Chapter 7

Organic Petrography

This chapter reveals the organic petrographical analyses of Barail coal and carbonaceous shale samples to study the hydrocarbon generation potential, types of organic matter, thermal maturity, characterize the depositional environments and diagenetic processes. Organic Petrographic study included maceral analyses, fluorescence study and vitrinite reflectance measurement has been reported in this chapter.

7.1 Introduction

Coal can be defined as a combustible sedimentary rock which originated due to the accumulation and potential decomposition of vegetable matters. The presence of various plant structures as seen under the microscope has proved that coals are formed from plant remains. The different types of coal represent different degrees in the chemical decomposition and physical alteration of original plant material.

The coal petrographic study involves both qualitative and quantitative assessment of macroscopic as well as microscopic constituents. The macroscopic examination is performed without any aid of instruments whereas microscopic study involves application of sophisticated microscopic system. The major macro petrographic units of brown coals are classified as litho-type group which can be readily identified in hand specimens or at the outcrop mine faces. The litho-type groups are designated based on the occurrence of components like xylite (coolified woody material), groundmass (fine detrital humic material) and mineral matter. The microscopic study was employed to the study of litho-types and has resulted in the recognition of ‘Macerals’ (Stopes, 1935) or optically homogeneous aggregates of organic substances possessing more or less distinctive physical and chemical properties.

Organic petrography deals with the microscopically visible organic matter present in rocks. Since coal/shale is a rock, consisting almost entirely of organic matter, it is understandable that organic petrology began with coal petrology. Petrographic
analyses provide information about the rank of coal, the maceral (vitrinite, liptinite and inertinite) compositions and the distribution of mineral matter in the coal/sediments.

Vitrinite reflectance has been used widely to study the thermal history and time-temperature models for stratigraphic successions within sedimentary basins, particularly for evaluating oil and gas generation. Since the coalification reactions and percent reflectance in oil ($\%R_o$) of huminite, vitrinite and bitumen increase with increasing temperature, these macerals provide an indirect geothermometer for evaluating the thermal conditions during sediment burial. The oil and gas generation potential of sedimentary rocks in general is determined by factors including geology, total organic carbon, organic type (facies), paleo-depositional environment and burial history. Source rocks deposited in dysaerobic to anoxic, marine depositional environments with moderate to high organic productivity such as the continental shelf and upper slopes are the most hydrocarbon prone regions. The amount and type of oil (e.g. crude oil) and/or gas (e.g. condensate, wet gas, dry gas) produced by sedimentary source rock depends upon the organic facies or kerogen type and its diagenetic conditions.

Various authors have studied the hydrocarbon source potential and depositional environment of different sedimentary basins were analyzed by using organic petrography (Singh et al., 2017; Farhaduzzaman et al., 2012, 2014; Obaje et al., 2006, 2004). Petro-chemical, petro-thermal and geochemical studies of Indian Eocene coals have been attempted on coal samples (Sharma et al. 2016; Baruah et al. 2013) and the data is available on the hydrocarbon evaluation of the Eocene coal and lignite resources of the country.

The generation characteristics, be of marine, lacustrine and coaly source rocks are specified from the distribution of activation energies of the various kerogen types and from artificial maturation experiments by hydrous pyrolysis methods (Jarvie, 1991; Petersen and Rosenberg, 2000; Petersena et al., 2001; Petersen et al., 2005; Tegelaar and Noble, 1994; Tissot et al., 1987). Based on different kerogen types, a composite petroleum generation model has been suggested by (Powell and Snowdon, 1983). Various studies have also confirmed that there is a variation in generation potential among different macerals and they generate hydrocarbons at different thermal maturities (Khorasani and Murchison, 1988; Lewan and Williams, 1987; Michelsen and
Khorasani, 1990, 1995; Murchison, 1987; Teichmüller and Durand, 1983; Tegelaar and Noble, 1994; Waples and Marzi, 1998). Though the hydrocarbon generation potential range shows similarities or overlaps among the different macerals or kerogen types, it indicates that in most of the cases a single oil window representing all source rock types but will be insufficient in describing the generation history of the organic matter as well as the source rocks dominated by different kerogen types.

Various studies have confirmed that the influence of depositional conditions not only represent the overall organic composition of coals, but also the chemical composition of the vitrinite maceral, for example, the higher hydrogen content in humic organic matter indicates their deposition is marine-influenced (Diessel, 1992; Petersen and Rosenberg, 1998; Petersen et al., 1996, 1998; Sykes, 2001).

A vitrinite reflectance ($R_o$) range from 0.5–0.55% $R_o$ to 1.3% $R_o$ for the oil window was suggested by Vassoevich et al. (1974), and generally in petroleum geology the oil window is considered to span the vitrinite reflectance range 0.5–0.6% $R_o$ to 1.3–1.35% $R_o$ (Hunt, 1996; Mukhopadhyay, 1994; Peters and Cassa, 1994; Pittion and Gouadain, 1985; Taylor et al., 1998; Teichmüller, 1987; Tissot et al., 1987). The onset of petroleum generation was determined to start at a vitrinite reflectance of about 0.5–0.6% $R_o$ and liquid petroleum build-up thus occurs from approximately 0.5–0.85% $R_o$.

In addition, several studies have revealed that the initial increase in HI up to a maximum value (HI max) is with the increasing maturity (Teichmüller and Durand, 1983; Huc et al., 1986; Sykes, 2001; Sykes and Snowdon, 2002).

Coal petrology is a rapidly expanding subject of great technological importance with a highly specialized nomenclature and several systems of classification (Francis, 1961; Krevelen 1961).

### 7.2 The Macerals

Microscopic examination of coal shows that it is constituted of a number of organic matters which differ significantly in their optical properties along with variable concentrations of mineral matter. The organic matters are called ‘macerals’ and the maceral associations are called micro-litho-type. The micro-constituents of coal (macerals) are classified into three groups:

1. Vitrinite
2. Liptinite
3. Inertinite

In general, the macerals of one particular group are similar in their origin, mode of conservation, colour and reflectance but differ in their morphology and maceral and sub maceral levels. In addition, the macerals of each group show close similarity in their chemical composition, such as vitrinite reach in oxygen, liptinite in hydrogen and inertinite in carbon.

### 7.2.1 Vitrite Group of macerals

Vitrinite designates a group of macerals whose colour is grey and whose reflectance is generally between that of the associated darker liptinites and lighter inertinites over the rank range in which the three respective maceral groups can be readily recognized. The reflectances are highly variable depending upon the rank of the coal. Vitrinite occurs in coal as:

1. Mostly as layers or lenses with thickness from several micrometers to several centimeters.
2. As continuous phase of the coal’s groundmass binding with other coal components
3. Amorphous fillings of cells, pores and fissures.

Vitrinite represents the macerals which originated from lingo-cellulosic tissues of terrestrial plants. Since the land plants flourished on the surface of the earth only after the Devonian, vitrinite macerals are usually not found in the sedimentary rocks of pre-Devonian age. They are highly abundant in coals and sedimentary rocks which were deposited in reducing environments in warm and humid climatic conditions. Vitrinite is usually the most abundant among the three maceral groups. Most coals of Paleogene are having a very high content of vitrinite. However in the Gondwana coals of Permian age, which was deposited in temperate and dry climate, the percentage of inertinite group of macerals usually higher than that of vitrinite. In sediments, vitrinite is the main component of Type III kerogen.

According to the ICCP-1994 scheme of classification, the vitrinite group is classified into three sub groups based on degree of destruction of plant tissues. Its
subgroup is classified into individual macerals-based morphology and degree of gelification. The scheme of classification is shown in Table 7.1.

Table 7.1 Subdivision of the maceral group vitrinite according to the new ICCP system 1994

<table>
<thead>
<tr>
<th>Group</th>
<th>Subgroup</th>
<th>Maceral</th>
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</thead>
<tbody>
<tr>
<td>Telovitrinite</td>
<td>Texinite</td>
<td>Ulminite</td>
</tr>
<tr>
<td>Telovitrinite</td>
<td>Collotelinite</td>
<td></td>
</tr>
<tr>
<td>Detrovitrinite</td>
<td>Attrinite</td>
<td>Densinite</td>
</tr>
<tr>
<td>Detrovitrinite</td>
<td>Vitrodetrinite</td>
<td>Corpohuminite</td>
</tr>
<tr>
<td>Gelovitrinite</td>
<td>Corpogelinite</td>
<td>Gelinite</td>
</tr>
</tbody>
</table>

7.2.1.1 Macerals of Telovitrinite subgroup

The telovitrinite subgroup of the vitrinite group of macerals represents intact plant tissues preserved as bands or lenses in coal. The cell structures may be observable under the reflected light and cell cavities may be filled with humid maters of colloidal origin. The lenses or bands are often parallel to bedding. Cross cutting relationship probably indicates an origin from root tissues. The telovitrinite must exceed 0.02 mm in largest dimension. Humified woody or leaf tissues, when humified but retain more or less intact cell structures are found to be preserved as telovitrinite.

a) **Texinite**: It is macerals of telovitrinite subgroup usually associated with low rank coals. Texinite has intact cell walls and cell lumens that are largely open. Texinite is present in low rank coals that have undergone burial from 300m to 600m.

b) **Ulminite**: It is another one maceral of the telovitrinite subgroup which is preserved as layers or lenses that are considerably massive but the layers may show small voids that typically represent the original plant structures. Ulminites are found when burial is higher than 900m up to a depth of 1500m.

c) **Collotelinite**: Collotelinite represent layers and lenses of telovitrinite that do not show cellular structure when viewed in oil immersion. They are derived
from stem, root barks and leaves. Collotelinite form when burial depth goes below 1500m.

### 7.2.1.2 Macerals of Detrovitrinite subgroup

Fragmentary plant tissues and materials precipitated from colloidal solutions of humic materials give rise to detrovitrinite subgroups of macerals of vitrinite group. Both cell walls and cells contains may be present with partial preservations of plant structures. The plant structures can be only seen in low rank coals. In medium rank coals, the vitrodetrinite usually homogeneous colloidal matter and discrete plant fragments show similar optical properties. Detrovitrinite macerals from the ground mass of coal in which other macerals are found to be embedded. Detrovitrinite form from degraded plant materials in peat swamps.

a) **Attrinite:** Poorly preserved fragmental cell wall and cell contents with discrete boundaries, which are usually found in low rank coals are known as attrinite. It is a maceral that is in burial depth lesser than 500m.

b) **Vitrodetrinite:** Fragmental vitrinitic particles with discrete boundaries are known as vitrodetrinite. The particle boundaries get obscured with increasing rank.

c) **Densinite:** It is a maceral intermediate in texture between attrinite and vitrodetrinite. It has a granular texture but the grains are cemented to the adjacent grains. Voids may be often present inside them. It forms when attrinitic grains are cemented by humic colloidal materials with sutures still visible.

d) **Collodetrinite:** Collodetrinite forms continuous ground mass in medium rank coal. It has a structure which is substantially massive. The formation of collodetrinite is when the grains in densinite become so fused (gelified) that the boundaries can not be distinguishable.

e) **Corpohuminite:** Structure less fillings found inside cell lumens are all corpohuminite.

### 7.2.1.3 Macerals of Gelovitrinite subgroup

The macerals of gelovitrinite subgroup form due to precipitation of humid colloidal materials. It reflects strong decomposition during the biochemical coalification under strong reducing environment. It is a minor component of vitrinite in most coal.
a) **Corpogelinite**: Corpogelinites are structure less bodies that derived from humic cell filling which generally occurred as isolated body from the source tissues or in situ.

b) **Gellinite**: It is a maceral of secondary origin and form when colloidal humic materials are found as discrete veins.

### 7.2.2 Liptinite Group of macerals

Liptinite is a group of macerals which indicate humifiable plant matter (Taylor *et al.*, 1998), relatively higher hydrogen content remains such as sporopollenin, resins, waxes and fats and comprise the macerals of the lowest reflectance among the other macerals. The important distinguishable features of liptinite from other macerals are its lower reflectance and fluorescence properties. Liptinite macerals have a low reflectance and high hydrogen content until their properties converge with those of vitrinite at about 1.3–1.4% $R_0$ depending on the characteristics of the coals.

Liptinite is less oxidized than vitrinite present in coals with > 25% Volatile Matter (ICCP, 1963). Liptinite is present in the dispersed organic matter and in coal, generally used to characterize the depositional environment (Tyson, 1995).

Liptinites are usually hydrogen rich with H/C ratio higher than 1, and rich in volatile matters. They react very readily to the increasing temperature of coalification, and thus, their amount decreases with increasing coalification rank. They begin to disappear in the coals of medium volatile bituminous coal and almost disappear in coals of very high rank coal. In low rank coals, they tend to preserve the original plant structures and thus, named after the type of precursor material, such as sporinite, cutinite etc. Although they are rich in hydrogen, with H/C atomic ratios commonly in excess of 1.0, many liptinite macerals probably do not contribute greatly to the generation of liquid hydrocarbons. Liquid hydrocarbons have paraffinic composition. The secondarily generated hydrocarbons trapped in the coal matrix in fractures or pores also show similar optical properties like primary liptinites and considered as macerals of liptinite group. The chemical affinities of the liptinite macerals are shown in the Table 7.2.
Table 7.2 Classification and chemical affinities of liptinite macerals

<table>
<thead>
<tr>
<th>Napthenic</th>
<th>Paraffinic</th>
<th>Aromatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resinite</td>
<td>Cutinite</td>
<td>Bituminite</td>
</tr>
<tr>
<td>Sporinite</td>
<td>Suberinite</td>
<td></td>
</tr>
<tr>
<td>Liptodetrinite</td>
<td>Alginate</td>
<td></td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Secondary macerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exsudatinite</td>
</tr>
<tr>
<td>Bitumen</td>
</tr>
<tr>
<td>Bitumen cokes</td>
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</tbody>
</table>

A detailed knowledge of the macerals present within the liptinite group is required for an assessment of hydrocarbon generation potential (and of the maturation windows within which generation takes place). Liptinite group abundance or the presence of high hydrogen contents in bulk analyses (for example Rock-Eval HI) are not an unequivocal indication of source potential. Some terrestrial facies are dominated by sporinite or resinite and have low oil source potential. Other coal-related facies have a high content of cutinite or of suberinite and have a much higher source potential. Most liptinite-rich lacustrine facies are dominated by alginate and usually have high source potential. Marine liptinite is dominantly alginate or bituminite and both of the macerals have a high source potential for petroleum liquids. Liptinite type and abundance is an important element of organic facies. A classification of liptinite-rich rock types has been proposed by Cook and Sherwood (1991) to assist in defining organic facies and petroleum source potential.

The macerals of this group possess distinct morphology with dark grey to black colour in low rank coals (lignite to medium volatile bituminous coals). They are divided into two types, as primary and secondary. The primary liptinite macerals are characterized by distinct morphology and derived from hydrogen rich constituents of plants such as spores, pollens, cuticles, resins, algae, suberine and others. The secondary liptinite macerals (such as bituminite, exsudatinite) are the products of coalification and therefore, characterized as expelled hydrocarbons. They occur in cleats, fissures and cavities of vitrinite and inertinite group of macerals.

In petroleum source rocks, hydrogen rich liptinite is considered a major source for liquid petroleum. It is of some significance for petroleum generation that the onset of hydrocarbon generation from liptinites varies for different liptinite macerals and
begins at different thermal maturities. Suberinite, bituminite and terpene resinite for example often generated petroleum at a lower maturity or rank (at about 0.4% R₀) (Pickel et al., 2017).

a) **Sporinite:** Spore and pollen coats or exines preserved in coal are called sporinite. The maceral sporinite constitutes exines (skin) of spores and pollens. It appears as lens shaped bodies and the size of sporinite ranges from 10-2000 microns. Sporinite is very common liptinite maceral having naphthenic structure. It commonly preserves ornaments and shows a flattened outline. They usually occur as dark colour long slender bodies in coal.

   In Paleozoic coals, megaspores (female) are commonly present, which are about 2mm in diameter and typically show weaker fluorescence than microspores (male). When it is not possible to determine the gender of smaller spores, they are referred to as miospores. In Paleogene coals, sporinite occurs in detrovitrinite groundmass as minor constituent. The fluorescence intensity is generally low even in low rank Paleogene coals and show a bias towards dull orange.

b) **Cutinite:** Cutinite represents outer coatings of leaves, needles, some roots, thin stems, fruits etc., and characterized by a long thread like structure with one end serrated. Its colour ranges from black to dark grey but lighter than sporinite in the same coal. It has cellular pattern and shows a very characteristics serrated appearance in cross sections. In thickness they range from 0.003 to 0.02 mm. Floras of dry climate usually have thicker cutinite. It has a waxy composition usually black in colour and fluorescing in low rank coals. When vitrinite reflectance is very high (0.6 to 0.75% R₀), they are usually non-fluorescing. In Cenozoic coals, cutinites with multiple cuticles are found which is transitional to suberinite. They are considered as Type II Kerogen and have a paraffinic.

c) **Suberinite:** It is derived from outer layers of woody tissue. The outer layers of woody tissues are usually impregnated with suberins for protection against desiccation and microbial or insect attack. The suberinites are similar to cutinites but much thicker, show a blocky appearance. Some suberinites in Cenozoic coals are thin wall and weakly to non-fluorescing. A second form of
suberinite occurs as much thicker and more brightly fluorescing tissues that are commonly well preserved, thick and laterally extensive.

d) **Resinite:** Resinites represent resins, a naphthenic compound produced by some plants to deter attack by insects, fungi and bacteria. The maceral resinite occurs commonly as cell fillings and as circular, oval or rod shaped and its colour is always darker than the vitrinite in the same coal, ranging from dark grey to black depending upon the rank of the coal. Resinites also include some resin like substances which are by-product of metabolism of plants. They are mostly dark coloured oval shape, lens or rod like bodies which may be opaque or semi translucent. In high sulphur coals, they are usually impregnated with dots of pyrites. Fluorescence of resinite is usually high but decreases with increasing vitrinite reflectance. Resinite is commonly associated with exsudatinite, especially in some sections of Paleogene coal measures.

e) **Liptodetrinite:** Liptodetrinite represents attrital form of various liptinite materials. They are product of mechanical or biochemical degradation that has no recognizable form. The maceral liptodetrinite includes the detritus of macerals such as sporinite, cutinite, resinite, alginate, and suberinite. The aggregate of these macerals show black colour and appear very similar to clay minerals in white incident light. In most cases, there identification is possible only under florescent light (blue excitation). They show greenish yellow, orange and very light brown colours.

Liptodetrinite is widely distributed liptinite maceral in coal. It is preferentially associated with attrital layers where it occurs with detrovitrinite, resinite and sporinite. It is also widely distributed maceral in sedimentary rocks other than coal.

f) **Alginitite:** The maceral alginitite appears darker than the other macerals of this group and its occurrence is found to be rare in bituminous coals. The cell structure of alginate is nearly indistinct in incident light but can be seen under fluorescent light (blue irradiation). Alginitite represents remnants of algal materials in coal. Based on morphology, they are classified into telalginitite and lamalginitite. Telalginitite are larger form of alginate which commonly shows botanical structures, and shows intense fluorescence than most of the liptinite
macerals other than resinites. Both marine and non-marine algae can occur as
telalginite. Telalginite within coals is typically derived from Botryococcus, but
some shaley coals with tasmanitids are known.

Lamalginite is derived from smaller algae and less commonly shows
botanical structure. They usually show a lamellar form and fluorescence is
usually lesser than telalginite. The fluorescence colour is usually biased towards
green and yellow. Lamalginite is derived from green algae and can be present
in marine and non marine rocks.

g) **Bituminite:** Bituminite is produced by the bacterial decomposition of fats,
proteins and algae, and occur as amorphous lamellar mass showing black colour
in incident white light. It shows yellow, orange and brown fluorescence
depending upon the maturation. Bituminite occur as low reflecting layers or
lenses in some marine rocks and sapropelic coals. Their origin in marine rocks
is thought to be related to contributions from cyanobacteria and red-green algae.
Its optical properties are intermediate between macerals of vitrinite and the
primary macerals of the liptinite group. The fluorescence is generally weak.
Micrinites (a macerals of inertinite group), when present in coal, is found to be
associated with bituminite.

h) **Exsudatinite:** The maceral exsudatinite is characterized as expelled
hydrocarbon and occurs usually as vein or pore fillings. It shows black colour
in incident white light but appears orange to yellow in fluorescent light. Veins
of bitumen-like material with coals have been referred to the maceral
exsudatinite. Earlier similar materials have been described as secondary
resinites. Sometimes they show clear spatial relationship with resinites. They
occur as weakly reflecting by moderate to strongly fluorescing material in vein
like forms across the matrix of the coal. They are considered as originated as
exude from coal. Frequent occurrence of exsudatinite is very common in
thermally altered coals.

The presence of more than one generation of veins is a common feature.
In thermally altered coals, meta-exsudatinite veins may be present. Meta-
exsudatinite has a reflectance similar to that of the associated vitrinite and does
not show fluorescence in form it is similar to exsudatinite.
7.2.3 Inertinite Group of macerals

Inertinite is a maceral group that comprises macerals whose reflectance in low- and medium-rank coals and in sedimentary rocks of corresponding rank is higher in comparison to the macerals of the vitrinite and liptinite groups. The macerals of inertinite group is shown in Table 7.3.

Table 7.3 Macerals of the inertinite group

<table>
<thead>
<tr>
<th>Macerals with plant cell structures</th>
<th>Fusinite</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Semifusinite</td>
</tr>
<tr>
<td></td>
<td>Funginite</td>
</tr>
<tr>
<td>Macerals lacking plant cell structures</td>
<td>Secretinite</td>
</tr>
<tr>
<td></td>
<td>Macrinite</td>
</tr>
<tr>
<td></td>
<td>Micrinite</td>
</tr>
<tr>
<td>Fragmented inertinite</td>
<td>Inertodetrinite</td>
</tr>
</tbody>
</table>

a) **Fusinite**: Fusinite is a maceral of the inertinite maceral group, which shows very high reflectance and well preserved vegetal structure with at least one complete cell of parenchyma, collenchymas or sclerenchyma. The macerals fusinite shows yellowish white to white colour and very high relief in incident white light. The reflectance is very high irrespective of the rank of coal. It chiefly represents charred material resulting from forest fires. In the anthracitic stage of maturation the reflectance of fusinite is overtaken by that of vitrinite. It does not fluorescence. It is characterized by high carbon content and low hydrogen and oxygen contents, and volatile matters. It originates from lignocellulosic cell walls. All fusinites are considered to be product of incomplete combustion during forest fire. However, some opines that fusinites can also form because of decarboxylation of woody tissues with the aid of bacteria and fungi or by degradation and weathering.

b) **Semifusinite**: Semifusinite is a maceral that shows optical properties intermediate between vitrinite and fusinite. It is characterized by cell structure comparatively fewer than the maceral fusinite. It has higher reflectance than coexisting vitrinite and lower reflectance than fusinite. Semifusinite may often
show cell structures but not as prominent as that of fusinite. A band or layer of vitrinite may grade laterally into semifusinite. It represents either partially charred material from forest fire or humic material that has become partially oxidized by biochemical activity. Very weak fluorescence may present, which is visible especially on long wavelength irradiation.

c) **Funginite:** Funginite is a maceral of inertinite maceral group consisting of highly reflecting single and multi-celled fungal spores, sclerotia, hyphae and mycelia and other fungal remains. Materials of fungi remains are only associated with Paleogene coals. In very low rank coals, lumens of the fungal spores are typically empty. In coals with mean vitrinite reflectance ~0.45% R\text{o}, the lumens of funginite commonly include strongly fluorescing material similar to resinite or exsudatinite.

d) **Secretinite:** It is generally a rounded, oval shaped bodies, vesicled or non-vesicled and do not show obvious plant structures. It is highly reflecting with high polishing hardness and does not fluorescence. It was formerly included in sclerotinite. It is considered to be an oxidation product of resin but it may originate from humic gels and to a lesser extent in cells or ducts of other vascular plants.

e) **Macrinite:** Macrinite is a maceral of the inertinite group which is highly reflecting and occurs either as an amorphous matrix or as discrete, structure less bodies of variable shapes. Its occurrence as oval to round shape isolated bodies. The colour and reflectance of macrinite is very close to fusinite in the same coal. It occurs principally as round or oval bodies with light grey to yellowish white color and reflectance between vitrinite and fusinite in the same coal. They may occur as groundmass or as lenses or bands. Large particles of macrinite usually show a mottled appearance. The reflectance is usually lower than that of fusinite. They may show fluorescence when irradiated by long wavelength light. It probably originates from flocculated humic matrix substances which underwent dehydration and redox processes in an early stage of peatification due to temporarily lowered groundwater table. They may also be metabolic product of fungi and bacteria.
f) **Micrinite**: The white to pale grey round shape fine particulate constituents (~1µ size) are characterized by micrinite, occurs in very small rounded grains. This inertinite maceral are considered to be reactive to a limited extend. The colour is pale grey to white and the reflectance is usually lower than other inertinite macerals. To distinguish it from the inertodetrinite, an upper size limit of 2µ is put for the micrinite grains. Micrinite tends to be widely dispersed in coals. It does not fluoresce.

Micrinite is a collective term applied to very fine grained inertinite that may have originated in various ways. It is generally considered as a secondary maceral which is formed during the coalification process. It represents either coalification product of sclerenchyma or residues of former liptinitic or hydrogen rich vitrinitic material.

g) **Inertodetrinite**: Inertodetrinite is a maceral of the inertinite maceral group, occurring as discrete small inertinite fragments of varying shape. The fragments of inertinite macerals especially of fusinite, semifusinite, sclerotinite and macrinite smaller than 30µ are designated as inertodetrinite. The reflectance and colour of inertodetrinite is non-fluorescent, except particles with relatively low reflectance in low- and medium- rank coals.

It has a variety of precursors, which have been subject to some degree of fusinization, which includes plant cell walls, phlobaphene from decomposed tissues, oxidized spores and constituent of fungal affinities. Many particles are also relics of wild fires in and around the peatland.

### 7.3 Experimental Procedure

#### 7.3.1 Polished Particulate Mount

Polished blocks and pellets were prepared following the procedure as suggested by Stach *et al.* (1982). Polished blocks are prepared from coal samples suitable for cutting into blocks of cubes with 1" x 1" surface area. Pellets were prepared from granular coal and carbonaceous shale samples (size of the grains ~1-2mm). In both cases, height of the blocks and pellets were kept at 25 mm. For preparation of pellets, granular coal or carbonaceous shale samples were mixed with epoxy resins in 1:1 ratio by volume and poured into molds made up of mild steel. Pellets were prepared without applying
pressure. Before the mixture is hardens it is repeatedly stirred in the mold so as to prevent settling and segregation of the grains. The mold is kept for 24 hours for the mixture of sample and epoxy resin gets hardened. The mold is then removed and the specimens marked in order to avoid confusion. The thoroughly hardened samples are taken for grinding. The grinding operation is done in automatic polishing machine with silicon carbide papers of different grades and distilled water. Polishing of the polished blocks and pellets are done in the same machine of Buehler make. Several stages of polishing are necessary and carried out on high speed polishing wheel using alumina powder of firm Grade I through Grade III. The last stage of polishing is done usually with hand on sylvet cloth with diamond paste and finally with distilled water.

This method is the most widely used method of coal petrography throughout the world because it allows quantitative maceral analysis and reflectance measurement with statistical accuracy.

7.3.2 Fluorescence Microscopy study

Developments in the field of coal petrology have envisaged that the microscopic investigation under normal white light is not sufficient in understanding the petrographic composition of coal. Coals should be studied under fluorescence. For this examination the same transmitted light or incident light microscope that are used for the study under white light are used. With suitable mechanism, as and when necessary instead of white light source, high pressure mercury or xenon lamps with suitable excitation and suppression filters are used for the generation of ultra-violet or blue irradiation. Under these excitations the macerals of liptinite group as well as perhydrous vitrinite became luminescent and appear in various bright colours such as green, yellow, orange and brown. As such, it becomes easier to identify fluorescent micro-constituents.

7.3.3 Vitrinite Reflectance analysis

Vitrinite reflectance is the measure of incident light reflected from the surface of vitrinite particles in a sedimentary rock reported as percentage (% R_o). Vitrinite reflectance is a strong thermal maturity indicator of organic matter. In general, it is a measurement of the maturity of organic matter with respect to whether it has generated hydrocarbons or could be an effective source rock. More recently, it is used to study
sedimentary organic matter from kerogen. It is sensitive to temperature ranges that correspond to hydrocarbon generation (60 to 120°C). This means that, with a suitable calibration, vitrinite reflectance can be used as an indicator of maturity in hydrocarbon source rocks. Generally, the onset of oil generation is correlated with a reflectance of 0.5 to 0.6% and the termination of oil generation with reflectance of 0.85 to 1.1% respectively. As indicators of thermal maturity, \( R_o \) values vary with the type of organic matter. And because the temperature range of the gas will show a corresponding increase over those of oil. Thus, the high maturation value (\( R_o >1.5% \)) generally indicate the presence of predominantly dry gas; intermediate maturation values (1.1% < \( R_o <1.5 \% \)) indicate gas with a tendency towards oil generation at the lower end of the range. Wet gas can be found still lower in range (0.8% < \( R_o <1.1 \% \)). Lower reflectivity values (0.6% <\( R_o <0.8\% \)) indicate predominantly oil, while \( R_o<0.6\% \) points to immature kerogen.

Vitrinite reflectance is a key diagnostic tool for assessing maturation. Vitrinite, a maceral formed through thermal alteration of lignin and cellulose in plant cell walls, is found in many kerogens. As temperature increases, vitrinite undergoes complex, irreversible aromatization reactions that increase reflectance. Vitrinite reflectance was first used to determine rank or thermal maturity of coals. This technique is now used to help geochemists to evaluate kerogen maturity over temperature corresponding to early diagenesis through metamorphism - a range spanning the sequence of petroleum generation, preservation and destruction of rock.

Reflectivity (R) is measured by a microscope equipped with an oil-immersion objective lens and photometer. Vitrinite reflectance measurements are carefully calibrated against glass or mineral reflectance standard, and reflectance measurements represent the percentage of light reflected in oil, designated as \( R_o \).

The relationship between vitrinite reflectance and hydrocarbon generation potential is dependent on the chemistry of the vitrinite as well as the kerogen. Oil and gas zone boundaries can be established using vitrinite reflectance data. The boundaries are approximate and vary according to kerogen type. The vitrinite are the chief contributor of Type III kerogen of sedimentary rocks and thus, an important contributor of oil and natural gas of primary origin. The approximate boundaries for kerogen Types I, II, and III are shown in Figure 7.1.
Vitrinite reflectance is also used to indicate inferences between hydrocarbon generation and migration. Hydrocarbon generation potential generally depends on the kerogen type in the source rock as well as its thermal maturity. While vitrinite reflectance can indicate if hydrocarbon generation is possible and suggest what types of hydrocarbon could be formed.

**Figure 7.1** Vitrinite reflectance maturity boundaries for oil and gas generation (Tissot and Welte, 1984)
Table 7.4 Petrographic composition of coal and carbonaceous shale samples

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7.4 Experimental Results and Discussions

10 numbers of representative coal and carbonaceous shale samples are subjected to organic petrographic analysis. Relative proportions of organic matter (macerals) are quantified visually under microscope. The organic matter typing data are shown in Table 7.4. The organic matter in the coal samples are dominantly represented by vitrinite and subordinate amount of liptinite and inertinite.

a) **Vitrinite**: The petrographic analysis reveals that the coals and carbonaceous shale of Barail Group are exceedingly rich in vitrinite. All the subgroups and macerals from this group have been recorded in considerable amounts. The most dominating maceral in this vitrinite group is collotelinite (structure less vitrinite), collodetrinite and vitrodetrinite. The colours of vitrinite group maceral are light grey to moderately dark grey. The collotelinite macerals (Figure 7.9-A) are found separately or in association with inertinite group macerals. At some places, it is highly oxidized and grade into semifusinite. The total vitrinite macerals ranges from 23.4 - 39.4% in volume percent of coal. The cell cavities are usually empty or filled with humic materials, resinite or mineral matters (Figure 7.9-C). Cell walls are in most cases deformed (Figure 7.9-C, E) as a result of the softening and swelling of the tissue, caused by the biochemical gelification.

In the Barail coal and carbonaceous shale samples, collodetrinite (3.0 - 30.2%) is the most dominant maceral of dextra-vitrinite subgroup of vitrinite group of macerals (Table 7.4). Collodetrinite (Figure 7.9-B, C, E and Figure 7.12-G) lacks textural continuity and it is a mixture of vitrinite particles less than 10 pm in size and amorphous vitrinitic matter. Collodetrinite contains more submicroscopic inorganic substances than other vitrinite macerals (Figure 7.9-C, E). Fluorescence colours range from yellow-brown to red-brown. The fluorescence intensity of collodetrinite is stronger than that of the corresponding collotelinite. It is influenced also by associated liptinite macerals. In the presence of alginite and cutinite the fluorescence intensity of collodetrinite is higher than when associated with sporinite. In sediments, especially shales, the fluorescence may be more intense than in accompanying coals. Collodetrinite
is derived from parenchymatous and woody tissues of roots, stems and leaves, composed of cellulose and lignin. The original plant tissues are destroyed by the strong decomposition at the beginning of the peat stage. The small particles are cemented by humic colloids within the peat and subsequently homogenized by geochemical gelification (vitrinitization). Collodetrinite is part of kerogen Type III.

Collotelinite is the dominant macerals of teliovitrinite subgroup in the studied coal and carbonaceous shale samples (7.4 - 19.6%) exhibit more-or-less homogenized vitrinite layers which may exhibit poorly defined structure or structure less appearance. In some cases, it may show a mottled texture or remnant cell structure (Figure 7.9-A, Figure 7.10-C and Figure 7.11-G, H). Its reflectance is commonly higher than that of collodetrinite. Presence of collotelinite in both coal and carbonaceous shale samples represents the parenchymatous and woody tissues of roots, stems and leaves, composed of cellulose and lignin and originating from herbaceous and arborescent plants. It is very common in coaly shales represents kerogen Type III.

Vitrodetrinite maceral of the maceral subgroup detrovitrinite is also a common maceral in both coal and carbonaceous shale samples in considerable amount (0.8 - 19.8%), occurring as discrete small vitrinitic fragments of varying shape (Figure 7.9-B). Presence of vitrodetrinite in the studied sample represent parenchymatous and woody tissues of roots, stems and leaves composed of cellulose and lignin.

High amount of detrovitrinite in the samples indicate fairly high cell degradation and biochemical gelification of the vegetal debries of the samples which could take place in warm, humid and low energy environments with a fairly high groundwater table throughout the formation time.

Corpogelinite maceral of maceral subgroup gelovitrinite within the maceral group vitrinite, consisting of homogeneous and discrete bodies representing cell infillings is identified in minor amount (0.4%). Corpogelinite bodies may occur isolated within an attrital matrix as a result of degradation of the enclosing plant tissue (Figure 7.9-G).
b) **Liptinite**: Liptinite group maceral is different from vitrinite and inertinite due to its hydrogen contents and heterogeneous origin. The common structured liptinite macerals are sporinite, cutinite and resinite, which were found in the studied coals and carbonaceous shale samples. The concentration of liptinite group macerals ranges present in the Barail coal and shale samples ranges from 7.2 - 25.4% (51.1%, exceptionally higher in the sample NR). The amount of the macerals from this group is shown in Table 7.4. In the studied samples Resinite, cutinite, liptodetrinite, suberinite and sporinite are the most dominant maceral of liptinite group. Resinite (0.2 - 11.0%) was identified mainly as oval shaped to round bodies (Figure 7.9-C, E; Figure 7.10-A, C, E; Figure 7.12-E) filling resin ducts within the plant and roots, which are embedded in the attrinitic groundmass. Its color in reflected light is dark gray (Figure 7.9-C, E) with internal reflections, and in fluorescent light ranges from pale yellow to strong yellow (Figure 7.9-D, F; Figure 7.10-B, D and Figure 7.12-F).

Cutinite is also common in both coal and shale samples, which appears as thread like bodies of dark grey to black colour under white light. Cutinite has been identified as leaf protection (Figure 7.12-A). The cutinite bodies occur in the samples ranges from 0.2 – 9.0% in percent of coal. Their color in fluorescence light is pale yellow to yellow (Figure 7.12-B), accordance to the low rank of the coals (Taylor *et al.*, 1998).

The sporinite occurs as small flattened elongated and thread-like bodies (Figure 7.11-C, E and Figure 7.12-G). The maceral is easily identified in fluorescent light (Figure 7.11-D, F and Figure 7.12-H) but in reflected light no distinction can be made with mineral inclusions, except when the spores are included within the vitrinite groundmass (Figure 7.11-C and Figure 7.12-H).

Suberinite is also an abundant maceral, usually forms the bark of plant roots and rarely can be seen as long linear bodies, representing bark tissue of plant stems (Figure 7.10-G, Figure 7.11-E and Figure 7.12-G). The cell walls are thin and curved. The color in fluorescent light is pale yellow (Figure 7.10-H; Figure 7.11-F and Figure 7.12-H). In reflected light it has slightly darker grey color. It was found in one sample some of the roots to be slightly fusinized
(Figure 7.11-F), most probably as a result of fungal activity. In this case suberinite has very dark grey to black color.

Bituminite (Figure 7.12-C) and exsudatinitite (Figure 7.12-E) is also present in minor amount of Barail coal and carbonaceous shale (Table 7.4).

Liptodetrinite is also an abundant maceral in Barail coal and carbonaceous shale ranges from 0.6 - 8.0% (Figure 7.10-C and Figure 7.11-A). The color in fluorescent light is pale yellow to bright yellow (Figure 7.10-D and Figure 7.11-B, F).

c) **Inertinite**: Inertinite group macerals have higher reflectance value than vitrinite and liptinite group macerals. The inertinite group macerals are commonly found lesser amount in the studied Barail coal and carbonaceous shale and the concentration ranges from 0.2 - 10.4% (Table 7.4).

Fungal remains are most common in all samples (0.2 - 8.8%). They are represented by twin- and multi-celled spores (Figure 7.9-B; Figure 7.10-C; Figure 7.11-G, H and Figure 7.13-A, B). A minor amount of semifusinite (0.0 - 2.4%) and macrinite (0.0 - 0.8%) are also present in some of the samples. The semifusinite (Figure 7.13-C, E, G), shows light grey to medium grey colour and occurs in thick and thin micro bands. The macrinite (Figure 7.13-B, F), is very rare and occur as small rounded to irregular amorphous bodies without any structure and show pale grey to grey colour. Its probable formation is through the oxidation of humic substances near to the peat surface, although bacterial activity and local low temperature fires are also possible.

Inertodetrinite maceral (Figure 7.13-H), is occurring in one sample (0.2%), which is mainly derived as detritus particles. The maceral fusinite is not identified in all the coal and carbonaceous shale samples.

d) **Mineral Matter**: The silicate minerals dominate with subordinate amount of arenaceous material i.e. pyrite. Sulphides are in very low concentration. The silicate minerals present in the samples ranges from 21.0 - 47.6% whereas the pyrites ranges between 0.8 - 20.0% (Table 7.4) (Figure 7.13-H). Presence of framboidal pyrites (Figure 7.11-D) in the samples indicates that the peat forming swamps were either connected to brackish water (Bustin and Lowe, 1987; Casagrande, 1987) or later on overlain by marain sediments (Cohen et al.,
Framboidal structure comprises roughly spherical aggregates of discreet microcrystals of about 0.5µm in diameter and is commonly found in coastal sediments, and very commonly observed in paralic coal and carbonaceous rocks.

e) Reflectance: Reflectance measurements help to find out the rank of maturity of coal and the carbonaceous shale samples. The maximum reflectance value of measured samples range between 0.39 - 0.49% whereas the minimum reflectance ranges from 0.16 - 0.31%. The mean reflectance shown by the coal and carbonaceous shale samples of Barail Group ranges from 0.30 - 0.43% respectively. The samples are mostly immature as the vitrinite reflectance values of the samples are lower than 0.5%. The lack of fluorescence of vitrinites also points to immature nature of the samples. The plot of vitrinite reflectance (\% R_o) against depth (m) also indicates the immature nature of the Barail coal and carbonaceous shale (Figure 7.2). In this plot the vitrinite reflectance value showing a linear trend, i.e. the vitrinite reflectance value increases with increasing depth. In the present study the thickness of Barail sediment increases towards SE i.e. towards Galeki oilfield, thus it can be concluded that the vitrinite reflectance also increases with depth.

![Vitrinite reflectance (% R_o) against depth (m)](image)

**Figure 7.2** Vitrinite reflectance (% R_o) against depth (m)
**Figure 7.3** Vitrinite reflectance ($\% R_0$) against TOC ($\%$)

**Figure 7.4** (A) Carbon content, (B) Rock-Eval $T_{\text{max}}$ temperature and (C) volatile matter content vs. mean random vitrinite reflectance for Barail coal and carbonaceous shales of upper Assam Basin.
7.5 Hydrocarbon generation potential

The liquid hydrocarbon potential in Barail coals and carbonaceous shales are implied by their maceral composition visible under a microscope (Table 7.4). The petroleum richness of the samples is relatively dependent on the amount and nature of liptinite and vitrinite macerals. There is a direct correlation between liptinite content and oil generation potential of coal and carbonaceous shale and that at least 15–20% liptinite (by volume) of total macerals in sediments is required to be considered as a source (Fowler et al. 1991; Hunt 1991; Mukhopadhyay et al. 1991). The abundance of liptinite macerals is, therefore, the major criterion when considering any sedimentary rock (including coal) as a potential source rock for liquid hydrocarbons (Stach et al. 1982; Thompson et al. 1985; Hunt 1991; Mukhopadhyay and Hatcher 1993; Hendrix et al. 1995).

**Figure 7.5** Ternary diagram of maceral group composition (vitrinite-liptinite-inertinite) for analyzed Barail coal and carbonaceous shale, showing Type II and Type III kerogen

In the present study, liquid hydrocarbon generation is anticipated from several coal and carbonaceous shale samples based on their liptinite contents. The ternary plot of vitrinite-liptinite-inertinite maceral for analyzed Barail coal and carbonaceous shale, showing both Type II and Type III kerogen of the samples (Figure 7.5). As the studied
sample contain hydrogen rich liptinite maceral (resinite, suberinite, bituminite) in considerable amounts with less than 4% $R_o$, which is a prime source for liquid petroleum, indicate that the Barail coal and carbonaceous shale can be considered as good source rock potential despite of its low maturity. Presence of suberinite, bituminite and terpene resinite also indicate the Barail coal and carbonaceous shale can generate hydrocarbon at a lower maturity or rank (at about 0.4% $R_o$).

The plot of TOC (%) vs. Vitrinite Reflectance ($R_o$ %) of the samples showing the immature nature of the Barail coal shale source-rock, and hydrocarbon generating phases (Figure 7.3). The other thermal maturity indicators i.e., carbon content (C$_{daf}$), $T_{\text{max}}$ and volatile matter (VM$_{daf}$) correlation with vitrinite reflectance for both coal and carbonaceous shale are shown in Figure 7.4 (A,B,C).

### 7.6 Depositional environment

The development of the peat or seam can be interpreted from the constitution of the maceral and mineral matter in the seam profile. The clastic partings in the seam are an indication of the termination of the peat development (Shearer et al., 1994). There are several bounding surfaces which appear in the coal seams. The presence of inertinite macerals such as fusinite, semi-fusinite and inertodetrinite indicates peat’s exposure to oxidation and fusain bands indicating forest fire (Shearer et al. 1994). There has been a large occurrence of fusain in the investigated coals which are signatures of paleo fires and dry periods in history of peat development.

The maceral composition of coals reflects the organic source materials which contributed to the accumulation of peat and further provides information about the conditions during deposition, i.e. height of the water table, pH, and decay by aerobic and anaerobic bacteria and mechanical breakdown of the organic matter related to transportation prior to final sedimentation (Kalkreuth et al., 1991). Maceral analysis measures the relative proportions and interrelationships of various maceral groups. This analysis provides a wealth of information that may be used to define the depositional environment if facies critical macerals can be selected (Kalkreuth and Leckie 1989). The diagnostic macerals and petrographic facies indices derived from the assemblage of these macerals have been used as an indicator for the palaeo-environment of the coal-forming peat. Diessel (1982, 1986 and 1992), Harvey and Dillon (1985) and Cohen et
al. (1987) have investigated the application of maceral composition in coal facies analysis and created a new trend of coal facies studies based on petrology.

On the basis of maceral present, diagnostic macerals as palaeo-environmental indicators are interpreted. The abundance of vitrinite group macerals in the studied coal and carbonaceous shale suggests that they originated in a wet forest swamp environment (Teichmüller and Teichmüller 1982; Bustin et al. 1983), mainly from arborescent vegetation (Rimmer and Davis, 1988). The high amount of vitrinite macerals with a general predominance of dextra-vitrinite also indicates that alteration of these peats was controlled largely by anaerobic, rather than aerobic processes and deposition in the peat-forming mires, whilst the low concentration of inertinite indicates the occurrence of low levels of peat (forest) fire and/or oxidation and the Barail coal and carbonaceous shales have been deposited in waterlogged conditions (Scott and Glasspool, 2007; Sykorova et al., 2005; Teichmüller et al., 1998; Flores, 2002; Diessel, 1992; Stach et al., 1982; Petersen et al., 2009; Erik, 2011). In the present study, large amounts of dextra-vitrinite in the studied Barail coal and carbonaceous shale samples are considered to be related to both the dominance of herbaceous plants in the palaeomires (Teichmüller, 1989) and the poor preservation of woody substance due to prolonged humification in slowly subsiding palaeomires (Diessel 1992; Petersen et al. 2009). In general, the herbaceous plants are consistent to those reported by Ahmed (2004) who described high contributions of dicots and herbaceous monocots and a complete absence of gymnospermic pollen. The predominance of dextra-vitrinite suggests that the resulting maceral composition is also influenced by the degradational conditions in the mires as indicated by the percent of funginite maceral (Hower et al., 2010; Hower et al., 2011). Presence of collotelinite as the dispersed organic matter in the studied samples indicates that they formed during a warm and humid climate under depositional environments with low pH and high groundwater throughout the year.

The presence of large amounts of liptinite group macerals (i.e. Resinite, sporinite, cutinite and liptodetrinite) suggests an accumulation within forested wet-raised bogs (Ratanasthien et al., 1999; Erik, 2011). The bacterial activities played a more important role in the destruction of lignocellulose material as compared with forest fire or oxidation (Sia and Abdullah, 2012). A considerable amount of inertinite presents in the coal and carbonaceous shale samples indicate a major portion of the
organic matters were contributed by dry and oxidizing environment. These oxidized organic matters were possibly produced in situ from the deposited plant detritus due to temporary lowering of the ground water. However, they could represent oxidized organic matters produced in the surrounding highlands to the peatland. The abundance of pyrite indicates influence of marine water in the peat forming environment. The organic matters and the pyrites of the coal and carbonaceous shale samples of Barail Group point to their deposition in near shore environment.

Petrographic facies could reflect, to some extent, differences in the type of peat-forming plant communities. Petrographic indices deduced from the maceral analyses have been in use by the coal petrologists for reconstructing paleo-environmental conditions of the swamps. Maceral ratios used for paleo-environment interpretations are based on the assumption that coal macerals are plant and environment dependent and thus can be used to assess the characteristics of the paleomire. There have been various suggestions to characterize the coal facies on the basis of the maceral ratios (Diessel, 1986; Diessel, 1992; Calder et al., 1991). Diessel (1986) introduces two indices – Tissue Preservation Index (TPI) and Gelification Index (GI) for interpretation of paleo conditions for Permian bituminous coals. The GI and TPI used to measure the degree and persistence of wet condition. On the basis of TPI and GI, the ratio can be used to determine particular peat-forming environment conditions (Siavalas et al., 2009; Kalkreuth et al., 1991; Jasper et al., 2010; Koukouzas et al., 2010; Životić et al., 2013). GI and TPI was a measure of tissue break down and amount of woody plants in the original peat forming assemblages (Lamberson et al., 1991; Singh and Shukla, 2004; Singh et al., 2013). This scheme was an attempt to throw light on paleo-facies, depositional setting and type of mire. This indices were later also applied for lignites and soft brown coals (Kalkreuth et al., 1991). The TPI can be used to determine the degree of humification of plant tissues, because it is contrasting less humified structured and strongly humified unstructured tissue-derived macerals (Diessel, 1992). In addition TPI is also an indirect indicator of the type of the vegetation. In this way high TPI values suggest predominantly wood-derived tissues or high rate of subsidence, resulting in preservation of the structure of the macerals. Low TPI values indicate either predominantly herbaceous vegetation in the paleomire or very low subsidence rate, accompanied with advanced humification, leading to strong decomposition of the plant.
material (Diessel, 1992). The low (<1) TPI values could be assumed as interpreted due to destruction of wood in forested swamps (Diessel, 1992; Amijaya and Littke, 2005) and the organic matter preservation as low due to prolonged humification in slowly subsiding raised bogs (Anderson, 1983; Diessel, 1992; Obaje et al., 1994; Cohen and Stack, 1996; Taylor et al., 1998; Amijaya and Littke, 2005; Siavalas et al., 2009). Tissue preservation depends mostly on the water level, the acidity/alkalinity and the climatic conditions during peat accumulation, rather than on the botanical properties of the vegetation (Dehmer, 1995; Životić et al., 2013). The low TPI values could be indicative of a moderate to high water column level (Životić et al. 2013) and represent predominantly topogenous mire conditions (Jasper et al. 2010).

The GI has been defined as a measure of the degree of wet conditions (Diessel, 1992), because it is taking into account the presence of inertinite macerals, which are indicators for dry conditions. There has been inertodetrinite are appropriate indicators, because they could be washed or blown into the mire system, or can be a result from crown fires, which are not necessary a consequence of dry conditions (Calder et al., 1991; Scott, 2000). However, these macerals were calculated in the formula, because usually their contents are very low and their presence does not change the trends in GI values.

The formulas, used for calculation of Diessel’s indices of coal facies were:

\[
\text{GI} = \frac{\text{Vitrinite+ Macrinite}}{\text{Semifusinite+ Fusinite+ Inertodetrinite}}
\]

\[
\text{TPI} = \frac{\text{Telinite+ Collotelinite+ Semifusinite+ Fusinite+ Desmocollinite}}{\text{Macrinite+ Inertodetrinite+ Vitrodetrinite+ Corpocollinte}}
\]

The petrographic data from the present study indicate significant fragmentation of the maceral groups in the Barail coal and carbonaceous shale (TPI ranges from 0.6 - 16.7) and high gelification (GI ranges from 14.3 - 82.0) for most of the coal and carbonaceous shale samples (Table 7.5). The maceral composition of studied samples on this facies diagram suggests that Barail coal and carbonaceous shale are dominantly terrestrial in origin with high tree density. The GI and TPI values of Barail coal and carbonaceous shale indicate that they have evolved under telmatic conditions and wet forest swamp. (Figure 7.6). According to Diessel (1965) the wet conditions of peat
development are characterized by high GI and telovitrinite based high TPI but peat formed in dry conditions gives low GI and low telovitrinite based on TPI. The high TPI value of the Barail sample of coal and carbonaceous shale also suggests the presence of well-preserved plant tissue, a high proportion of arboreal vegetation (collotelinite and semifusinite) and aerobic condition.

**Table 7.5** GI, TPI, GWI and VI values of the Barail coal and carbonaceous shale

<table>
<thead>
<tr>
<th></th>
<th>L-1</th>
<th>A-1</th>
<th>G-1</th>
<th>G-2</th>
<th>G-3</th>
<th>CH-1</th>
<th>Ku-1</th>
<th>NR-1</th>
<th>R-1</th>
<th>R-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GI</td>
<td>14.3</td>
<td>15.4</td>
<td>45.0</td>
<td>17.0</td>
<td>68.0</td>
<td>82.0</td>
<td>86.0</td>
<td>27.2</td>
<td>80.7</td>
<td>68.2</td>
</tr>
<tr>
<td>TPI</td>
<td>16.7</td>
<td>6.8</td>
<td>1.4</td>
<td>4.4</td>
<td>0.6</td>
<td>1.1</td>
<td>0.6</td>
<td>9.4</td>
<td>2.4</td>
<td>1.1</td>
</tr>
<tr>
<td>GWI</td>
<td>1.6</td>
<td>5.8</td>
<td>2.7</td>
<td>2.3</td>
<td>5.9</td>
<td>4.1</td>
<td>5.0</td>
<td>2.4</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>VI</td>
<td>3.5</td>
<td>3.2</td>
<td>2.3</td>
<td>1.4</td>
<td>7.5</td>
<td>3.5</td>
<td>2.3</td>
<td>0.5</td>
<td>1.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>

*GI: Gelification Index, TPI: Tissue Preservation Index, GWI: Ground Water Index, VI: Vegetation Index

The studied Barail coal and carbonaceous shale having high GI values (>10) could arise during peatification under a moderate to high water column (Životić et al. 2013) and represent predominantly topogenous mire conditions (Jasper et al. 2010). Moreover, the high values of GI further suggest gelification of plant tissues in continuous wet forest swamp (Diessel 1992; Sia and Abdullah 2012). The TPI-GI diagram of the present study, where all coal and carbonaceous shale samples are located within wet area, shows that palaeomire was created by herbaceous plants able to thrive in a marsh-wet forest swamp environment under limno-telmatic conditions (Figure 7.6).

According to the diagrams and after considering the petrographic data we could speculate that the deposition of the Barail coal and carbonaceous shale was processed in limno-telmatic to telmatic environment from predominantly herbaceous vegetation, mixed with higher plants. Limnic environment is also probable. The latter is characterized by high liptinite and particularly high resinite content, which is common in the case with the studied samples.

According to Calder et al. (1991), the type of the paleomire was swamp to forest swamp. The inertinite content in the Barail coal and carbonaceous shale samples are
very small, resulting in high GI values (Figure 7.6). The latter suggest continuously wet conditions through deposition, although some seasonal dryings are not excluded, as indicated by the presence of macrinite. A typical constituent of the inertinite group is funginite, which contributors are the fungi, attacking the wood tissue.

Figure 7.6 Diagram of TPI versus GI showing the peat-forming conditions of the Barail coal and carbonaceous shale facies (after Diessel 1965)

Facies model based on quantitative relationships of macerals proposed by Calder et al. (1991) retrieves coal facies on the basis of Ground Water Index (GWI) and Vegetation Index (VI), and the fundamentals therein are very close to Diessel’s GI and TPI indices. They are describing two maceral indices – GWI and VI with respect to the classification of the mires proposed by Moore (1987). The GWI is a ratio of strongly to weakly gelified macerals. Detritic mineral matter content is used in the numerator of the formula to determine the type of the mire. The contrasts macerals of forest affinity with those of herbaceous and marginal aquatic affinity (Calder et al., 1991) and thus be an indicator of the vegetation type. The water depth in the peat swamp plays an important role affecting the nature of vegetation in the swamp and has a bearing on the mode of preservation of the petrographic entities. The parameters applied
in the reconstruction of peat lands (peat land = marsh + swamp) are the degree of groundwater control, relative rain fall (Kalkreuth et al. 1991) changes in ground water level, vegetation, mineral matter content and degree of preservation of maceral precursors (Calder et al. 1991). The GWI and VI are calculated with the help of following formula:

\[
GWI = \frac{\text{Gelocollinite} + \text{Corpocollinite} + \text{Claymineral} + \text{Quartz} + \text{Vitrodetrinite}}{\text{Tellinite} + \text{Telocollinite} + \text{Desmocollinite}}
\]

\[
VI = \frac{\text{Telinite} + \text{Telocollinte} + \text{Fusinite} + \text{Semifusinite} + \text{Secretinite} + \text{Resinite}}{\text{Desmocollinite} + \text{Inertodetrinite} + \text{Alginate} + \text{Liptodetrinite} + \text{Cutinite}}
\]

For interpreting the paleo-environment, a cross-plot diagram of TPI versus GI (Figure. 7.6) and VI versus GWI (Figure 7.7) were used. Most of the samples from Barail coal and carbonaceous shale of Upper Assam Basin are characterized by high TPI indicating the presence of high plant vegetation in the paleomire and low VI values, suggesting increased contribution of swamp vegetation.

**Figure 7.7** Palaeo-environment of mires based on ground water index (GWI) and vegetation index (VI) (after Calder et al. 1991)
Major mire paleo-environments identified by Calder et al. (1991); Singh et al. (2012a); Singh et al. (2012b) were based on parameters such as limnic (open water marsh), swamp, fen and bog (Figure 7.7). Besides making important revelations about hydrological conditions in terms of rheotrophic, mesotrophic and ombrotrophic mires, the GWI values of coals and carbonaceous shale of Barail Group of Upper Assam Basin suggest that they evolved as limnic (open water marsh), swamp and fen under rheotrophic conditions. The VI values are indicative of inundated forest and swamp forest in the formation of Barail coal and carbonaceous shales of Upper Assam Basin.

Figure 7.8 Depositional condition of coals and carbonaceous shales based on macerals and mineral matter (after Singh and Singh 1996)

In another facies model (Figure 7.8), proposed by Singh and Singh (1996) based on maceral and mineral matter content, the data plots of the studied coal and carbonaceous shale suggest the development of peat took place in highly wet moor with intermittent moderate to high flooding conditions. The Barail coals and carbonaceous shales of Upper Assam Basin being comparatively rich in vitrinite indicate their formation in a deeper basin. This variation of depth has also been shown by TPI Index.
Figure 7.9 (A) Collotelinite; (B) Collodetrinite groundmass, Funginite; (C) Collodetrinite, Resinite; (D) Resinite (under fluorescence light); (E) Collodetrinite, Resinite; (F) Resinite (under fluorescence light); (G) Corpogelinite; (H) Corpogelinite (under fluorescence light)
Figure 7.10 (A) Resinite; (B) Resinite (under fluorescence light) (C) Collotelinite, Resinite, Funginite, Liptodetrinite; (D) Resinite (under fluorescence light); (E) Resinite (F) Resinite (under fluorescence light); (G) Suberinite; (H) Suberinite (under fluorescence light)
Figure 7.11 Liptodetrinite, Resinite; (B) Liptodetrinite, Resinite (under fluorescence light); (C) Sporinite; (D) Sporinite (under fluorescence light); (E) Sporinite; (F) Sporinite, Liptodetrinite (under fluorescence light); (G) Collotelinite, Fungal spore; (H) Collotelinite, Funginite.
Figure 7.12 Cutinite (B) Cutinite (under fluorescence light); (C) Vitrodetrinite, Bituminite; (D) Bituminite (under fluorescence light); (E) Resinite, Exsudatinite; (F) Resinite, Exsudatinite (under fluorescence light); (G) Sporinite, Suberinite, Collodetrinite groundmass; (H) Sporinite, Suberinite (under fluorescence light)
Figure 7.13 (A) Fungle spore; (B) Funginite, Macrinite; (C) Semifusinite; (D) Framboidal Pyrite; (E) Semifusinite; (F) Macrinite; (G) Semifusinite, Resinite; (H) Pyrite, Inertodetrinite.