannel coals, compost of sporinite and liptodetrinite, and boghead coals, compost of alginite, embedded in gelovitrinite

PPL = Plane polarized light, XPL = Cross polarized light, UV ex = UV-excitation,

Gel = Gelinite, Tex-Ul = Texto-ulminite, Pg = Porigelinite, Sc = Sclerotinite,

Cu = Cutinite, Re = Resinite, Fl = Fluorinite, S = Sporinite, Li = Liptodetrinite

(A) C8-2. The sapropelic coal compost of d (black), liptodetrinite (yellow to green), and resinite (dark yellow) in difference character under UV- excitation.

(B) C6-2. Diagonal cut of cutinite shows ledge shape of thick leaf cuticle with groups of sporinite or sporangia in forest peat under UV-excitation.

(C) B15-4. Vitritinite mainly of texto-ulminite (upper) and telocollinite (lower) with minor sclerotinite of inertinite shows a pale pattern of plant tissue in PPL.

(D) B17- 12. Cannel coal displays pale gray to gray of gelovitrinite in PPL deposited with sporinite displays white yellow and spore shape under UV-excitation (d) deposited with resinite, displays a bright yellow row and oval or rod lets bodies.

(E) A5-2. Channel coal of sapropelic origin, consists mainly of liptodetrinite with various types of oxidizing resistant organic matter, such as sporinite and resinite, in gelovitrinite.

(F) A9-1. Leaf layer in well preserved coal shows cutinite and fluorinite under UV-excitation.

(G) A2-7. Massive coal shows suberinite in tree barks, displays yellow – greenish yellow under UV-excitation.

(H) A2-4. Gelinite layer filled in voids by exsudatinite displays pale yellow to yellow under UV - excitation.

The telovitrinite appeared as textinite, texto-ulminite, and porigelinite or eugelinite plant tissue. Both gelinite and telinite usually displayed

bright banded coals and appeared in white to pale gray in the PPL (Figure 5(c)) and dark gray to black in the XPL. Liptinite consists

mainly of macerals resistant to oxidation, i.e. sporinite, resinite, and liptodetrinite. Liptodetrinite displays pale gray to dark gray in the PPL and brown to black in the XPL (Figure 5(d)). The sclerotinites of the inertinite group were found in a sample in which wood tissues were transformed to vitrinite and that were lacking in the liptinite group (Figure 5(c)).

Coal A consists mainly of 70.5% vitrinite and 23.2% liptinite with a small amount (0.3%) of inertinite. The vitrinite was made up of preserved plant tissue as telovitrinite in gelovitrinite which is composed of 48.3% telovitrinite, 0.6% detrovitrinite, and 21.6% gelovitrinite. The liptinite consists mainly of maceral resistant to oxidation, i.e. 3.4% cutinite and fluorinite, 1.7% sporinite, and exsudatinites (Figure 5(f)).

The oil shales are made up mainly of alginite, usually deposited with fine-grained inorganic sediments and gelovitrinite cemented between the grains (Figure 6(a)). This period induced an algae bloom which was represented by oil shale units and oil shale parting layers and was related to boghead coal. The alginite in the oil shale varies from 14.7–46.6%, dominated by lamalginite and some telalginite. Lamalginite appeared as a yellow to orange colour with a lamellar shape. It showed a different character and was abundant in 2 main types: the long form, with a length that varies from 0.004 to 0.016 mm and the short form, with a length that varies from 0.001 to 0.004 mm. Its thickness in the perpendicular section is 0.001 to 0.006 mm (Figure 6(b)). The short lamalginite looks like sporinite but lamalginite has a shape on both of its nibs while the sporinite has a bend on the end of the body. In addition, the colour of sporinite was often brighter than lamalginite. In the parallel sections, it showed circular-shaped colonies. These significant morphological features were identified as *Pediastrum* (Tsukii, 2014). The telalginite was mostly of *Pila* algae, which live in freshwater lakes (Figure 6(c)). They appeared in a spheroid, ovoid to a circular shape being 0.004 to 0.024 mm long and 0.004 to 0.005 mm thick in a massive colony (Figure 6(d)). Some macerals in the oil shale were identified as telalginite of the *Botryococcus* sp., displaying rounded shapes with a greenish

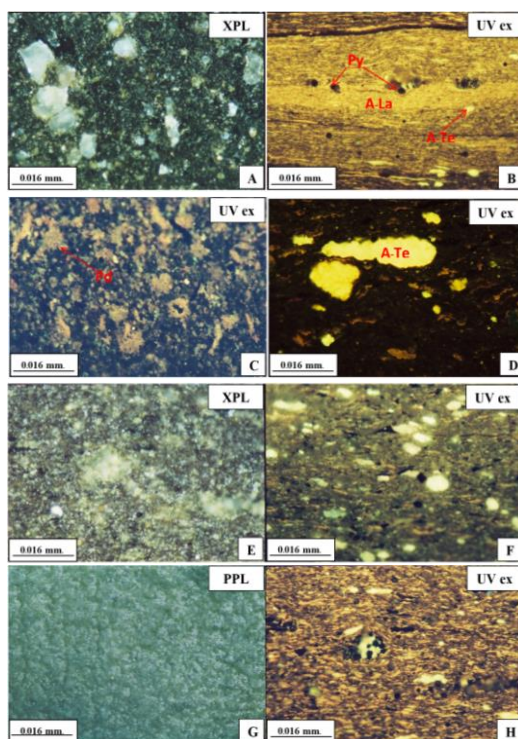
yellow to white-yellow fluorescence. Minor framboidal pyrite was also found to be associated with it.

### Depositional Environment with Maceral of Organic Sequences

In the beginning, the swamp developed as a part of a lake which was covered with deep water in the middle part and became gradually shallower along the banks' slope toward the land. The facies association is interpreted as a deep water deposit with fine floating plant debris including algae in the deepest area, together with muds as sapropelite. They show low organic sediments, varying from 4.0–26.4% with an average of 20.6% in leonardite, 26.4% in the oil shale in coal A, and 4.8% in the lower and upper oil shale. The organic sediments consist mostly of vitrinite, containing more than 67.0% with an average of 71.1%, while the liptinite is likely to increase from impure coal and leonardite to oil shale and the highest content was found in the oil shale in coal A.

The result from the water level change significantly affected the amount of abundant oxygen dissolved in the water and caused the different oxidizing levels. The presence of plant tissue such as cuticle structures with well-preserved cuticles and cell walls of barks or roots, indicated that they were preserved in the reducing environment under the oxidized gel layer which occurred in the upper layer of peat (International Committee for Coal and Organic Petrology, 1998; Sykorova, 2005). The layer in the shallower water with reed-sedge peat and other submerged plants was subjected to a more readily available oxygen condition, that caused higher destruction and produced detrovitrinite and gelovitrinite, with a minor amount of telovitrinite. Those coals were dominated by detrovitrinite in the lower part and telovitrinite in gelovitrinite in the upper part. The high mineral matter content indicated shallow water associated with a waterway.

The liptodetrinite is the degraded remains of sporinite, cutinite, resinite, and suberinite which are concentrated in subaquatic areas, especially in sapropelic coals. They are yellow to yellowish brown irregular shapes for



**Figure 6. Petrographic micrograph of oil shale unit samples show different types of algae and sizes in the algal mat**

PPL = Plane polarized light, XPL = Cross polarized light UV ex= UV-excitation

A-LA = Lamalginites, A-Te= Telalginites, Pd= Pediatrism, Cl = Clay

(A) AS3-8. Oil shale in the lower part showing character of sapropelic deposit associated with poorly sorted coarse- and fine-grained sediments in XPL.

(B) AS3-21. Rich oil source rock in the upper part of oil shale in coal A shows contact layers of short and long bodied lamalginites.

(C) AS2-6. Colonies of *Pediatrism* of lamalginites in parallel section in the lower part of oil shale in coal A.

(D) AS3-21. Colonies of telalginites (*Botryococcus* sp.) in the upper part of oil shale in coal A.

(E) LOH 9-8. Algal mat showing fine-grained sediments groundmass in XPL.

(F) LOH 2-4 Algal mat showing association of *Pila* algae (*Botryococcus* sp) displays white fluorescence with short bodied lamalginites and some sporinite (brownish-yellow to brown fluorescence) in the groundmass.

(G) UOH 10-3. Very fine-grain (clays) of oil shale in PPL show flog texture of algal mat.

(H) UOH 10-3. In UV excitation, showing the algal mat made up mainly of lamalginites, displays brownish-yellow fluorescence with black framboidal pyrite.

liptodetrinite, globular for resinite, and a variety of shapes and ornaments for sporinite (Figure 5(a-e)). Sporinite appeared bright to dark yellow in UV excitation as a spore shape, deposited together with the humic gel of transformed wood tissues into gelinite by partial oxidation-dissolution in the forest swamp.

The sporinite was embedded in the humic gel which transformed into gelinite from the woody tissues in the forest swamp (Figure 5(d)). In such a condition, cutinite and suberinite could be completely preserved in gelinite and are normally found together with telovitrinite and gelovitrinite. In addition, the presence of

cutinite with chlorophyllinite (fluorinite) strongly indicated a reduction in the environment (Figure 5(f)).

Some parts of coal B showed discernible characteristics of woods and barks showing the structural outline of telinite (Figure 5(g)). The presence of liptodetrinite together with sporinite indicated the extension of the reed swamp to a subaquatic environment of the forest swamp, and they were deposited with organic mud. The resinite in gelovitrinite associated with cutinite is similar to that found in pine leaves and generally tends to be a rich source for hydrocarbon in terrestrial deposits due to the abundance of conifers in the Tertiary flora (Figure 5(e)). Resinite globules accumulated in the gelovitrinite groundmass where their coatings were destroyed under a mild oxidizing condition.

Towards the end of the coal deposit, the environment changed to high standing water resulting in the deposited oil shale, followed by the overlaid sequences of fluvial deposits. The investigation showed a sequence of organic deposits with water level changes inferred by the existing remnants of plants. Liptinite is highest in the oil shale in coal A at 56.4%, 19.54% in the lower oil shale, and 26.2% in the upper oil shale. The liptinite varies from 11.9-23.2% in the coal units with an average of 16.0% (Table 3). The inertinite content varies from 0-0.7%, mostly in the form of sclerotinite but only in a small amount in the coals and none at all in the leonardite and oil shales.

The duration of a suitable level of stagnant water, the availability of nutrients, and the climatic conditions are the key factors for the thick and dense algal mat deposit leading to the high quality of the source rocks. If the basin kept changing its water level, the current velocity, sediment loading, lack of nutrients, unsuitable chemistry of the water, and the temperature would affect the algal bloom together with the thickness and quality of the algal mats (Figure 6). The altered thick and thin algal mats indicated that the algal bloom was related to the seasons' supply of nutrients and temperature. Like all plants, algae need nutrients and nitrogen from the water and

would grow faster in warmer temperatures. Moreover, the water chemistry conditions could lead to different characteristics of the algae (Francis, 1961; Teichmuller, 1975; Hutton, 1982). In the Mae Teep basin, the lamalginite in the lower oil shale shows both long and short bodies, but they are thinner and shorter than in the other sub-units (Figure 6(h)). The high standing, still, and nutrient-rich water led to thick algal deposits and then gradually receded before a strong current when a large amount of inorganic sediments flooded into the basin and ended the organic accumulation. Later, there must have been some catastrophic events that caused the facies to change. Sediments accumulated in the upper part of the basin were mainly transported by fluvial processes during the Quaternary activities.

#### **Relationship Between Geochemical Composition and Macerals in Organic Sequences**

The amount of the chemical contents (hydrogen, carbon, volatile matter, and fixed carbon) conformed to the vitrinite and liptinite obtained from the petrographic results. This relationship of the geochemical and petrographic results (Tables 1, 2, and 3) shows low ash contents but high vitrinite related to the high carbon contents in the coals. The high ash contents were found in the leonardite and oil shale with the mineral matter being up to 85.68 wt% ash. The organic macerals associated with the carbonaceous clay were mainly vitrinite and liptinite (together less than 38%). Liptinite was dominated by liptodetrinite with a small amount of resinite and sporinite in the gelinite cement. The volatile matter depended on the high hydrogen/hydrocarbon macerals such as liptinite and vitrinite. These samples showed a high volatile matter content (27.43-45.78 wt%) in the coals. They were composed of 3.16-46.31 wt% fixed carbon, 18.29-50.48 wt% carbon, and 2.10-5.56 wt% hydrogen. The liptinite in coal C consists mainly of sporinite and liptodetrinite with well-preserved cutinite and suberinite in gelinite. This indicates the environment with an extent of shallow water to reed swamp with mild oxidation which occasionally transported tree trunks into the

basin. Coal B contains both telovitrinite and gelovitrinite. The liptinite of coal B is dominated by liptodetrinite with minor amounts of cutinite, resinite, and sporinite which indicates the moderately oxidizing environment of a shallow swamp to a forest swamp. Coal A was composed of 70.5% vitrinite including telovitrinite, gelovitrinite, and detrovitrinite. The liptinite in coal A consists mainly of liptodetrinite, suberinite, cutinite, resinite, and layers of interbedded algal mat. A small amount of sclerotinite associated with telovitrinite suggested tree fungus and the macerals suggested a forest swamp environment with some period of flooding. In the oil shale, the average compositions of the lower and upper oil shales are 78.90 wt% ash, 18.72 wt% volatile matter, 2.38 wt% fixed carbon, and 4.42 wt% moisture, while the average composition values of the oil shale in coal A are 54.44 wt% ash, 36.59 wt% volatile matter, 8.99 wt% fixed carbon, and 6.76 wt% moisture. Elementary analysis of these oil shales result in 11.73-29.75 wt% of carbon, 2.13-4.16 wt% of hydrogen, 0.17-0.94 wt% of nitrogen, and 0.30-1.06 wt% of sulfur. The maceral consists mainly of liptinite, alginite, and the form of the algal mat. The high volatile matter in the oil shale referred to the abundant alginite which is the direct origin of the hydrocarbon source rock. The liptinite macerals in the oil shale are dominated by alginite which is deposited together with abundant fine- to very fine-grained sediments suggesting a period of high standing, stagnant water with seasonally transported fine-grained sediment loading. The dense alginite in the oil shale in coal A suggested abundant nutrients at the time of the flooding.

## Conclusions

The Mae Teep basin is a small terrestrial Cenozoic basin formed as a result of the collision between the Indian-Australian and the Eurasian terranes. Strike-slip faults associated with the tectonic collision, especially the Red River, Mae Ping, and Three Pagoda fault zones, created numerous basins with the

potential for petroleum development throughout Thailand including the Gulf of Thailand and Andaman Sea (Lacassin *et al.*, 1997; Morley and Racey, 2011). The investigations regarding the organic compositions of the Mae Teep deposits and their depositional environments based on the results of the petrographic and geochemical analyses arrive (Table 1) at the following conclusions:

The majority of the stratigraphic successions in Mae Teep coal mine could be classified into 3 environments: (a) a swampy environment where the leonardite, coal C, coal B, and coal A sub-units are; (b) the lacustrine environment where the oil shale in coal A, the lower oil shale, and the upper oil shale sub-units are included; and (c) the fluvial environment consisting of the fine-grained sedimentary sequences unit.

The maceral types and their association indicated the environment of the deposition and relationship to the kerogen type that was classified by a modified Van Krevelen (1993) method. The leonardite sub-unit was deposited in the high water level with a small amount of swamp plant growth. It was high in fine-grained inorganic matter but low in organic content and was dominated by gelovitrinite, which indicated a moderately oxidizing environment. In the coal C, coal B, and coal A sub-units, the presence of detrovitrinite, liptodetrinite, and moderately high ash contents indicated a low water level with a moderately oxidized reed-sedge peat swamp environment. The low ash coal with good preservation of plant tissue was represented by telovitrinite, with some cutinite, fluorinite, sporinite, and resinite association, which indicated a reducing condition in the forest swamp environment. The maceral composition corresponds to type II and III kerogen, indicating oil and gas source rocks.

In the lacustrine environment, the fine-grained sediments caused the high ash content with alginite maceral, indicating high standing, deep water and an undisturbed environment. The alginite rich thick algal mat indicated the available nutrients resulted in good oil source rocks of kerogen type I.

The fluvial association which lay on top of the organic sediments indicated a strong current environment and the end of the petroleum source rock deposits.

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