

Petrography, genesis and deposition of Tertiary coals from Northeastern India

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ABSTRACT

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The coalfields of Arunachal Pradesh, Assam and Nagaland are disposed along a linear belt of overthrusts where the coal-bearing Oligocene (Tikak Parbat Formation, Barail Group) strata are folded and dispersed into a number of thrust slices. Whereas, in Garo, Khasi and Jaintia hills of Meghalaya the coal seams are associated with an almost undisturbed and sub-horizontal Late Palaeocene Sylhet/Tura formations of Jaintia Group.

The coals are bright, non-banded, vitrinite-rich and have moderate to low amounts of liptinite and inertinite macerals. Pyrite and calcite are the dominant associated minerals, besides generally low proportions of clay and quartz. The coals have moderate to very high amounts of fluorescing macerals consisting chiefly of perhydrous vitrinite, liptodetrinite and resinite. Macerals, cutinite, sporinite, suberinite, exsudatinitite, alginite and fluorinitite are also present. The rank of the coals ranges between high volatile bituminous C and B stages, on the basis of vitrinite reflectance (Garo Hills: 0.54-0.62%; Jaintia Hills: 0.68-0.81% and Assam: 0.70-0.74%).

The coals from northeastern India were derived essentially from tropical deciduous mangrove-mixed angiospermous forest vegetation. The coals, presumably, originated from autochthonous to hypo-autochthonous eutrophic peat accumulations in lagoons and/or near-shore back swamps in Assam, Arunachal Pradesh and Nagaland and in small isolated estuarine back swamps in Meghalaya. The vegetal matter, in general, was subjected mainly to anaerobic biodegradation under neutral to mildly alkaline subaqueous conditions and facilitated the precipitation of early diagenetic pyrite and calcite and *in situ* release of plant-bound minerals in the peat. Seasonal freshwater ponds or lakes developed occasionally on the ancient-peat surfaces hosted the growth of aquatic and water-edge taxa whose remains are present in the coal seams. Especially pteridophytic herbaceous and shrubby vegetation growing in the vicinity of ancient peat swamps appear to be mainly responsible for the presence of structured and detrital inertinites. Occasional burning of the wet peat surfaces has been inferred to be the reason for relatively high inertinite contents in the coals from Meghalaya. It has also been presumed that whenever biodegradation of organic matter was severe the normal supply of vegetal matter fell short to produce a peat layer, instead some minor and major authigenic partings were developed within the pre-existing peat. The variation in the rank and thickness of the coal seams was presumably controlled by the prevailing geothermal gradient and tectonic conditions in different areas.

Key-words—Petrography, Coal genesis, Depositional environment, Tertiary coal, North-East India.

उत्तर-पूर्व भारत से प्राप्त टर्शियरी युगीन कोयले का शैलविज्ञान, उद्भव एवं निक्षेपण

बसन्त कुमार मिश्र

सारांश

अरुणाचल प्रदेश, असम एवं नागालैण्ड के कोयला क्षेत्र अधिक्षेप की एक रैखिक पट्टी के साथ व्यवस्थित हैं, जहाँ पर कोयलाधारी ओलिगोसीन स्तर (तिकक परबत शैलसमूह, बरेल समूह) वलित हैं तथा अनेक क्षेप स्तरी खण्डों (स्ताइस) में परिक्षिप्त हैं, जबकि मेघालय की गारो खासी एवं जयन्तिया पहाड़ियों में कोयला सीमें प्रायः जयन्तिया समूह के अविशुद्ध एवं उपक्षैतिज अन्तिम पेलियोसीन युगीन सिलहट/तुरा शैलसमूहों के साथ साहचर्य रखती हैं।

इस क्षेत्र के कोयले चमकदार, पट्टविहीन, विट्रीनाइट सम्पन्न हैं तथा इनमें लिप्टीनाइट एवं इनर्टीनाइट मैसेरलों की न्यूनधिक मात्रा विद्यमान है। इनमें सामान्यतः मिट्टी एवं क्वार्ट्ज की अल्प मात्रा होने के अतिरिक्त पाइराइट एवं कैल्साइट प्रमुख साहचर्य खनिजों के रूप में मिलते हैं। कोयलों में सामान्य से अधिक मात्रा तक प्रतिदीप्तीय मैसेरल प्राप्त होते हैं, जिनमें प्रमुख रूप से परहाइड्रस विट्रीनाइट, लिप्टोडेट्रीनाइट एवं रेजीनाइट पाये गये हैं। इनमें मैसेरल, क्यूटीनाइट, स्पेरीनाइट, सुबेरीनाइट, एक्स्यूडेटीनाइट, एल्जीनाइट एवं फ्लोरीनाइट भी उपस्थित हैं। विट्रीनाइट परावर्तन (गारो पहाड़ियाँ : 0.54-0.62% जयन्तिया पहाड़ियाँ : 0.68-0.81% एवं असम : 0.70-0.74%) के आधार पर कोयले की श्रेणी उच्च वाष्पशील बिटुमिनस 'सी' एवं 'बी' अवस्थाओं के बीच की है।

उत्तर-पूर्वी भारत से प्राप्त कोयले मूलतः उष्णकटिबन्धीय पर्णपाती मैंग्रोव मिश्रित आवृतबीजी वनस्पतियों से निर्मित हुए हैं। सम्भवतः इन कोयलों का उद्गम स्वस्थानिक से अधो स्वस्थानिक सुपोषी पीट संचयन से असम, अरुणाचल प्रदेश तथा नागालैण्ड के लैगूनों और/अथवा निकटस्थ पृष्ठ समुद्री अनूपों में तथा मेघालय में छोटे पृथक् ज्वारनदमुखी पृष्ठ अनूपों में हुआ। सामान्यतः वानस्पतिक पदार्थ प्रमुख रूप से उदासीन से तनु क्षारीय उपजलीय स्थितियों के अन्तर्गत अवायवीय जैव निम्नीकरण द्वारा अपघटित हुए होंगे तथा इन्होंने पीट में प्रारंभिक प्रसंघाती पाइराइट एवं कैल्साइट के अवक्षेपण को तीव्र किया होगा तथा पादपधारी खनिजों को स्वस्थानिक निर्मुक्त किया होगा। प्रायः प्राचीन पीट पृष्ठों पर विकसित हुए मौसमी ताजे जल के तालाबों अथवा झीलों में जलीय एवं जल तटीय वर्गक उत्पन्न हुए होंगे, जिनके अवशेष कोयला सीमों में उपस्थित हैं। संरचनात्मक एवं अपरदी इनर्टीनाइटों की उपस्थिति के लिए प्राचीन पीट अनूपों के परिवेश में वृद्धि कर रही टेरिडोफ़ाइट शैलीय एवं गुल्मी वनस्पतियाँ विशेष रूप से उत्तरदायी हैं। आर्द्र पीट पृष्ठों के यदा-कदा जलने के कारण ही सम्भवतः मेघालय के कोयलों में अपेक्षाकृत अधिक इनर्टीनाइट तत्व हैं। यह भी सम्भावना व्यक्त की जाती है कि जब कभी कार्बनिक पदार्थों का जैवनिम्नीकरण अधिक रहा होगा, पीट पपड़ी उत्पन्न करने हेतु वानस्पतिक पदार्थ की सामान्य आपूर्ति कम हो गई होगी तथा उस स्थिति में कुछ छोटे तथा बड़े तत्रजनिक टुकड़े पूर्व प्राप्त पीट के अन्दर विकसित हो गये होंगे। कोयला सीमों की श्रेणी एवं स्थूलता में विविधता सम्भवतः विभिन्न क्षेत्रों में उपस्थित भूतापीय प्रवणता तथा विवर्तनिक स्थितियों द्वारा नियंत्रित हुई होगी।

संकेत शब्द—शैलविज्ञान, कोयले का उद्भव, निक्षेपणीय पर्यावरण, टर्शियरी युगीन कोयला, उत्तर-पूर्वी भारत.

INTRODUCTION

NORTHEASTERN India is known as a repository of country's important Tertiary coal deposits (Fig. 1), from Garo, Khasi and Jaintia hills of Meghalaya, in the west, to Mikir Hills, in central Assam, the coal bearing strata are Late Palaeocene in age. The coal deposits in Nagaland, Assam and Arunachal Pradesh are associated with the Oligocene sediments. In Nagaland and Assam few thin seams with thickness between 0.5 to 1.5 m, especially in Makum, Dilli-Jeypore and Nazira (or Borjan) coalfields, are known from

the sediments underlying the coal measures. In Meghalaya the coal seams are thin (0.2-2 m, occasionally up to 3 m thick), few in number and laterally non-persistent. Eastwards from Mikir Hills, in Nagaland, Assam and Arunachal Pradesh, the coal seams are distinctly thicker (4-18 m) and relatively more in number. The coal-bearing strata in Meghalaya are either undisturbed or have suffered only minor structural disturbance. On the other hand, the coal-bearing sediments in Nagaland, Assam and Arunachal Pradesh are exposed discretely along a narrow linear belt expressed in a series of complex and imbricate overthrusts, the "belt of Schuppen". The coalfields

of Nagaland (Nazira or Borjan and Changki-Valley), Assam (Dilli-Jeypore and Makum) and Arunachal Pradesh (eastern part of Makum and Namchik-Namphuk), economically the most important Tertiary coal resources of India, are aligned along this belt.

The present contribution deals with the genesis of some of the Tertiary coal deposits of northeastern India on the basis of petrographic data along with the available mega- and micro-floral and sedimentological information.

GENERAL GEOLOGY AND LITHOSTRATIGRAPHY

The general geology, structure and lithostratigraphic sequence of coal-bearing areas in northeastern India described here are based primarily on Raja Rao (1981). For the details about the chemical properties of the coals and number and thickness of coal seams present in Arunachal Pradesh, Assam, Nagaland and Meghalaya, the reader is referred to Raja Rao (1981).

Nagaland, Assam and Arunachal Pradesh

The coalfields of Nagaland, Assam and Arunachal Pradesh (Figs 1-2) are aligned along an active mobile belt which experienced intense tectonic disturbance resulting into a series of imbricate overthrusts, known as "zone" or "belt of Schuppen." Thrusting along this belt accompanied folding and interlocked slicing of Tertiary strata. The most important synclinal structure developed is in Makum and Namchik-Namphuk coalfields. The anticlinal structure is reported from Makum and Dilli-Jeypore coalfields. The Tertiary sedimentation in this belt commenced in an external trough near the platform corresponding to miogeosynclinal belt. Along this belt rapid subsidence and detrital supply resulted in a >2000 to 6000 m thick pile of Tertiary sediments. However, during Barail (Oligocene) sedimentation intermittent phases of slight emergence allowed the development of widespread coal-facies.

The Tertiary sediments in Nagaland, Assam and Arunachal Pradesh exhibit rapid lateral and vertical variations

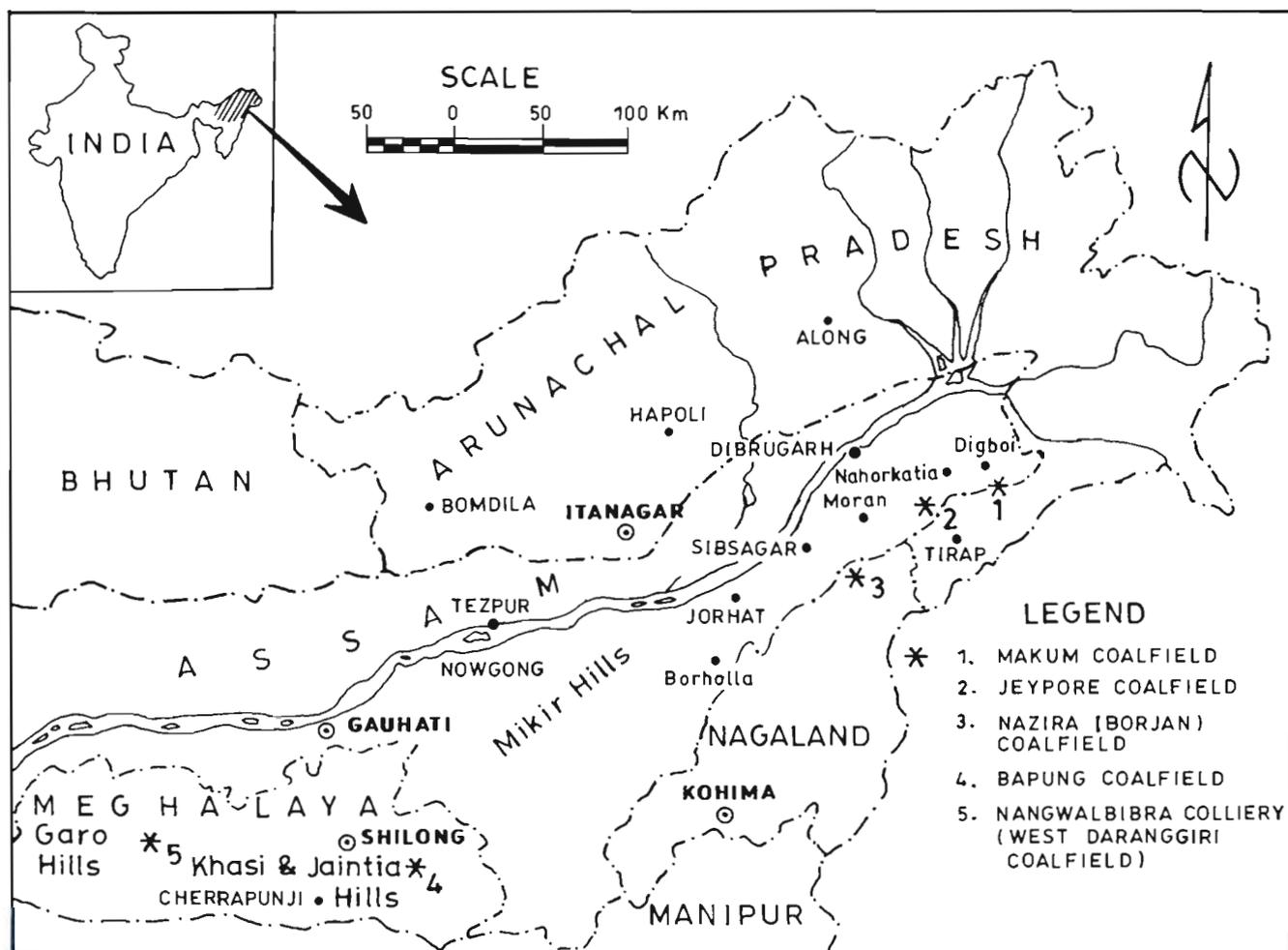


Fig. 1—Map showing locations of some of the important Tertiary coal deposits in Northeastern India (modified after Misra, 1992).

and range in age from Eocene to Pliocene. The lithostratigraphic sequence in these areas has been given in Fig. 3.

The coal-bearing sediments of Tikak Parbat Formation (Oligocene), in the 'belt of Schuppen', are preceded by marine and followed by fluvial sedimentary sequences. The predominance of fine-grained sediments comprising sandy-shale, siltstone, shale, mudstone and clay units are characteristic of deposition by tractive currents. Presence of arenaceous foraminifers, although not diagnostic of age, and sporadic limestone beds (Misra, 1981) indicate a definite marine influence. The Barail Group comprises a wide spectrum of lithofacies deposited under shallow marine, lagoonal, deltaic and fluvial environments.

Meghalaya

The major part of Meghalaya (Fig. 2), covered by Precambrian granites and gneisses, is a plateau—Shillong Plateau, which is a horst, uplifted during Early Cretaceous. Its evolution is linked with the basaltic effusion (Shylhet Trap) during Jurassic-Early Cretaceous periods. The coal-bearing

strata were deposited under stable shelf condition along the periphery of the plateau. The coal measures are sub-horizontal in attitude. The sedimentary exposures in the area range in age from Late Cretaceous to Eocene and show frequent lithofacies variations. The main lithostratigraphic sub-divisions are given in Fig. 4.

The workable coal seams in Khasi and Jaintia hills are associated with the Lakadong Sandstone Member (Late Palaeocene) of Sylhet Limestone Formation, Jaintia Group. In Garo Hills, the approximate equivalent of Lakadong Sandstone Member is the Middle Member of Tura Formation, which itself is considered partly equivalent to the Sylhet Limestone Formation. In Meghalaya, coal-bearing sediments comprising essentially lithomargic clays, shales, argillaceous sandstones and coal seams, are sandwiched between foraminiferal limestone units which implies a short duration episode of emergence between two marine incursions. The peat accumulation in Meghalaya, during this interphase occurred in deltaic, estuarine and lagoonal environments (Raja Rao, 1981).

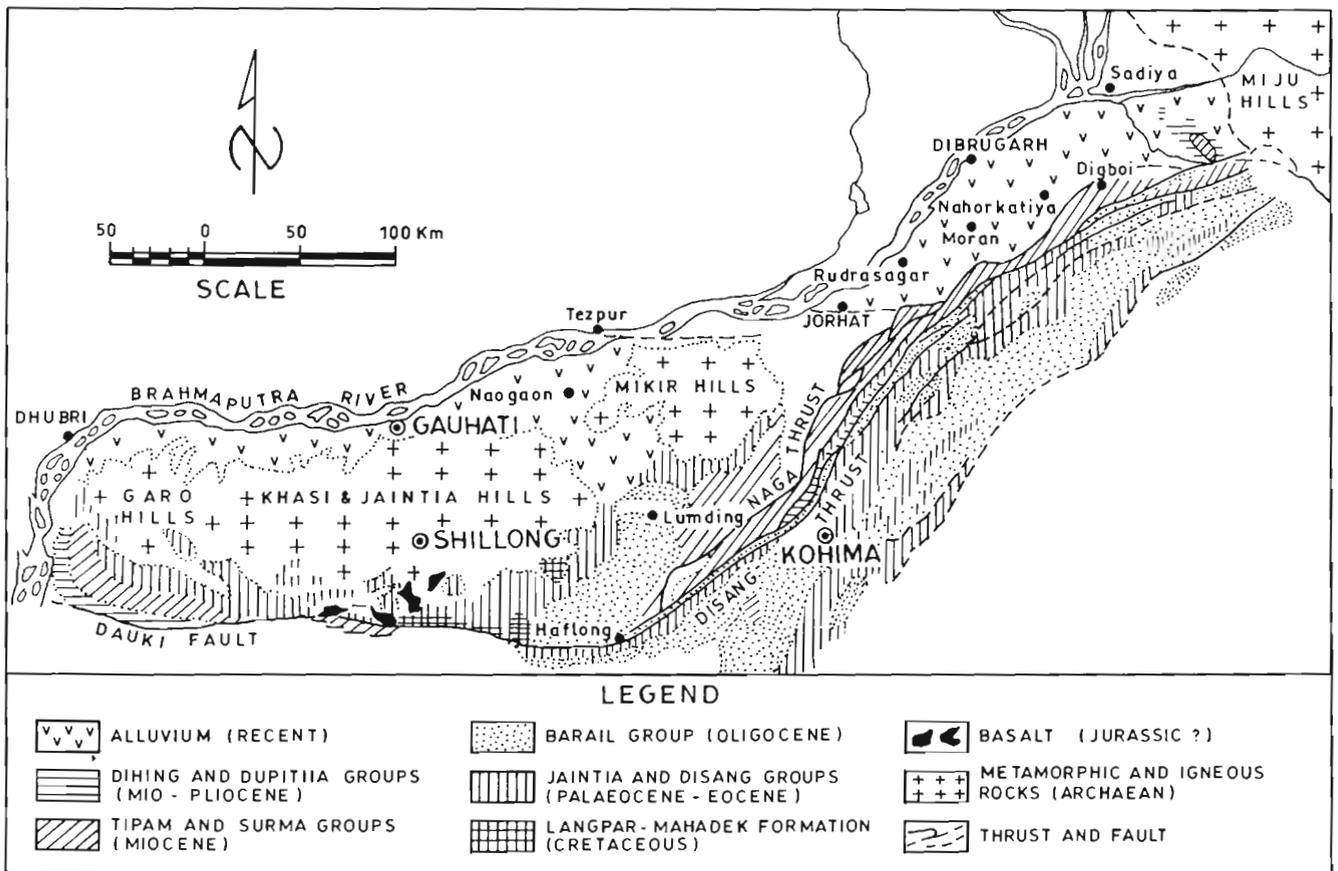


Fig. 2—Map showing geological and structural setting in Northeastern India.

STATUS OF PETROLOGICAL INFORMATION

Petrographic study of Tertiary coals in India was initiated by Ganju (1955). The earlier studies were made on thin sections of coals, and dealt with the morpho-petrography only. After about a decade, quantitative assessment of macerals and microlithotypes, under incident light, on polished coal surfaces (particulate pellets) was introduced by Ghosh (1964, 1969) and Sen and Sen (1969). Determination of coal rank through reflectance measurement, earlier used only sporadically (Ghosh, 1969), was routinely established by Navale and Misra (1980) and Misra (1981). The use of fluorescence microscopic study was made only during the latter part of eighties (Misra, 1992a, b, c; Misra & Navale, 1992; Misra *et al.*, 1990).

Obviously, most of the earlier petrographic investigations, in general, were primarily oriented towards the understanding of coal microconstituents as such, under both normal transmitted and incident light modes. However, since 1964 some available petrographic data provide general information about quality and grade of some of the important Tertiary coal deposits of northeastern India, viz., Makum and Dilli-Jeypore coalfields, Assam (Ghosh, 1969; Sen & Sen, 1969; Mukherjee,

1976; Navale & Misra, 1979; Goswami, 1985, 1987; Ahmed, 1991a); West Daranggiri Coalfield, Garo Hills, Meghalaya (Ghosh, 1964, 1969; Ahmed & Bharali, 1985; Ahmed, 1991b; Mishra & Ghosh, 1996) and Laitryngew Coalfield, Khasi Hills, Meghalaya (Ghosh, 1964, 1969; Sen & Sen, 1969; Ahmed, 1971). Most of these petrographic data (Fig. 5) are of only very limited use in the present context, because they do not provide the requisite information for ascertaining the specific nature of coal genesis. The majority of the information referred to is based on the study of a few samples (Ghosh, 1969; Sen & Sen, 1969; Ahmed, 1971; Ahmed & Bharali, 1985; Navale & Misra, 1979; Mukherjee, 1976). Whereas, in some cases the data appears to be unreliable as the authors (Sen & Sen, 1969) have recorded very low proportion of liptinite and inertinite macerals or extremely high amount of liptinite macerals (Goswami, 1987) not supported by fluorescence microscopic studies (Misra, 1992a, b, c). Besides, some of the petrographic data are on mineral matter-free basis (Sen & Sen, 1969; Navale & Misra, 1979; Goswami, 1987). The record of low to very low contents of inertinite macerals presumably resulted from the unrecorded fractions of fungal remains (sclerotinite: spores, sclerotia, hyphae, etc.) that are frequent in these coals.

Age	Group/Formation	Thickness (metres)	Lithology
Pliocene	Dihing Gr.	1,800	Mostly pebbly sandstone with thin greyish clay bands.
Pliocene	Namsang Fm.	800	Fine to coarse grained sandstones with clay beds.
Miocene	Tipam Gr. Girujan Clay Fm.	1,800	Mottled clays with greyish sandstones.
	Tipam Sandstone Fm.	2,300	Fine to coarse grained ferruginous bluish green micaceous and felspathic sandstones, sandy shales, sandy clays and clays.
Oligocene	Barail Gr. Tikak Parbat Fm.	600	Greyish to yellowish white massive fine grained sandstones, sandy shales, siltstones, mudstones, sporadic dolomitic limestones and coal seams.
	Baragolai Fm.	3,500	Greyish to bluish grey or yellowish mudstones, massive sandstones, sandy shales, carbonaceous shales, clays and thin coal seams.
	Naogaon Fm.	3,000	Hard massive medium grained sandstones, dark grey splintary shales with sandstone alternations.
Eocene	Disang Fm.	-	Grey to dark grey splintary shales, sandy shales with thin alternations of quartzitic sandstones.

Fig. 3—A generalized lithostratigraphic sequence of Tertiary sediments in Arunachal Pradesh, Assam and Nagaland (after Raja Rao, 1981).

Age	Formation/ Member	Thickness (m)	Lithology
Late Eocene	Kopili Formation	-	Ferruginous sandstones, grey siltstones, and pyritous splintary shales.
Middle Eocene	Sylhet Limestone Formation Prang Limestone (Siju Limestone) Member	60-150	Bluish massive to thinly bedded limestones with marly interbands (Rich in foraminifers).
Early Eocene	Nurpuh Sandstone Member	15-26	Coarse to medium grained sandstones with bands of sandy limestones.
	Umlotdoh Limestone Member	70-110	Grey to pinkish grey limestones, sandy limestones and calcareous sandstones (Rich in foraminifers).
Late Palaeocene	Lakadong Sandstone Member (= Mid. Member of Tura Formation In Garo Hills)	35-250	Buff coloured medium to coarse grained arkosic sandstones with pebbly interbands, thin grey carbonaceous shales, clays and coal seams.
Palaeocene	Lakadong Limestone Member	25-60	Grey to brownish grey limestones, siliceous limestones (Rich in foraminifers).
	Therria Sandstone Member	20-80	Buff coloured medium to coarse grained arkosic sandstones with thin bands of pyrite-rich silty sandstones (Unfossiliferous).
Late Cretaceous (Danian)	Langpar Formation	10-50	Buff coloured calcareous-ferruginous sandstones and earthy limestones.
Maastrichtian		160-335	Massive coarse grained glauconitic sandstones containing dark grey shales and calcareous horizons.

Fig. 4—Generalized lithostratigraphic sequence of Tertiary sediments in Meghalaya (after Raja Rao, 1981).

MEGASCOPIC CHARACTERS

In general, the Tertiary coal seams of northeastern India are devoid of lithotype banding, unlike the Permian Gondwana coal seams. They are bright and appear to comprise entirely vitrain lithotype (Raja Rao, 1981; Misra, 1981, 1992a). However, certain coal seams of Laitringew-Cherrapunjee area, Khasi Hills, Meghalaya are thinly banded, containing <1 to 3 cm thick alternating bands of bright and semi-bright bands, and also occasionally dull bands. The Waktung seam (main seam) of Nazira Coalfield, Nagaland has a thick dull band in its basal part (Raja Rao, 1981). The coals, especially from Nagaland, Assam and Arunachal Pradesh, show greasy to vitreous lustre and break with sub-conchoidal to conchoidal fracture. They are blocky but crumble easily because of rapid oxidation on aerial exposure. These coals commonly contain tiny pyrite specks and in certain seams concretions and encrustations of pyrite are also present, e.g. Bapung Coalfield, Jaintia Hills, Meghalaya and Makum Coalfield, Assam, besides criss-cross veins of secondary pyrite (Raja Rao, 1981; Misra, 1981, 1992a, b, c; Ahmed, 1971; Ahmed & Bharali, 1985).

OPTICAL PROPERTIES OF COALS

Maceral* Composition

In comparison to most of the Permian Gondwana coals of India, the Tertiary coals of northeastern India are rich in

vitritine macerals (41-79%, occasionally as low as 37%) with low to moderate amounts of liptinite (5-19%) and inertinite (3-20%, rarely up to 34%) macerals. Associated minerals comprise mainly pyrite, calcite and argillaceous matter (clay and quartz). Their contents vary between 4% to 20%, rarely up to 35% (Fig. 6). These coals are well known for their pyrite contents (1-20%, max. 33%, Misra, 1992a, b).

The Tertiary coals of northeastern India, under fluorescence mode (Fig. 7 on mineral matter-free basis), are characterized by high to very high proportions of fluorescing macerals (47-88% max. up to 91%) comprising chiefly perhydrous or fluorescing vitritine (25-62%, max. 78%) and liptodetrinite (8-35%, max. 40.5%) with subordinate amounts of other liptinite macerals (4-22%, max. 28%). The liptinite fractions in these coals, excluding liptodetrinite, are formed mainly by resinite (1-18%), and cutinite+suberinite (0.4-7.6%). The sporinite content is always low (0.3-2%, max. 3.3%). Alginite (up to 1%) maceral is represented by alga *Botryococcus*. In addition to these, bituminite, exsudatinitite and fluorinitite are also commonly present (Misra, 1992a, b).

Maceral Characteristics

The vitritine macerals in the Tertiary coals of northeastern India comprise chiefly collodetrinite (earlier termed as desmocollinitite) and collotelinitite (telocollinitite), besides low amounts of collogelinitite (corpocollinitite) and telinitite (Misra, 1981, 1992a, b). Invariably, collodetrinite is the dominant maceral in all the coal seams. Collodetrinite and some of the collotelinitite display granular or spongy texture with relatively

* The terminology for description of macerals, excluding those of vitritine group, is as per ICCP (1971). For vitritine macerals, revised terms of the ICCP (1995) have been used.

weaker reflectance than the associated vitrinite. Frequent occurrence of fungal spores, sclerotinite, and fine clusters and knots of hyphae in vitrinite indicates that the vegetal matter forming the coal seams experienced high degree of biodegradation. On the basis of thin section study, Ganju (1955) had already reported the presence of highly degraded woods due to fungal activity in the coals from Makum Coalfield, Assam. Framboids, crystal and granules of pyrite in vitrinite, especially in collodetrinite, and clarite and trimacerite are frequent (Misra, 1992a). Occasionally, fine microgranules of pyrite are seen inside the lumens of collotelinite, e.g. coals of Nazira Coalfield, Nagaland. Crushing and shattering of vitrinite and inertinite macerals, including microfaults and brecciation, are frequent in the coals from Arunachal Pradesh, Assam, Nagaland and Garo Hills of Meghalaya.

The main inertinite macerals recorded are semifusinite, fusinite (rank-, degrado- and pyro-inertinite types), inertodetrinite and sclerotinite with sporadic macrinite and micrinite. Usually the inertodetrinite and sclerotinite together constitute the major fraction of the total amount of inertinite present, especially in the coals from Assam and Nagaland (Misra, 1992a, b). The structured inertinites (semifusinite and fusinite) embedded in vitrinite normally have empty cell-lumens. Occasionally, the lumens are filled with calcite and frambooids of pyrite and also small amount of argillaceous matter. In contrast to the coal seams of Assam and Nagaland, those from Meghalaya have relatively higher proportion of inertinite macerals consisting mainly of semifusinite and fusinite (Fig. 6).

Pyrite and calcite are the main minerals associated with the coals from northeastern India. Clay and quartz (argillaceous matter) together are normally between 20% to 40% of total mineral matter content of the coals.

Under fluorescence mode, perhydrous or fluorescing vitrinite constitutes the bulk of the total fluorescing macerals recorded in the coals from northeastern India (Misra, 1992a, b). Among the liptinite macerals, liptodetrinite and resinite are the dominant followed by cutinite+suberinite and sporinite. Exsudatinite and fluorinite are common in almost all the coal seams. Tenuicutinite is common and crassicutinite is sporadic. Suberinite occurs commonly in clarite, trimacerite as thin to thick bands, fragments and shreds. It is also associated with liptodetrinite as highly degraded and amorphous bodies. Resinite is especially common in Dilli-Jeypore (Assam), Nazira (Nagaland), and Bapung and Jarain (Meghalaya) coalfields. The liptodetrinite present in these coals is formed chiefly either by resinite or resinite+cutinite+suberinite. Well-preserved and partially degraded alginite (*Botryococcus*) has been observed in Khasi and Jaintia hills of Meghalaya. However, highly degraded and disorganized alginite, on the basis of fluorescence properties, has been observed in most

of the coal seams. Granular bituminite is commonly associated with trimacerites, clarites and in collodetrinite. Pyrite is usually associated with almost all the liptinite macerals.

Most of the coal seams of Assam, Arunachal Pradesh, Nagaland and Meghalaya (Khasi and Jaintia hills) have very high total fluorescing maceral contents (normally 72-91%). However, certain coal seams, especially from Nazira Coalfield (52-61.4%) and some patchy seams of Jaintia Hills, and the main seam (25-54%) of West Daranggiri Coalfield (Garo Hills) have relatively lower proportions of total fluorescing macerals. In general, the coal seams from Jaintia Hills have higher liptodetrinite content than those from the other areas. The coal seams of Garo and Jaintia Hills are also characterized by relatively higher amount of particulate liptinite macerals, excluding liptodetrinite, than that of Assam and certain coal seams (Sutunga area) of the Jaintia Hills.

Microlithotypes

Misra (1981) carried out quantitative assessment of microlithotypes in the coals of Makum Coalfield, Assam. He found that the coals are rich in vitrite microlithotype (68.4-94.4%) with subordinate proportions of vitrinertite (3.4-25.6%) and clarite (2.2-9.8%). Since the data was obtained on mineral matter-free basis, therefore, it is incomplete. Goswami (1987) and Ahmed (1996a) and Ahmed (1991a) provided some qualitative information about the microlithotypes (by plotting of maceral data on triangular diagram for knowing the microlithotype composition of coals) in the coals, respectively, from Makum and Dilli-Jeypore coalfields. This information is only qualitative and not quantitative and also on mineral matter-free basis. Goswami (1987) found clarite-V and duroclarite-V dominance in the microlithotype assemblage of the Makum coals, whereas other associated microlithotypes are vitrite and vitrinertite-V. Ahmed (1991a, 1996a) observed only two microlithotypes-vitrinertite-V and duroclarite-V in the coals from Dilli-Jeypore Coalfield, whereas in the Makum coals only one (vitrinertite-V) was reportedly present. Presence of only one or two microlithotypes in these coals is inconceivable, therefore the observations are unrealistic and unreliable. However, on the basis of author's observation, the coal seams of Assam and Nagaland have the dominance of vitrite and sporinite-poor clarite along with subordinate amounts of duroclarite and vitrinertite microlithotypes, besides occasionally low proportions of carbopyrite. The clarodurite and inertite microlithotypes are uncommon, whereas durite is almost absent. Some of the coal seams from Jaintia Hills, Meghalaya have almost the similar microlithotype composition as the preceding ones. However, the coal seams of Meghalaya generally have higher proportions of duroclarite and clarodurite than that of Assam and Nagaland. Associated

Area Coalfield Author	R _o %	Vitrinite %	Liptinite %	Inertinite %	Mineral Matter %
Makum Coalfield, Assam					
Ghosh (1969)		74.5-87.3	2.8-4.7	4.7-18.6	3.0-4.2
Sen & Sen (1969)*		87.8-96.4	0.9-1.5	2.7-10.7	-
Mukherjee (1976)		86.5-94.2	0.9-5.0	2.2-6.2	2.2-3.7
Goswami (1985)*		86.3-94.0	1.1-6.3	5.0-7.3	-
Goswami (1987)*		52.0-94.0	6.0-48.0	0.0-28.5	-
Ahmed (1996b)	0.66-0.71	82.8-86.6	3.9-5.2	5.0-6.7	3.4-6.7
Mishra & Ghosh (1996)	0.62-0.73	71.1-88.2	3.0-14.0	1.3-16.4	2.0-18.57
Dilli-Jeypore Coalfield, Assam					
Goswami (1985)*		95.0-98.0	0.3-2.4	1.5-2.4	-
Ahmed (1991a)	0.60-0.67	79.7-81.4	2.7-2.9	12.0-13.0	3.4-4.7
Mishra & Ghosh (1996)	0.60	73.4	14.1	8.3	4.2
Namchik-Namphuk Coalfield, Arunachal Pradesh					
Mishra & Ghosh (1996)	0.53-0.68	68.8-83.7	3.7-15.4	3.5-5.7	7.1-12.6
Jhanzi-Disai Coalfield, Nagaland					
Mishra & Ghosh (1996)	0.72-0.74	86.8-87.9	1.4-3.3	0.6	8.2-11.2
Nazira Coalfield, Nagaland					
Goswami (1985)*	-	72.5-78.8	3.0-9.7	17.8-18.3	-
Coalfields of Khasi Hills, Meghalaya					
Ghosh (1969)	-	80.2-89.4	1.3-2.8	2.9-12.8	4.2-6.4
Sen & Sen (1969)*	-	94.0	1.2	4.2	-
Goswami (1985)*	-	89.6-93.0	2.0-3.4	3.6-8.4	-
Mishra & Ghosh (1996)	0.54-0.63	52.1-74.9	7.9-11.6	5.8-18.1	5.0-20.1
Ahmed <i>et al.</i> (1997)	-	62.0-72.8	8.2-21.6	4.1-14.7	4.8-9.2
Coalfields of Jaintia Hills, Meghalaya					
Ahmed (1971)	-	82.1-83.4	5.2	7.2-7.6	4.1-5.0
Ahmed (1996a)	0.74-0.75	81.5-83.0	5.5-6.1	5.1-5.3	6.3-7.0
Mishra & Ghosh (1996)	0.54-0.85	50.6-87.8	2.5-12.0	6.6-25.3	4.2-21.7
Coalfields of Garo Hills, Meghalaya					
Ghosh (1969)	-	84.0-85.0	5.0-6.0	6.0-7.0	3.0-4.0
Goswami (1985)*	-	86.9-92.5	1.5-5.2	6.0-7.8	-
Ahmed (1991b)	-	58.5-73.0	3.8-5.0	14.8-31.5	5.0-7.6
Mishra & Ghosh (1996)	0.37-0.54	60.0-79.2	3.1-9.6	3.4-16.7	5.5-27.0

Fig. 5—Maceral composition (volume %) of Tertiary coals from Northeastern India, under normal reflected light (data from other sources).

common microlithotypes are vitrinertite and inertite, and sporadic durite, especially in the coal seams of Garo Hills, Meghalaya, and occasionally minor amount of carbopyrite.

RANK

The rank (Figs 5, 6) of the Tertiary coals was determined by reflectance measurements (mean maximum) on vitrinite (collotelinite) maceral, in oil (R_o max. %). The coals of Assam (R_o max. 0.71-0.75%), and those of Jaintia Hills, Meghalaya (R_o max. 0.64-0.69%, occasionally 0.72-0.86%) have attained

a rank corresponding to high volatile bituminous B to occasionally A stages. The coals of Nazira Coalfield, Nagaland (R_o max. 0.59-0.67%) and West Daranggiri Coalfield of Garo Hills, Meghalaya (R_o max. 0.54-0.62%) have reached only high volatile bituminous C stage. With few exceptions, probably influenced by heating from some subsurface igneous bodies (Fig. 6: Sutunga area R_o max. 0.72-0.86%), the younger coal seams (Oligocene) of Assam and Nagaland have attained higher maturity than the Late Palaeocene coals seams of Meghalaya. As a result, there is an eastward increasing trend in coal rank from the West Daranggiri Coalfield, Garo Hills of Meghalaya to Makum Coalfield, Assam, coinciding with the westward increasing age of the deposit (Fig. 8). This inverse relationship between the coal rank and age of the deposit is evidently related to the greater depth of burial of the coal seams (>2,000-6,000 m thick overlying sediments), prevailing high geothermal gradient and intense tectonic activity in Assam and Nagaland. On the other hand, in Meghalaya the coal seams experienced shallow burial (± 500 m thick overlying sediments) and show least tectonic effect (Misra, 1992a, b; Raja Rao, 1981).

When compared with the chemical properties, the R_o max. % of the coals, in most cases, do not correspond with each other. Instead their volatile matter contents indicate relatively lower rank than that ascertained by the R_o max. %. Whereas, on the basis of calorific values and moisture contents their rank seems to be higher than that estimated by the reflectance measurements (Misra, 1992b). The abnormality in the rank of these coals as estimated by chemical properties and reflectance measurements has been attributed to their higher sulphur contents (Das Gupta, 1979; Raja Rao, 1981). It is well known that the Late Palaeocene and Oligocene coals of northeastern India contain high amount of total sulphur present mostly in the organic form (60-99%). The remaining inorganic fraction is associated as pyrite (Raja Rao, 1981; Misra, 1992a). The organic sulphur occurs as thiols, thiophenes, heterocyclic thionaphthyl, sulphides and disulphides, etc., and also partly in ring structures. About 50% of the organic sulphur is reactive and a part of that displaces oxygen instead of carbon from oxygenated groups. Consequently, they contain relatively low amount of reactive oxygen for their rank. Low reactive oxygen

Area, Coalfield & Coal Seam	R_o max. %	Vitrinite %	Liptinite %	Inertinite %	Mineral Matter %
Makum Coalfield, Assam					
Seam no. 3	0.72-0.75	60.5-74.2	5.0-9.5	10.6-19.5	7.7-21.8
Seam no. 1	0.73-0.75	60.9-76.9	5.4-8.1	9.1-20.1	5.2-18.3
Dilli-Jeypore Coalfield, Assam					
Seam no. 6	0.71	52.8-66.0	8.4-16.2	13.8-16.0	4.0-22.8
Seam no. 4	0.71	54.0	10.2-14.0	6.4-19.8	12.2-29.4
Nazira Coalfield, Nagaland					
Main Seam	0.59-0.67	76.4-79.0	8.6-9.2	3.0-7.2	6.6-9.0
Bapung area, Jaintia Hills, Meghalaya					
Top Seam	0.64-0.69	42.0-66.0	7.0-18.6	13.6-32.6	5.6-22.2
Middle Seam	0.66-0.68	53.0-63.4	11.8-13.6	6.2-20.0	13.8-20.6
Bottom Seam	0.64-0.69	42.6-68.2	4.0-15.6	6.8-35.0	5.4-22.4
Sutunga area, Jaintia Hills, Meghalaya					
Top Seam	0.81-0.86	70.4-74.4	6.0-9.8	7.4-11.8	5.6-10.4
Middle Seam	0.72	68.8	10.8	8.8	11.6
Bottom Seam	0.73	58.0	9.2	15.8	17.0
Jarain area, Jaintia Hills, Meghalaya					
Top Seam	0.68-0.69	46.6-59.6	10.8-14.0	7.4-19.6	16.6-35.2
Bottom Seam	0.68-0.69	54.8-56.0	8.4-11.0	5.0-10.0	26.8-28.0
West Daranggiri Coalfield, Garo Hills, Meghalaya					
Main Seam	0.54-0.62	36.8-64.8	7.6-13.2	15.4-34.4	10.6-26.2

Fig. 6—Maceral composition (volume %) and rank of Tertiary coals from northeastern India, under normal incident mode.

content in these coals has been ascribed to be responsible for their high swelling index (B.S.S.) at relatively lower rank stage than the normal humic coals. It is because of these properties that they were termed as 'abnormal' coals by Iyenger and Lahiri (1958). This abnormal property of the coals has been confirmed by both spectralfluorescence measurements on sporinite maceral and fluorescence alteration measurements on vitrinite maceral in the coals from Garo and Jaintia hills, Meghalaya (Misra, 1998).

COAL FORMING PLANT COMMUNITIES AND THEIR ENVIRONMENTAL SIGNIFICANCE

The mega- and microplant remains recovered from the coal-bearing sequences of different areas are listed in Fig. 9. The letter 'P', in the list, denotes the record of pollen related with a taxon/family, and the symbol habitat/community. In the following text only significant taxa (at family and generic levels) and those without established affinities have been mentioned.

Makum Coalfield, Assam

The microfloral assemblage recovered from the coal seams and associated sediments in the basal part of the Tikak Parbat Formation, Barail Group is either dominated by the angiospermous pollen or pteridophytic spores (Misra, 1981). Fungal remains including a variety of epiphyllous elements, excluding hyphae and mycelia, are abundant (25-69%, rarely below 25%) in the working seams (nos. 1 & 3). The assemblage from the coal seams generally has the dominance of angiospermous pollen (13-42%) in the top sections of the seams. Pteridophytic spores are sometimes in high amounts (26-57%), i.e., more than the angiosperms.

Pteridophytic spores recovered from the coal seams are represented mainly by Parkeriaceae (*Striatriletes*), Cyathea-ceae (*Cyathidites*), Polypodiaceae (*Polypodiisporites* and *Polypodiaceasporites*), Schizaeaceae (*Lygodiumsporites*) and Matoniaceae (*Dandotiaspora*). Spores of *Striatriletes* are present in very high frequency (40-60%) in the basal part of seam no. 1 in Baragolai and Tipang collieries. The palynological assemblage, though rich in dicot pollen comprises persistently high percentages of monocots, belonging to families Arecaceae and Agavaceae alone. The most represented dicot families are – Rubiaceae, Anacardiaceae, Alangiaceae, Oleaceae, Lecythidaceae, Meliaceae, Rhizophoraceae, Onagraceae, Myrsinaceae, Sapotaceae, Nyssaceae, Ericaceae and Droseraceae. Some significant pollen genera, of unknown affinities, are *Tricolpites* (*T. levis*), *Meyeripollis*, *Polycolpites* and *Engelhardtioipollenites*. *Octaplata* and *Palania* are the common microplanktons

recorded, besides salt glands of mangrove plant leaves (*Oudhkusumites*=*Heliospermopsis*) by Banerjee (1985).

Plant megafossil genera referable to families— *Lansea*, *Mangifera* and *Parishia* (Anacardiaceae), *Saccopetalum* (Annonaceae), *Alstonia* (Apocynaceae), *Avicennia* (Avicenniaceae), *Santiria* (Burseraceae), *Calophyllum*, *Garcinia* and *Kayea* (Clusiaceae), *Terminalia* (Combretaceae), *Bridelia* (Euphorbiaceae), *Dalbergia* and *Entada* (Fabaceae), *Apollonias* (Lauraceae), *Heynea* (Meliaceae), *Memecylon* (Memecylaceae), *Myristica* (Myristicaceae), *Rhizophora* (Rhizophoraceae), *Nephelium* (Sapindaceae) and *Pterygota* (Sterculiaceae), and a gymnospermous plant, *Podocarpus* are known to occur in the coal-bearing sediments of the area (Misra, 1992c; Awasthi & Mehrotra, 1995).

From the plant fossil records, a humid tropical climate with high annual precipitation has been inferred (Misra, 1992c; Awasthi & Mehrotra, 1995). This climate facilitated the growth of luxuriant coastal to near-shore, including mangrove, forest vegetation with prolific undergrowth during the deposition of coal-bearing sediments in the area. It has also been presumed that the climate and vegetation (unpublished palynological report by the author from the coalfields of Dilli-Jeypore, Assam and Nazira, Nagaland) in the nearby areas of Assam and Nagaland were almost similar.

Khasi Hills, Meghalaya

The palynological assemblage recovered from coal-bearing Lakadong Sandstone Member, Sylhet Formation (Dutta & Sah, 1970; Kar & Kumar, 1986) is highly rich in pteridophytic spores (up to 70%). Significant taxa are—*Lygodiumsporites* and *Dandotiaspora* along with sub-ordinate amount of Schizaeaceous and Cyatheaaceous spores, etc. Angiospermous pollen are chiefly monocots, viz., Arecaceae (*Proxapertites*, *Spinomonosulcites* and *Spinozoncolpites*), Liliaceae (*Matanomadhiasulcites*) and Potamogetonaceae (*Retipilonapites*). Whereas, commonly present dicot pollen taxa belong to families Euphorbiaceae, Onagraceae, Labiatae, Clusiaceae (*Kielmeyerapollenites*), Bombacaceae, Gunneraceae, Pellicieraceae, Fabaceae, Anacardiaceae, Meliaceae, Oleaceae, Myricaceae, Sapindaceae, Rhizophoraceae, Lecythidaceae, Polygonaceae, Proteaceae and Droseraceae.

All the five coal seams in Laitryngew and three coal seams in Cherrapunjee areas (Kar & Kumar, 1986) have yielded a trilete dominant assemblage with varying proportions of *Lygodiumsporites* (22-45%) and *Dandotiaspora* (18-40%). Angiospermous pollen are mainly those belonging to families Arecaceae, Liliaceae and Potamogetonaceae, Clusiaceae, Gunneraceae and Droseraceae.

On the basis of the preceding microfloral evidences, Dutta and Sah (1970) and Kar and Kumar (1986) inferred a near-shore shallow water coastal environment. The vegetal accumulation for the formation of coal seams took place in a stretch of freshwater coastal swamps.

Jaintia Hills, Meghalaya

The coal seams and associated sediments of Palaeocene Sylhet Formation in Jaintia Hills (Tripathi & Singh, 1984; Singh & Tripathi, 1986; Mandal, 1986) have yielded higher proportions of angiospermous pollen (29-66%) than the pteridophytic spores (30-58%). The coal seams in Bapung area have yielded almost equal proportions of pteridophytic spores and angiospermous pollen, besides fungal elements (Tripathi & Singh, 1984). The pteridophytic spores are mainly *Lycopodiumsporites* (Lycopodiaceae), *Lygodiumsporites* (Schizaeaceae), *Dandotiaspora* (Matoniaceae) along with spores of Polypodiaceae and Parkeriaceae. Angiospermous pollen are mostly represented by *Proxapertites*, *Palmaepollenites*, *Spinomonosulcites* and *Palmidites* of Arecaceae. Other pollen associates are of the families Liliaceae, Euphorbiaceae, Oleaceae, Myricaceae and Chenopodiaceae. There is a dominance of *Lygodiumsporites* and sub-dominance of *Dandotiaspora* in the lower three seams,

including one local seam. The 3rd and 5th seams are also characterized by the presence of fair amounts of dinoflagellate cysts, viz., *Cordosphaeridium*, *Adnatosphaeridium*, *Polysphaeridium* and *Homotriblium* (Tripathi & Singh, 1984).

In Lad-Rymbai (Bapung area) either three (top, middle and bottom) or only two (top and bottom) coal seams are present in different localities. They have yielded angiosperm dominant assemblage. The main pollen genera recovered are *Proxapertites*, *Spinimonosulcites*, *Spinizonocolpites*, etc. of family Arecaceae. Subordinate amounts of associated dicot pollen belong to families Liliaceae, Bombacaceae, Clusiaceae, etc. Lycopodiaceous, cyatheaceous and polypodiaceous spores are the main pteridophyte representatives.

The coal seam in the Sutunga area (Mandal, 1986) yielded a fairly high amount of angiospermic pollen, of which monocot pollen genera *Proxapertites*, *Spinomonosulcites*, *Spinizonocolpites* and *Acanthotricolpites* of family Arecaceae constitute about 68.0% of the bulk. Other pollen forms belong to families Bombacaceae, Gunneraceae, Oleaceae,

Area Coalfield Coal Seam	Fluorescing Vitrinite %	Liptinite Sp, Cu, Re, Sub, Alg, Flr, Ex (%)	Lipto- detrinite %	Total Fluorescing Macerals %	Total Non-fluo. Macerals %
Makum Coalfield, Assam					
Seam no. 3	42.2-62.1	8.2-12.0	15.3-23.2	78.4-88.5	11.5-21.6
Seam no. 1	47.4-59.7	7.2-17.1	15.7-22.3	78.0-88.6	11.4-22.0
Dilli-Jeypore Coalfield, Assam					
Seam no. 6	29.7-47.9	18.7-22.1	Recorded.	48.4-70.0	30.0-51.6
Seam no. 4	50.1-56.7	25.5-27.9	Flour Vit.	78.0-82.2	17.8-22.0
Nazira Coalfield, Nagaland					
Main Seam	35.3-40.9	16.7-20.5	''	52.0-61.4	38.6-48.0
Laitryngew Coalfield, Khasi Hills, Meghalaya					
Main Seam	31.6-67.4	6.4-13.4	8.2-27.2	47.2-88.4	11.6-52.8
Bapung area, Jaintia Hills, Meghalaya					
Top Seam	23.0-42.0	11.5-17.6	22.0-34.1	72.3-79.2	10.8-27.7
Middle Seam	41.0-60.0	11.8-19.7	11.0-25.6	82.1-86.8	13.2-17.9
Bottom Seam	30.7-50.0	15.0-20.7	20.2-35.0	74.1-88.3	11.7-25.9
Sutunga area, Jaintia Hills, Meghalaya					
Top Seam	57.5-78.1	2.0-7.0	8.0-9.2	59.5-91.2	8.8-40.5
Middle Seam	34.5	4.5	14.0	53.0	47.0
Bottom Seam	67.5	7.4	8.1	83.0	17.0
Jarain area, Jaintia Hills, Meghalaya					
Top Seam	37.0-48.5	12.0-14.0	27.3-34.1	77.0-90.5	9.5-23.0
Bottom Seam	25.5-50.6	13.9-18.8	26.0-40.5	84.8-90.5	9.5-15.2
West Daranggiri Coalfield, Garo Hills, Meghalaya					
Main Seam	35.0-56.0	12.1-18.8	9.3-22.0	70.0-81.4	18.6-30.0

Fig. 7—Maceral composition (% on mineral matter-free basis) of Tertiary coals from northeastern India, under incident blue light excitation.

Anacardiaceae, Clusiaceae, Fabaceae and Onagraceae. Besides, certain unaffiliated forms like *Retitribrevicolporites* have also been recorded. Pteridophytic spores of the assemblage, in the coal seams, are mainly constituted by *Lycopodiumsporites* (Lycopodiaceae), *Lygodiumsporites* (Schizaeaceae), *Cyathidites* (Cyatheaceae), etc.

Singh and Tripathi (1986) envisaged that the prevailing climate during Palaeocene-Eocene epochs was humid tropical. Besides, the persistent presence of a variety of dinoflagellate cysts even in some coal seams indicate that the coal-bearing sediments "appear to have been deposited under brackish-water to shallow-marine conditions". However, no marine indications have been recorded from Sutunga (Mandal, 1986), Lad-Rymbai and Jarain areas. Nevertheless, coastal to near-shore conditions are evident from the palynological assemblage.

Garó Hills, Meghalaya

Palynological assemblage recovered from the coal seams and associated sediments (Singh *et al.*, 1975; Singh, 1977a, b; Saxena *et al.*, 1996) of Tura Formation, Jaintia Group in Nangwalbibra area, West Daranggiri Coalfield, is dominated by pteridophytic spores belonging chiefly to families Lycopodiaceae, Matoniaceae, Polypodiaceae, Osmundaceae, Schizaeaceae and Gleicheniaceae. The two important coal seams (No.1 and 2 main seam) contain almost identical taxa. Pollen are represented most by the genera *Spinomonosulcites*, *Proxapertites*, *Spinozonocolpites* (Arecaceae) and *Matanomadhiasulcites* (Liliaceae). Other significant angiospermous pollen associates belong to families Bombacaceae, Braccicaceae, Fabaceae, Gunneraceae, Meliaceae, Onagraceae, Nyssaceae, Labiatae, Polygonaceae, Myrtaceae, Myrsinaceae, Rhizophoraceae, Rubiaceae, Lentibulariaceae (*Utricularia*) and Droseraceae. Some coal seams, older than the main seam, in the southern part of the area are characterized by the persistent presence of microforaminifera (Singh *et al.*, 1975). Saxena *et al.* (1996) also recorded some dinoflagellate cysts from the coal-bearing section of the Tura Formation.

Ambwani (1993) carried out palynological investigation on coal-bearing sediments, comprising three thin coal seams, from Rekmangiri coalmine. The palynological assemblage consists of more or less similar microflora as that reported by Singh *et al.* (1975), Singh (1977a) and Saxena *et al.* (1996), besides dinoflagellate cysts of *Apectodinium* in the 3rd seam (top seam).

Singh *et al.* (1975) and Singh (1977a, b) presume that the coal seams and associated sediments in the northern and southern parts of the Nangwalbibra area were deposited under warm humid climate near coastal area in a shallow fresh water milieu, probably representing deltaic regime. However, sediments below main coal seam in the southern part of the area locally experienced marine incursions. On the basis of

pollen-spore assemblage, Saxena *et al.* (1996) concluded that the Nangwalbibra area (West Daranggiri Coalfield) was in close proximity to the shoreline and the presence of a few specimens of dinoflagellate cysts indicate shallow marine conditions of deposition.

Plant megafossil records (Bhattacharyya, 1983; Mehrotra, 1999) from Garó, Khasi and Jaintia Hills, Meghalaya include several plant genera (Fig. 9): *Heteropanax* (Araliaceae), *Mangifera* (Anacardiaceae), *Polyalthia* (Annonaceae), *Nypa*, *Phoenix* and *Amesoneuron* (Arecaceae), *Bombax* (Bombacaceae), *Bursera* (Burseraceae), *Calophyllum* (Clusiaceae), *Terminalia* and *Calycopteris* (Combretaceae), *Desmodium*, *Derris*, *Millettia*, *Pongamia*, *Pterocarpus*, *Bauhinia*, *Trachylobium*, *Sindora* and *Albizia* (Fabaceae), *Listea*, *Neolistea*, and *Phoebe* (Lauraceae) *Barringtonia* (Lecythidaceae), *Artocarpus* (Moraceae), *Syzygium* (Myrtaceae), *Nelumbo* (Nymphaeaceae), *Osmanthus*, *Ligustrum* and *Antholithes* (Oleaceae), *Atalantia* (Rutaceae), *Schleichera* (Sapindaceae), *Chrysophyllum* (Sapotaceae), *Sonneratia* (Sonneratiaceae), *Sterculia* (Sterculiaceae), *Grewia* and *Triumfetta* (Tiliaceae), and *Trema* (Ulmaceae). Taxa like *Terminalia*, *Nypa*, *Barringtonia*, *Sonneratia*, *Calophyllum*, *Litsea*, *Neolitsea*, *Phoebe*, *Osmanthus*, *Ligustrum*, *Antholithes* and *Derris* are typical beach forest, including mangrove elements and suggest estuarine conditions with large amount of swampy vegetation (Bande, 1992; Mehrotra, 1999). Whereas, the occurrence of *Nelumbo nucifer* indicates the existence of ponds (Mehrotra, 1999).

The preceding mega- and micro-floral records indicate that the climate during coal formation in Garó Hills was warm and humid (tropical) with much higher rainfall than today (Mehrotra, 2000). The flora, in Meghalaya during Late Palaeocene Epoch, consisting of evergreen to moist deciduous forest vegetation, including coastal and mangrove plants, was responsible for the formation of coal seams (Singh & Sarkar, 1990; Mehrotra, 2000).

DISCUSSION

The geological, sedimentological, palaeobotanical and petrological information available on the coal-bearing areas of northeastern India are mostly of general nature, non-sequential, of very restricted type and rather incomplete in relation to the present context. For some areas, there is a complete lack of petrological and palaeobotanical information. Therefore, an attempt to deduce the origin of these Tertiary coals would be only of a general nature, and in certain respects imperfect till further data are available.

The fossil mega- and micro-floral evidences (Fig. 9) establish that the vegetal matter for the formation of Tertiary coal deposits in northeast India was chiefly derived from coastal/near-shore tropical semi-evergreen to evergreen deciduous forests, including back mangroves, mangrove

associates and mangrove plant communities (Dutta & Sah, 1970; Kar & Kumar, 1986; Singh & Tripathi, 1986; Singh & Sarkar, 1990; Misra, 1992a, b, c; Awasthi & Mehrotra, 1995; Mehrotra, 2000). Herbs and shrubs, including pteridophytes, grew profusely as undergrowths in the forests and back mangroves, especially the taxa of Lycopodiaceae, Polypodiaceae and Schizaeaceae, besides other moisture and shade loving cosmopolitan ferns belonging to families Cyatheaceae, Matoniaceae, Parkeriaceae, etc., were also commonly associated. Aquatic and water-edge (freshwater) angiospermous plants like *Nymphaea* (waterlily), *Nelumbo* (lotus), *Potamogeton*, *Utricularia*, *Drosera*, etc., were also associated.

The vegetation that formed Late Palaeocene coals in Meghalaya was dominated by arborescent and herbaceous angiosperms, besides herbaceous pteridophytic taxa. Among angiosperms, contribution of monocots, especially the palms, was much more significant than the dicots. Pteridophytes were mostly the plants of Lycopodiaceae, Matoniaceae and Schizaeaceae along with Cheilanthaceae, Cyatheaceae, Osmundaceae, etc. However, during Oligocene in Arunachal Pradesh, Assam and Nagaland an apparent change, both in quality and quantity of pteridophytic contribution, is witnessed together with higher representation of dicots over monocots in the coal-forming vegetation. Important pteridophytic taxa recorded belong to families Parkeriaceae, Polypodiaceae and Schizaeaceae. The pteridophytes registered further decrease and were represented mostly by the spores of Schizaeaceae and Polypodiaceae.

The depositional models suggested for the Tertiary coal-bearing sediments of northeastern India during Late Palaeocene and Oligocene epochs by earlier workers are broad and of generalized nature. Pascoe (1964, p. 1580) thought that the coals from Meghalaya were formed "not far from the coast, possibly in brackish water lagoons". From fossil floral evidences, dominance of aquatic and 'marshy' taxa and presence of dinocysts, Biswas (1962) presumed that in Garo Hills the vegetation "grew right within the basin of deposition" and there was "periodic brackish water influence". On the basis of geological and sedimentological studies, Mathur and Evans (1964), Das Gupta (1979), Raja Rao (1981) and Misra (1981) inferred coastal, deltaic, lagoonal, estuarine, shallow-marine and back-swamp depositional conditions for the coals in Assam and Nagaland. Raja Rao (1981) and Misra (1981) suggested autochthonous origin of coals in Assam and Nagaland. However, Bhandari *et al.* (1973) presumed that, in Assam and Nagaland, the coal seams formed under fluvial conditions on a delta plain. On the basis of vitrinite-rich nature of coals, presence of framboidal pyrite and high organic sulphur content (in the total sulphur), association of current-bedded and ripple-marked sandstones with shale and coal, and absence of seat-earth (clay bed), Ahmed (1991b) and Ahmed *et al.* (1997) concluded that the coals in West Daranggiri Coalfield, Garo

Hills and Mawbeharkhar area, East Khasi Hills (Meghalaya) are, respectively of allochthonous origin. Where deposition took place under oscillating conditions in shallow near-shore basins (lagoons or embayments) on unstable shelf. According to Ahmed (1991a), the coal seams of Dilli-Jeypore Coalfield (Assam) were formed mostly from woody plants under shallow water and reducing conditions in neutral to weakly alkaline milieu. There were fluctuations in water table and the "coal swamp" was "dry oxygenated". Mishra and Ghosh (1996), on the basis of gelification (GI) and tissue preservation index (TPI), concluded that the Late Palaeocene and Oligocene coals were "deposited in wet forest swamps and in marshy environment." They also infer marine influence during coal formation.

Cohen (1984) and Mac Cabe (1984) observed that the deltaic model for the coal formation has been overplayed by the geologists and that the peats of deltaic environments would produce only thin seams with too much of ash or mineral matter to be of economic value. However, presence of typical mangrove, mangrove associate and back mangrove taxa, viz., *Rhizophora*, *Sonneratia*, *Avicennia*, *Nypa*, *Barringtonia*, *Calophyllum*, *Terminalia*, etc., along with several varieties of other coastal/beach taxa (Fig. 9) and dinoflagellate cysts in certain coal seams, cannot be rejected for the fear of over emphasizing similar conditions of deposition. The good quality coal seams with thickness varying between 0.5 to 18 metres testify for their economic significance.

Low amounts of clastic minerals in most of these coals [presumably produced *in situ* from the degradation of vegetal matter under alkaline milieu (Renton *et al.*, 1979)] and thick seams either devoid of or only with minor parting bands. Besides, clean to very clean nature of vitrinite macerals and presence of clay, carbonaceous clay/shale or other fine-grained sediments as seam floor and roof, wherever present, preclude the possibility of the formation of these Tertiary coals primarily from drifted vegetal matter (Raja Rao, 1981; Misra, 1992a, b).

Bright non-banded coal seams with high to very high vitrinite and poor sporinite contents (Figs 5, 6, 7) are indicative of their formation from forest vegetation (Stach *et al.*, 1982; Misra, 1992a, b). High frequency of collodetrinite and common occurrence of fungal remains in the coal seams imply the accumulation of ancient peat under subaqueous conditions. The vegetal matter appears to have been subjected to high degree of aerobic fungal and bacterial degradation in the acrotelm (aerobic upper zone of a peat) and anaerobic bacterial degradation in the catatelm (Clymo, 1987). Since syngenetic pyrite and calcite occurring together are the definite indicators of anaerobic and alkaline milieu, and the ombrogenous-oligotrophic (raised and nutrition poor) peat bogs are acidic in nature (Teichmüller, 1989; Cameron, 1989), the possibility of these coals to have formed as raised-bogs is improbable.

Instead, they appear to have originated from eutrophic peat swamps.

In Garo, Khasi and Jaintia Hills of Meghalaya, the exposures of coal seams, as published in maps (Raja Rao, 1981), are generally aligned parallel to Precambrian rocks. They occur in isolated patches of various shapes and trends with lengths ranging from approximately 1 to 7 km and width between 1 and 5 km either directly over the Precambrians or underlain by older sedimentary units (Raja Rao, 1981; map plates III, IV & VI-VIII). Besides, there are some smaller patches of coal-bearing sediments within the Precambrian rocks themselves, e.g. Balphakram and Pendengru areas in Garo Hills and northwest of Langrin Coalfield, Khasi Hills

(Raja Rao, 1981; map plates IV & VI). Here, isolated exposures of coal-bearing strata intervened by Precambrian rocks are only 1 to 2 km apart from each other. Evidently, most of these coal-bearing exposures represent original shapes of the basins. The preceding geological facts imply that peat accumulation in Meghalaya took place in estuarine back-swamps (Misra, 1992c) rather than in the back-swamps on delta plain as visualized by other workers. In a progradational deltaic setting, swamps develop away from the existing landmass not closure to it, whereas estuarine back-swamps form along and parallel to landmass and coastline, as is the case in Meghalaya. Possibly, it is because of the estuarine sedimentation set up that the dinoflagellate cysts and

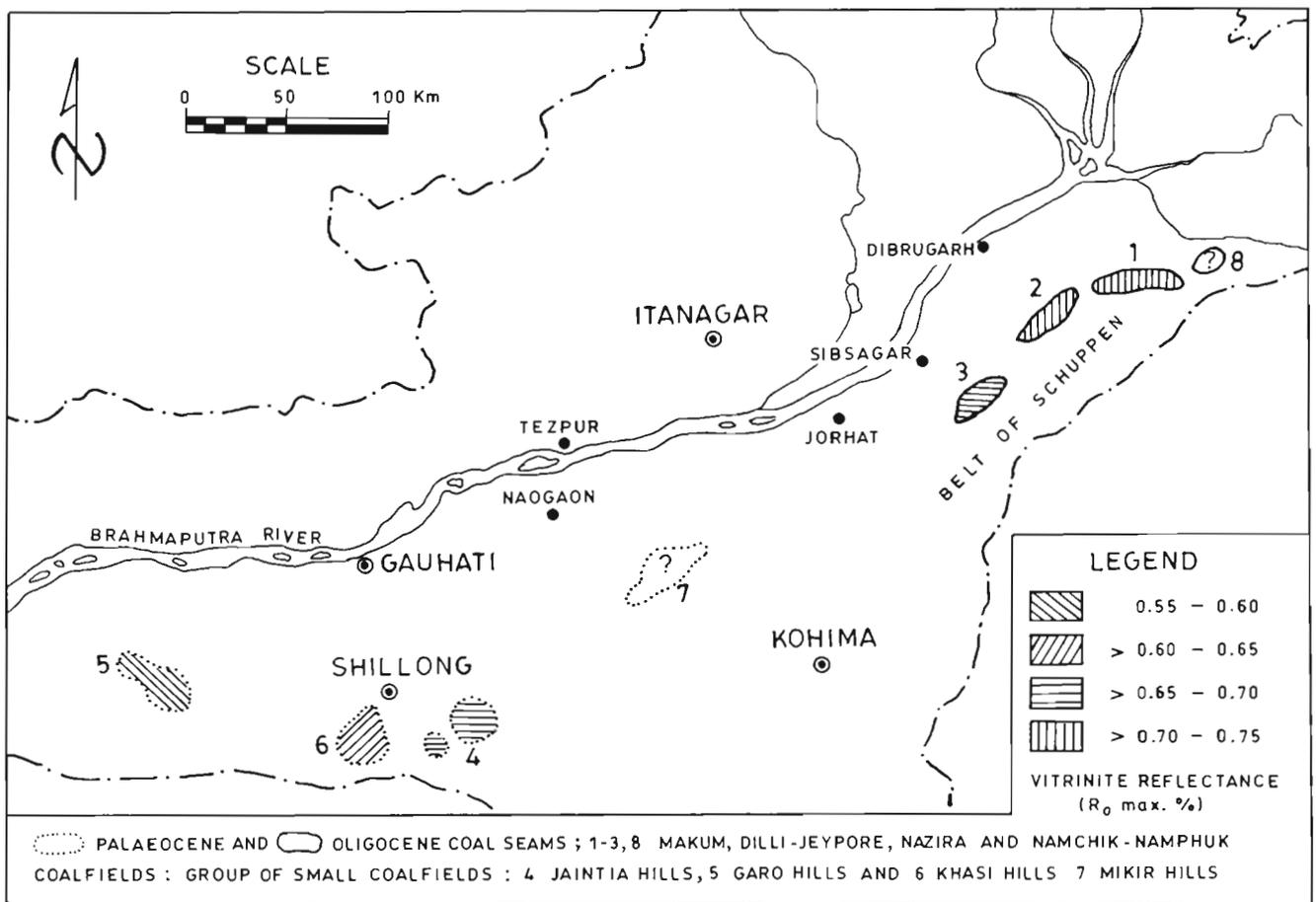


Fig. 8— Normal reflectance (R_0 max. %) trend in the Palaeocene and Oligocene coal seams of Arunachal Pradesh, Assam, Nagaland and Meghalaya (coalfield areas, especially of Meghalaya, are exaggerated for illustration) (after Misra, 1992a).

Fig. 9— List of angiospermous plant megafossils recorded from coal-bearing horizons of Assam and Meghalaya, with their living affinities. 'P' denotes pollen record, and different symbols habitat/communities.

* Mangrove plants; φ Mangrove associates; # Back mangrove plants; ° Trees /herbs /shrubs of coastal or near-shore (littoral/swampy) habitat. Data compiled from: Bande (1992); Awasthi (1974, 1984); Singh *et al.* (1975); Singh (1977); Dutta and Sah (1970); Sah and Kar (1974); Tripathi and Singh (1984); Kar and Kumar (1986); Kar (1985); Misra (1981); Mandal (1986). Bhattacharyya (1983); Ambwani (1991, 1993); Awasthi and Mehrotra (1995); Saxena *et al.* (1995) and Mehrotra (2000).

Families	Assam Makum Coalfield	Meghalaya Garo, Khasi & Jaintia Hills
Agavaceae	P ^o	
Alangiaceae	P ^{o#}	
Anacardiaceae	<i>Mangifera</i> ^o , <i>Lannea</i> ^o , <i>Parishia</i> ^o P ^{*o}	<i>Mangifera</i> ^o P ^{*o}
Annonaceae	<i>Saccopetalum</i> ^o	<i>Polyalthia</i>
Apocynaceae	<i>Alstonia</i> ^o	
Araliaceae		<i>Heteropanax</i>
Arecaceae	<i>Nypa</i> [*] P ^{*o#}	<i>Nypa</i> [*] , <i>Phoenix</i> , <i>Amesoneuron</i> P ^{*o#}
Avicenniaceae	<i>Avicennia</i> [*]	
Bombacaceae		<i>Bombax</i> P ^o
Brassicaceae		P
Burseraceae	<i>Santiria</i> ^o	<i>Bursera</i>
Chenopodiaceae		P
Clusiaceae	<i>Calophyllum</i> ^{o#} , <i>Kaya</i> ^o , <i>Mesua</i> , <i>Garcinia</i> ^o P	<i>Calophyllum</i> ^{o#} P
Combretaceae	<i>Terminalia</i> ^{#o}	<i>Terminalia</i> ^{#o} , <i>Calycopteris</i>
Droseraceae	P	P
Ericaceae	P ^o	
Euphorbiaceae	<i>Bridelia</i> ^o	P
Fabaceae	<i>Dalbergia</i> ^{#o} , <i>Entada</i> ^o P	<i>Desmodium</i> , <i>Derris</i> [#] , <i>Millettia</i> , <i>Pongamia</i> , <i>Albizia</i> , <i>Bauhinia</i> , <i>Pterocarpus</i> ^o , <i>Trachylobium</i> , <i>Sindora</i> P
Gunneraceae		P
Haloragaceae		P
Labiatae		P
Lauraceae	<i>Apollonias</i> ^o	<i>Listea</i> , <i>Phoebe</i> , <i>Neoliste</i>
Lecythidaceae	P ^{o#}	<i>Barringtonia</i> ^{o#} P ^{o#}
Lentibulariaceae		P
Liliaceae	P	P
Meliaceae	<i>Heynea</i> ^o P ^{*#o}	P ^{*#o}
Memecylaceae	<i>Memecylon</i> ^o	
Moraceae		<i>Artocarpus</i> , <i>Ficus</i>
Myricaceae		P
Myrsinaceae	P ^o	P ^o
Myristicaceae	<i>Myristica</i> ^{#o}	
Myrtaceae		<i>Syzygium</i> ^o P
Nymphaeaceae		<i>Nelumbo</i> ^o P
Nyssaceae	P	P
Oleaceae	P	<i>Osmanthus</i> ^o , <i>Ligustrum</i> , <i>Antholites</i> P
Onagraceae	P	P
Pellicieraceae		P
Polygalaceae		P
Polygonaceae		P
Potamogetonaceae		P
Proteaceae		P
Rhizophoraceae	<i>Rhizophora</i> [*] P [*]	P [*]
Rubiaceae	P [#]	P [#]
Rutaceae		<i>Atalantia</i>
Sapindaceae	<i>Nephelium</i> ^o	<i>Schleichera</i> P
Sapotaceae	P	<i>Chrysophyllum</i>
Sonneratiaceae		<i>Sonneratia</i> [*]
Sterculiaceae	<i>Pterygota</i>	<i>Sterculia</i>
Tiliaceae		<i>Grewia</i> , <i>Triumfetta</i>
Ulmaceae		<i>Trema</i> ^o

foraminifers are recovered commonly from the sediments, besides the coal seams.

In Garo Hills, the provenance was a positive landmass since the beginning of the Tura Formation, whereas in Jaintia Hills a peneplained surrounding landmass ensured the precipitation of the Lakadong Limestone Member. Later the uplift of source area accompanied by basin subsidence resulted in the deposition of the coal-bearing Lakadong Sandstone Member on Early to Middle Palaeocene sediments. Periodic high-energy sedimentation and shifting of distributary channels encroaching upon the accumulating peats may have caused temporary or local cessation of peat formation and probably also controlled the ultimate thickness of the coal seams in different localities and sections. Complete cessation of vegetal accumulation for peat formation in Meghalaya resulted with the beginning of rapid basinal subsidence due to activation of the existing tectonic lineaments, as is evident by the high-energy sedimentation (medium to coarse grained sandstones and pebble beds) above the sediments of the Tura Formation in Garo Hills and towards upper part of the Lakadong Sandstone Member in Jaintia Hills. Latter, a marine transgression in both the regions caused the deposition of fossiliferous Siju and Umlatdoh limestone members (Fig. 4).

Palaeoshore-line parallel orientation of the coal deposits in Assam and Nagaland with relatively greater areal extent than those of Meghalaya in spite of intense tectonic disturbances, including moderate to intense folding and slicing of strata along with coal seams implies the existence of lagoonal swamps (Raja Rao, 1981). Tectonically least disturbed, non-persistent and thin coal seams (<1-3 m thick), in Garo, Khasi and Jaintia hills of Meghalaya (Raja Rao, 1981), suggest peat accumulation in small isolated low lying estuarine or estuarine back-swamps caused by the encroachment of the sea on undulating Precambrian (Garo hills) or Cretaceous (Khasi and Jaintia hills) sediments, under unstable basin conditions. Thin and non-persistent coal seams occurring at close intervals (2-8 seams) also reflect frequent and relatively unstable conditions during Late Palaeocene coalforming episodes. In Assam and Nagaland, on the other hand, the basins enjoyed far more stable tectonic conditions during coal formation of Oligocene Epoch, as is evident from thick and extensive nature of the coal seams.

Association of fine-grained sediments with coal seams indicates deposition mostly from suspended-load material by sluggish low-energy channels with sediment source, quite probably from an almost peneplained source area. This condition is quite evident in Meghalaya where three limestone members occur alternating with arenaceous members including that which bears the coal seams (Raja Rao, 1981). On the preceding evidences, it has been presumed that short-lived peat swamp formations in Meghalaya were controlled by minor sea-level fluctuations caused by episodic and slightly increased rate of basin subsidence just perturbing the prevailing rate of

vegetal supply, but not significant enough to cause any apparent change in the provenance. The shortfall in vegetal supply, in certain cases, was responsible for relatively high mineral matter content in certain coal seams of Meghalaya. The fact that no drastic vegetational change has been recorded during coal formation in Meghalaya, clearly suggests that minor sea-level fluctuations did not cause extermination of the existing flora in the area. More or less similar (continuance of existing flora) conditions appear to have been there in Assam as most of the common taxa are well recorded throughout the section.

The dominance of freshwater taxa with those typical of brackish water affinity (mangrove plants) in the coal seams is not some thing unusual when considering ancient, virgin coastal and near-shore forest vegetation. Because intermixing of flora in fossil record, i.e., in swamp, is controlled by several factors, e.g., seaward distributary channels and seawater inlets in the swamps, etc. Major complications arise from the dispersal pattern of allochthonous spores and pollen. In this regard a gross analogy of the ancient peat swamps, disregarding specific details, can be made with the existing near-shore marine influenced lakes on the eastern coastal margins of India. Presumably, certain landward swamps, especially in Meghalaya, remained unaffected by marine influx for a period of time. Consequently, freshwater aquatic angiosperms (*Potamogeton*, *Nymphaea*, *Nelumbo Utricularia*, etc.) flourished in and around seasonal lakes/ponds developed over the peat surface to be recorded, occasionally, in high frequencies in the coal seams (Dutta & Sah, 1970).

Contrary to the high frequency of pteridophytic spores present in the pollen-spore assemblages, their megafossil records are rather poor. The pteridophytes are normally slender and delicate seasonal plants. As per their lifecycle strategies, they do not shed leaves and die out standing through drying and complete dehydration. Therefore, fossil remains of pteridophytic plants are generally not found preserved. The preceding facts and a general correlation between high pteridophytic content with high fungal activity and high inertinite contents in coal seam sections (Misra, 1992b) imply that the pteridophytic plants played a primary role in the formation of inertinite. Since the cell-lumens of structured inertinites, in these coals, are invariably empty, i.e., without clastic mineral fillings, it has been presumed that the pteridophytes and associated shrubby angiosperms also grew in nearby peat swamps.

The association of perhydrous vitrinite, liptodetrinite and bituminite along with biogenic pyrite and calcite is characteristic of subaquatic and sapropelic including calcium-rich coals (Stach *et al.*, 1982; Teichmüller, 1989) and the Tertiary coals of northeastern India contain high proportions of these macerals and minerals (Misra, 1992a, b). The syngenetic (biogenic) pyrite precipitation requires anaerobic bacterial growth (negative *Eh*-potential), neutral to mildly alkaline milieu (*pH* 6.5-8) and stagnant water body (Stach *et*

al., 1982). The conditions favouring pyrite precipitation are readily available near marine influenced zones in lagoons and estuaries where wave and current action is negligible (Cecil *et al.*, 1979). Under such conditions, in the presence of abundant organic matter, though acrotelm may still have aerobic influence, coalification in the catatelm proceeds by putrefaction (fermentation) with the help of anaerobic bacterial degradation instead of normal peatification or humification. Consequently, perhydrous vitrinite, bituminite and liptodetrinite macerals are produced with the enrichment of proteinaceous, fatty-lipoid and other hydrogen-rich microbial, algal and microfaunal degradational products (Stach *et al.*, 1982; Teichmüller, 1989). Similar conditions with varying degree of putrefaction influence have been visualized for the genesis of Tertiary coal seams of northeastern India (Misra, 1992a, b).

CONCLUSIONS

The Tertiary coal seams of northeastern India are generally bright non-banded in appearance, rich to very rich in vitrinite macerals along with subordinate amounts of inertinite and liptinite macerals. The vitrinite macerals are represented chiefly by collodetrinite, the vegetal degradational products. Structured vitrinite maceral, collotelinite, are occasionally predominant. Main inertinite macerals are sclerotinite (fungal remains) and inertodetrinite, besides subordinate amounts of structured inertinites— semifusinite and fusinite. Structured inertinites are especially significant in some coal seams of Garo and Jaintia Hills, Meghalaya. Main minerals associated with the coal seams are syngenetic pyrite and calcite, and also minor to moderate amounts of clay and quartz (argillaceous matter). The latter two minerals are only occasionally common in certain coal seams of Meghalaya.

Under fluorescence mode, the coals are characterized by high to very high amount of fluorescing macerals comprising chiefly perhydrous vitrinite, liptodetrinite and resinite. Maceral bituminite is intimately associated commonly with the former two macerals. Maceral resinite is quite significant in certain coal seams of Assam and Meghalaya. Other macerals of the liptinite group—cutinite, suberinite, sporinite, exsudatinite, fluorinite and alginite, in order of decreasing abundance, are present in subordinate amounts. Alginite (*Botryococcus*), present in almost all the coal seams is especially common in the coals of Garo Hills.

The coal deposits of northeastern India were formed primarily from the accumulations of hypo-autochthonous to autochthonous deciduous angiospermous forest vegetation comprising inland, coastal, beach, back mangrove, mangrove associate and mangrove plant communities, besides moisture and shade loving angiospermous herbs and shrubs as well as pteridophytes growing under humid tropical climate. The peat swamps were eutrophic in nature. Occurrence of foraminifera,

dinoflagellates and phytoplanktons, in Garo and Jaintia Hills, Meghalaya, indicate definite influence of marine or brackish water.

The vegetal matter accumulating under subaqueous conditions in lagoon or near shore back-swamps in brackish water milieu in Assam and Nagaland and in small isolated estuarine swamps in Meghalaya experienced high aerobic biodegradation (fungal and bacterial) in the acrotelm and extensive anaerobic bacterial degradation in the catatelm. Occasionally small freshwater lakes/ponds formed on the peat surface facilitated the growth of aquatic and water-edge plants. Shrubby pteridophytes and angiosperms growing in the vicinity of the peat swamps were responsible for the major part of the structured and detrital inertinites. However, occasional cindering of peat surfaces, especially in the coal seams of Meghalaya, presumably produced more structured inertinites. The variations in the seam thickness and rank of the coal seams appear to have been controlled by the then existing tectonic and geothermal gradients in different areas.

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