Jour. Geol. Soc. India (2022) 98:1697-1707
https://doi.org/10.1007/s12594-022-2240-6

ORIGINAL ARTICLE

Tertiary Himalayan Coal-bearing Sequences of India: A Reappraisal of their Evolutionary Consequences

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Received: 18 April 2022 / Revised form Accepted: 26 May 2022

ABSTRACT

This paper presents a comprehensive account on the evolution of the Tertiary Himalaya coals of India and their various attributes. The coal bearing sequences in Himalaya have formed in two different geotectonic settings, first under foreland basin (Oligocene coals of Assam, Nagaland and Arunachal Pradesh of northeastern India) and second under Platform basin (Eocene coals of Meghalaya of north-eastern India) conditions. The Jammu coals of northwest India developed in the late Paleocene in the western Himalayan foreland basin. A sea transgression inundated the Jammu area which gave rise to forest swamp and Jammu coals eventually formed under tropical humid climatic conditions in the tropical climatic belt of northern hemisphere. In northeastern India, the Oligocene coals have shown more maturity than the Eocene coals and have relatively high carbon content and they also have developed caking characters in many coalfields. This may be because the Eocene coal developed in the tropical climatic belt when the northern part of the northeast India was still in the southern hemisphere and the Oligocene coal evolved when the northern part of the northeast India was in the northern hemisphere and the collision during the Oligocene in this part improved the maturity of Oligocene coal due to Himalayan orogeny. The Himalayan coals are exceedingly rich in vitrinite with variable quantities of liptinite and inertinite macerals. Dominance of typical Tertiary angiospermic floral assemblage in the Himalayan coals is well indicated by the occurrence of single, double and triple celled telutospores.

INTRODUCTION

The Tertiary coal and lignite bearing sequences of India occur in the region far away from the main coal producing Gondwana belt of the country. This is the main reason they are being given more impetus during last few decades. These deposits, however, have been studied individually in some detail by a number of geoscientists. The current study is an attempt to present a comprehensive account focusing the evolutionary consequences and development of coal bearing sequences of the entire stretch of Himalaya occupying the Indian Territory.

The coal deposits of the Upper Assam, Arunachal Pradesh and Nagaland region developed in foreland basins and are located along a narrow linear belt along the margins of the Naga Patkoi range (Biswas et al., 1993; Biswas, 1998). The main coal resources of this belt include the coalfields of Makum and Dilli-Jeypore (Upper Assam), Namchik-Namphuk (Arunachal Pradesh) and Borjan (Nagaland). While the coal bearing sequences developed in Platform basin of Northeast India occur in Meghalaya and are located in Garo hill (West Daranggiri and Siju coalfields) and Khasi hill (Mawlong-Shella and Langrin coalfields). The coalfields of Bapung, Cherrapunji and Laitryangew are the minor ones.

The coal bearing sequences of western Himalaya occur in Sub-Himalayan zone along a linear belt. Jammu coal deposits occur in lower part of Subathu Formation of this belt and are reported from Kalakot, Metka and Mahogala. Coal occurrences have also been reported from Ladda (Jangalgali), Chinkah, Chakkar, Gantha-Thangrote-Khabar-Bhainala, Megal, Kura, Lodhra, Dhandli and Dhansal-Sewaklot (Prakash, 1992). These coal occurrences are associated with marine sediments. First report of coal occurrence in Jammu region came from Medlicott (1876) and subsequently contributions were made by La Touche (1888), Simpson (1904), Wright (1906), Middlemiss (1928, 1929), Fox (1934), Gee (1945), Srivastava (1972) and Srivastava and Nanda (1976). Prakash (1992) has provided a detailed account on the Tertiary and Permian coal deposits of Himalaya. Two coal bearing horizons have been identified in Jammu area, lower horizon and upper horizon. Pareek (1983) has described that the coal of lower horizon are hard and compact with vitreous lustre while coal of upper horizon is relatively fragile in nature. Lignite occurrences have been reported in the northeastern flanks of Pir Panjal range in Kashmir valley which covers part of Baramula, Srinagar and Anantnag districts (Tripathi, 1987). First record of lignite occurrence was, however, provided by Middlemiss (1924) in Nichahom area and Shaliganga river section. These lignites are associated with Karewa Group which is Plio-Pleistocene in age and occur as lower Karewa and upper Karewa; the lower Karewa bears lignite seams. Tripathi (1987) has reported the existence of eleven seams in Nichahom area in his review work, while the petrographic observations are given by Pareek (1976).

GEOLOGICAL SETTING OF THE COAL BEARING SEQUENCES

Geology of the Foreland Basin

The coal bearing horizons in northeastern India evolved under Foreland basin and Platform basin having two distinct geotectonic

Table 1. Geological succession of coalfields of Nagaland, Assam & Arunachal Pradesh showing foreland basin (modified after Raja Rao, 1981)

Age	Group & Formation	Thickness	Rock Types
Pliocene	Dihing Group	1800 m	Mostly pebbly sandstone with thin greyish clay beds
Unconformity			
Mio-Pliocene	Namsang Formation	800 m	Fine to coarse grained sandstone with bands of clay
Unconformity			
Miocene	Tipam Group		
	(i) Girujan Clay	1800 m	Mottled clay with greyish soft sandstone
	(ii) Tipam Sandstone	2300 m	Ferruginous, fine to coarse grained micaceous to felspathic sandstone
Unconformity			
Oligocene	Barail Group		
	(i) Tikak Parbat Formation	600 m	Greyish to yellowish white sandstone, sandy shale, coal seams.
	(ii) Baragolai Formation	3500 m	Greyish to bluish grey or yellowish red mudstone, shale, sandstone, cabonaceous shale and thin coal seam.
	(iii) Naogaon Formation	2200 m	Compact, fine grained, dark grey sandstone with bands of splintery shale.
Eocene	Disang Group	3000 m	Splintery dark grey shales and thin sandstone interbands.

settings. The stratigraphic succession (after Raja Rao, 1981) of the sedimentary formations containing the coalfields of foreland basin is given in Table 1. The geological map of northeastern India and location of coalfields are shown in Fig.1. The stratigraphy, tectonic settings and structures of these coalfields are provided in detail by the Geological Survey of India (GSI, 1974, 1981, 1989, 1994). The coal bearing horizons occur in the rocks of Barail Group of Oligocene age which has a cumulative thickness of over 6km comprising of Tikak Parbat Formation (TPF) underlain by Bargolai Formation (BF) and Naogaon Formation (NF) at the bottom.TPF bears the main coal seams while BF has few thin seams only. The Barail Group is underlain by Disang Group which conformably lies below Naogaon Formation. The rocks of Naogaon Formation are developed in Makum and Dilli-Jeypore coalfields of Upper Assam, Borjan coalfield of Nagaland and Namchik-Namphuk coalfield of Arunachal Pradesh. Barail Group is unconformably overlain by Tipam Group of rocks which are also developed in Dilli-Jeypore, Namchik-Namphuk and Borjan coalfield areas; and they crop out as hills. The Tipam Group of rocks is unconformably overlain by Namsang Formation which in turn is unconformably overlain by Dihing Group of rocks.

Geology of the Platform Plateau Area

The platform areas are developed in the Shillong plateau of Meghalaya and the coal deposits of Eocene age were deposited in its peripheral margins. Shillong plateau is considered to be an extension of the Precambrian shield of India. It is further believed that this shield got uplifted to form a horst structure sometime during Cretaceous period and its peneplanation eventually led to the formation of plateau. Subsequently, the coal bearing sequences developed in peripheral regions of the plateau. The sediments deposited on shallow marine

Table 2. Geological succession of coalfields of Meghalaya (modified after Raja Rao, 1981)

Age	Formation & Member	Thickness (in m)	Lithology	
Late Eocene	Kopili	-	Ferruginous Sandstone, grey siltstone and shale	
Middle Eocene	Sylhet limestone: Prang limestone/Siju limestone	60-150	Bluish massive to thinly bedded limestone with marly interbands	
Early Eocene	Nurpuh sandstone	15-26	TURA SANDSTONE	Coarse to medium grained ferruginous sandstone with bands of sandy limestone
Early Eocene	Umlatdoh limestone	70-110	TURA SANDSTONE	Grey to pinkish grey limestone, sandy limestone and calcareous sandstone
Early Eocene to Paleocene	Lakadong sandstone	35-250	TURA SANDSTONE	Predominantly buff coloured medium grained arkosic sandstone with thin grey and carbonaceous shale and coal seams.
Early Eocene to Paleocene	Lakadong limestone	25-60	Grey to brownish grey limestone, siliceous limestone	
Early Eocene to Paleocene	Therria sandstone	20-80	Buff coloured medium to coarse grained arkosic sandstone with thin bands of pyritic rich silty sandstone	
Late Cretaceous (Danian)	Langpar	10-50	Buff coloured calcareous-ferruginous sandstones, earthy limestones etc.	
Late Cretaceous (Maestrichtian)	Mahadek	160-335	Massive coarse grained gluconitic sandstones containing dark grey shales and calcareous horizons	
Jurassic to Early Creataceous	Sylhet Trap	250-400	Aa and pahoehoe type basalts	

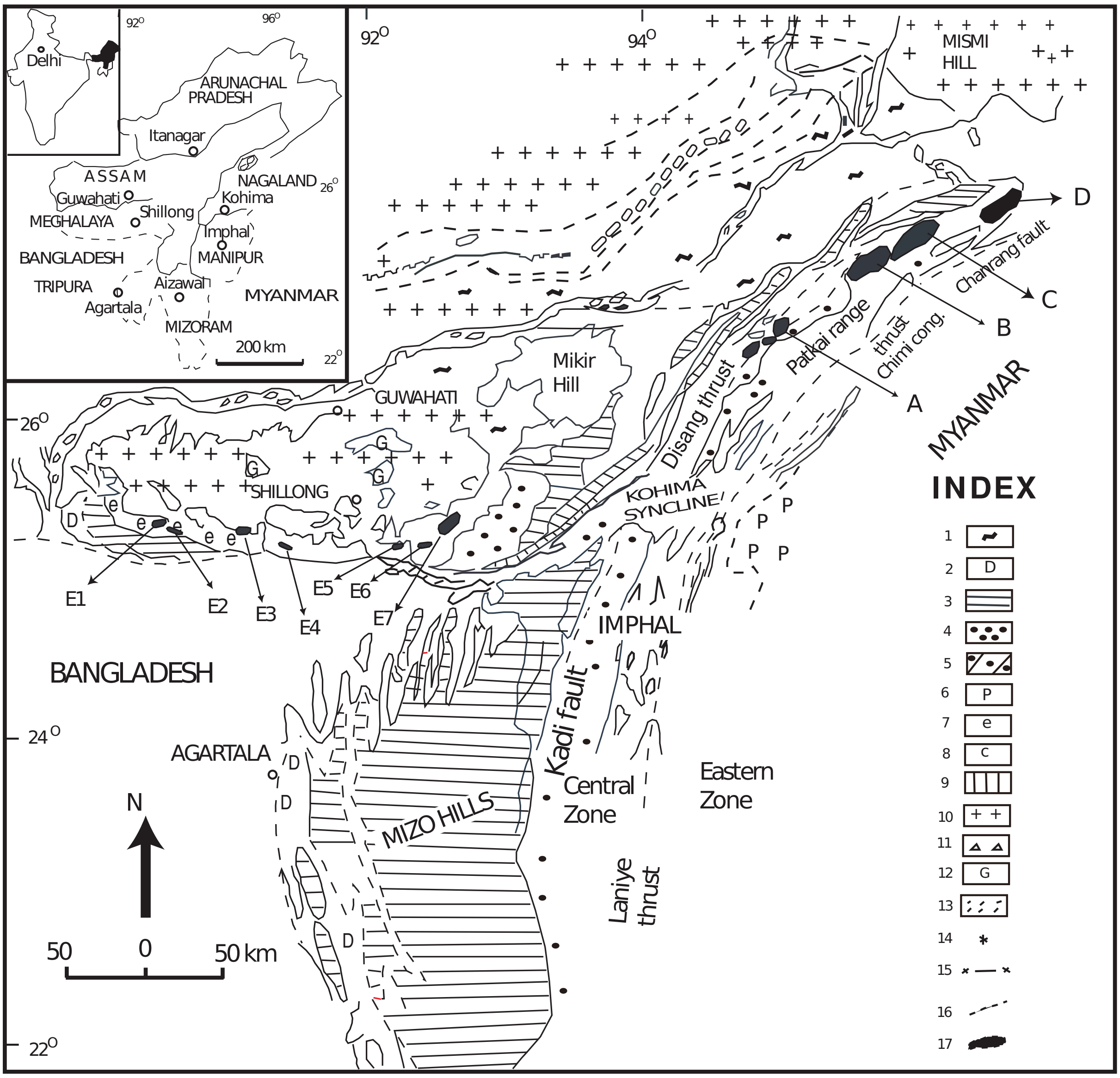

Fig.1. Geological map and coalfield location of north-eastern India. 1-Alluvium, 2-Dihing and Dupi Tila Group, 3-Tipam and Surma Group, 4. Barail Group, 5-Undifferentiated Sandstone Group 6-Pondaungs and Younger sediment 7-Jaintia and Disang Group 8-Longpar and Mahadek Formation, 9-Lower Gondwana System 10-Metamorphic and Igneous rocks 11-Granite 12-Serpentine intrusion, 13-Basalt, 14-Salt springs 15-Line of demarcation between high and low intensity foldings, 16-Faults, 17-Coalfields (A- Borjan coalfield, B- Dilli-Jeypore coalfield, C-Makum coalfield, D- Namchik-Namphuk coalfield, E1- West Daranggiri, E2 - Siju, E3 - Langrin, E4 - Mawlong - Shella, E5-Cherrapunji, E6 - Laitryngew, E7- Bapung).

shelf which extended as an embayment and there is lateral variation of the lithofacies which consequently led to the diverse types of lithostratigraphic units (GSI, 1981, 1989). The stratigraphic succession of sedimentary fromations in Meghalaya is provided in Table 2. The coal bearing horizons of Garo hills occur in Tura Sandstone Formation of Jaintia Group while that of Khasi and Jaintia hills, the coal bearing horizons occur in Lakadong Sandstone Formation and lower Sylhet Sandstone Formation.

Geology of the Jammu Coalfield

The outcrops in and around Jammu coalfield belong to Subathu Formation and Murree Group which vary in age from late Paleocene to early Eocene and late Eocene to early Miocene respectively. They are unconformably underlain by the Precambrian basement as shown in the stratigraphic succession (Table 3). Coal bearing sequences are restrained in lower part of the Subathu Formation where they occur as lower coal measures and upper coal measures along with carbonaceous shales, and limestones alternating with green shales containing foraminifera lie at middle and upper parts of the Subathu Formation, while its top is comprised of purple shale and marl containing vertebrate fossils (Singh, 2012). Murree Group lies over the Subathu Formation and comprise of cross-bedded and planar-bedded sandstones possessing tidal bundles interbedded with purple shales, siltstones and calcretes (Singh and Singh, 1995a). Kalakot, Metka and Mahogala are the main coalfields here and they occur in detached outcrops (Fig. 2).

RESULT

Petrographic and Geochemical Attributes of Himalayan Coals

Coals of Foreland Basin of Northeast India

Dark grey to grey vitrinite bands of variable thickness occur in the coals of the foreland basin of the northeast Himalaya. Telinite is rare among the macerals of this group but shows well preserved cell structures. Both, oval and slit-like cell lumens are seen which are frequently filled-up with gelinite, resinite and mineral matter. Wide

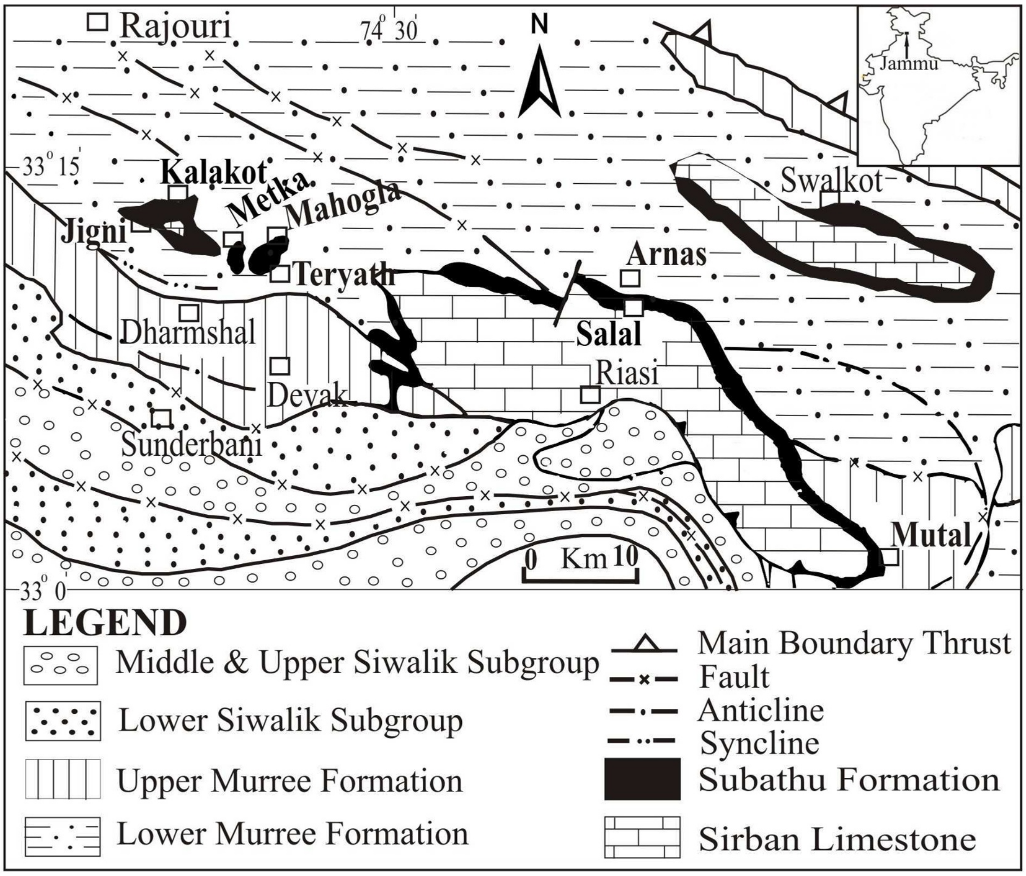

Fig. 2. Geological map of the Jammu area, Jammu and Kashmir state, India showing locations of the important coalfields.

bands of collotelinite occur having cracks and fissures filled with pyrite, calcareous material and argillaceous mineral matter. The fissures are occasionally filled with macerals like exsudatinite and fluorinite, chiefly in the coals of Makum coalfield of Assam (Singh et al., 2013). Oval to round isolated bodies of corpogelinite are common in these coals. In some patches they show high reflectance due to oxidation. Round to oval discrete or oval bodies of phlobaphinite occur individually or as infillings of cell lumens. Collodetrinite occurs as mottled ground mass and has lower reflectance than the associated collotelinite. Pseudovitrinite has a transitional character between semifusinite and collotelinite and it is commonly observed in the Namchik-Namphuk coals of Arunachal Pradesh and Borjan coals of Nagaland. Dark vitrinite (saprovitrinite) is also observed in these coals which are characterized by low reflectance and brown to brownish-yellow fluorescence. The comparative distribution of macerals in the Assam, Nagaland and Arunachal Pradesh coals of foreland basin is shown in Figs. 3a, b & c and photomicrographs of selected macerals are presented in Fig.4. Singh et al. (2013) have observed that among the coalfields

Table 3. Geological succession of coalfields of Jammu Coalfield

Age	Group/Formation		Lithology
Sub-Recent to Recent	Alluvium		Soil, scree, terrace deposits and morains
Late Eocene to Early Miocene	Murree Group		Hard, grey, massive sandstone interbedded with dark red or purple shale containing various calcareous layers. These shales in places become highly ferruginous and concretionary
Late Paleocene to lower Early Eocene		Nummulitic Limestone	Siliceous, unfossiliferous limestone, limestones with lamellibranchia, olive-grey shales, lenses of carbonaceous shales with sulfur and nummulitic limestones at the base.
	Subathu Group	Upper Coal Measures	Grey shales and carbonaceous shales. Upper coal measures containing one or two thin coal seams.
		Lower Coal Measures	Grey shales, carbonaceous shales with limestone bands, coal measures containing one coal seam.
Overlap Late Paleocene		Bauxite Formation	
Unconformity			
Precambrian		Sirban Limestone	Dolomitic limestone, in places cherty with stromatolites. Quartzitic beds in places brecciated and silicified (Unfossiliferous)

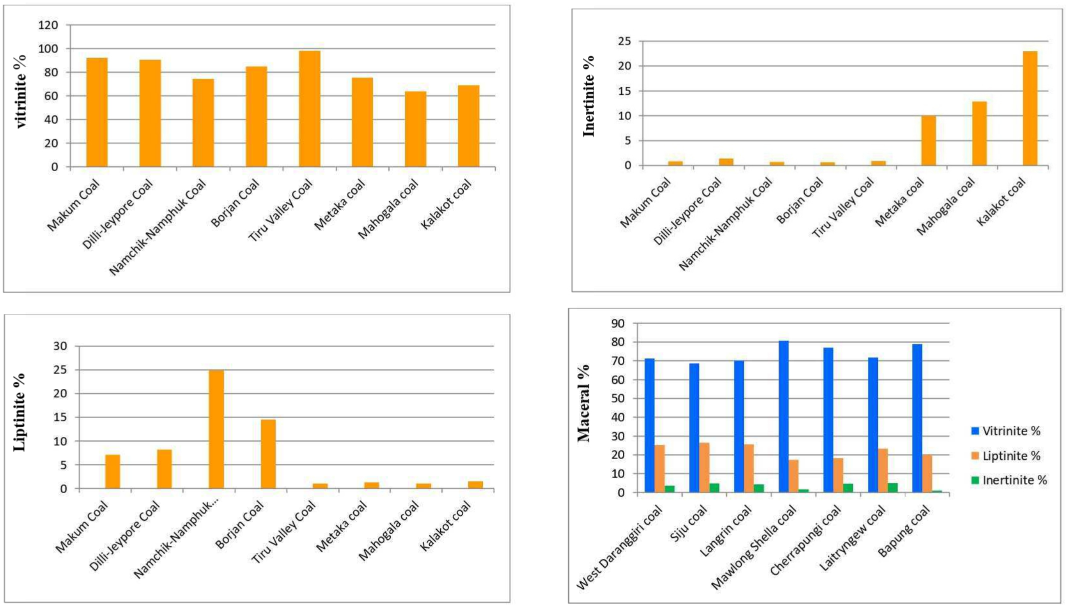

Fig. 3. (a) Distribution of mean Vitrinite (mmf basis) in the Foreland basin coals of Assam (Makum and Dilli-Jeypore coal), Arunachal (Namchik-Namphuk coal) and Nagaland (Borjan and Tiru Valley coal), Jammu (Metka and Mahogala coal). **(b)** Distribution of mean Liptinite (mmf basis) in the Foreland basin coals of Assam (Makum and Dilli-Jeypore coal), Arunachal (Namchik-Namphuk coal) and Nagaland (Borjan and Tiru Valley coal), Jammu (Metka and Mahogala coal). **(c)** Distribution of mean Inertinite (mmf basis) in the Foreland basin coals of Assam (Makum and Dilli-Jeypore coal), Arunachal (Namchik-Namphuk coal) and Nagaland (Borjan and Tiru Valley coal), Jammu (Metka and Mahogala coal). **(d)** Distribution of mean Vitrinite, Liptinite and Inertinite macerals (mmf basis) in the Platform basin coals of Meghalaya (West Daranggiri, Siju, Langrin, Mawlong-Shella, Cherrapunji, Laitryngew, Bapung coals).

of the foreland basin, the Makum coals of upper Assam are significantly rich in vitrinite which ranges from 81.7 to 94.7 vol % (84.6 to 96.6 vol % mmf basis) while in the Dilli-Jeypore coals of upper Assam, it varies from 71.4 to 95.2 vol % (81.7 to 95.8 vol % mmf basis). In the Namchik-Namphuk coals of Arunachal Pradesh the vitrinite content ranges from 41.3 to 77.7 vol % (68.8 to 84.4 vol % mmf basis) and in the Borjan coals of Nagaland it ranges from 53.2 to 81.4 vol % (80.6 to 89.7 vol % mmf basis).

Liptinite has its highest content in the Namchik-Namphuk coals of Arunachal Pradesh followed successively by Borjan coals of Nagaland, and Makum and Dilli-Jeypore coals of Assam. Liptinite ranges from 13.9 to 32.9 vol % (15.9 to 35.4 vol % mmf basis) in Namchik-Namphuk coals, while in Borjan coals it varies from 8.5 to 16.1 vol % (9.3 to 21.8 vol % mmf basis). In Makum coals, the liptinite content ranges from 2.6 to 14.4 vol % (2.7 to 14.9 vol % mmf basis). The liptinite content in the Dilli-Jeypore coals varies from 2.9 to 12.7 vol % (3.1 to 15.7 vol % mmf basis). Sporinite, cutinite, resinite, suberinite, alginite and liptodetrinite represent the structured liptinite macerals in these coals. Both microspores and megaspores occur as elongated, disc and spindle shaped bodies. Sporangium with numerous microspores is also observed. Cutinite shows thread like bodies having serrated margin. Oval to spherical resinite bodies of variable sizes commonly occur. Sometimes, large and elongated resin bodies also occur in these coals. Oxidation rims and cracks have also been noticed in resinites. Suberinite is a common maceral of the Tertiary coals and occurs as laminated band in clarite having variable thickness. Alginite is more common in Namchik-Namphuk coals and both Pila and Reinchia types occur. Bituminite, fluorinite and exsudatinite are unstructured macerals of liptinite present in these coals (Singh et al., 2013). Bituminite is amorphous and sometimes lamellar in forms and depicts a characteristic orange to brown fluorescence while exsudatinite occurs as fillings in the cracks and fissures within collotelinite. Fluorinite is rare and looks dark grey, elongated to lensoid body under white reflected light but has a greenish yellow to brilliant yellow fluorescence colour.

The concentration of inertinites in the Dilli-Jeypore coals varies from 0.1 to 3.1 vol % (0.1 to 3.3 vol % mmf basis) while in the Makum coals it varies from 0.4 to 2.2 vol % (0.4 to 3.3 vol % mmf basis). The Namchik-Namphuk coals have inertinite content only upto 1.4 vol % (nil to 1.5 vol % mmf basis) while it varies from nil to 1.3 vol % (nil to 1.6 vol % mmf basis) in the Borjan coals (Singh et al., 2013).

Funginite is the chief contributor among the inertinite macerals and occurs as oval or round bodies in the ground mass of collotelinite. Singh et al. (2013) have reported multi celled sclerotium (Sclerotites brandanianus) in these coals and the vesicles of multi cellular sclerotium have mineral matter fillings. Teleuto spores with single, double and triple cells are common and so are the fungal spores with well preserved cell structure. Inertodetrinite is seen in the coals of Dilli-Jeypore coalfield and appears to be derived from crushing of teleuto spores. Fusinite has a rare occurrence but it has preserved cell structure and the cell lumens are filled with mineral matter. Semifusinite has been observed only in Dilli-Jeypore coals. Round to oval shaped bodies of macrinite has been recorded in Makum and Dilli-Jeypore coals while fine micrinite particles occur in the form of lenses.

Clay minerals, carbonates, and sulphides have been observed in these coals. Clay minerals form a ground mass and at places they occupy the cracks, fissures, and cleats. Sulfide is mainly represented by pyrite which occurs as cavity fillings, cracks and fissure infillings, massive replacement, discrete grains, disseminations, and also as framboids. The carbonates occur as ground mass, strings and fissure fillings.

Though the Eocene and Oligocene coals of NE India have close similarity chemically yet the Oligocene coals have attained relatively more maturity and therefore, have higher carbon content on an average as revealed by Mishra and Ghosh (1996). Thermally these coals are matured to high volatile bituminous rank. Some coal samples have shown the development of caking properties. Accordingly, Makum coals of Assam and Namchik-Namphuk coals of Arunachal Pradesh have shown caking property whereas the Oligocene coals of Dilli-Jeypore, Borjan coals of Nagaland are non-caking in nature. Tiru valley

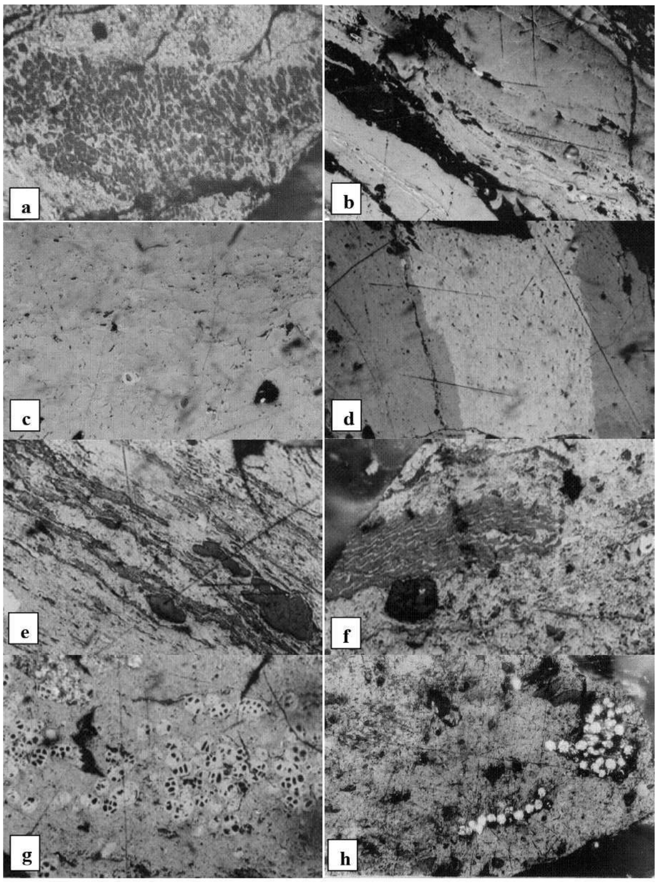

Fig 4. Photomicrographs of macerals: **a**-Telinite with resinite filling the cell lumens. Band is characterized as clarite (Makum coalfield); **b**-Argillaceous mineral matter occurring as layers in collotelinite. Band is characterized as carbominerite (Dilli-Jeypore coalfield); **c**- Thick band of telovitrinite (Makum coalfield); **d**-Transition of vitrinite to inertinite (Dilli-Jeypore coalfield); **e**-Sporinite and resinite in collotelinite. Band is characterized as clarite (Makum coalfield); **f**-Suberinite, cutinite and resinite in collodetrinitic ground mass. Band is characterized as clarite (Makum coalfield); **g**-Multi celled teleutospore in collotelinite (Makum coalfield); **h**-Framboidal pyrite intergrown with collotelinite. Band is characterized as carbopyrite (Namchik-Namphuk coalfield).

coals of Nagaland were studied by Singh et al. (2012a). They have shown that these coals are also exceedingly rich in vitrinite content (95 – 100 % mmf basis) while the other macerals are negligible. Liptinite varies from <1 % to 3 % (mmf basis) and inertinite from <1 % to 2 % (mmf basis).Their visible mineral matter content occurs in variable amount. They have further noticed that chemically they are perhydrous in nature and contain elevated amount of sulfur (5 – 11 %). The distribution of sulfur components in Tertiary coals of Assam have also been attempted by researchers. Geochemistry and nano-mineralogical studies of medium sulfur coal samples of Assam have been carried out by Saikia et al. (2014) while a multi-analytical study on sulfur components in some sulfur-rich Assam coals have been performed by Choudhury et al. (2016).

Coals of Platform Basin of Northeast India (Meghalaya Coals)

Petrographic and chemical components of Meghalayan coals are studied by a number of workers on local scale and contributions are made by Goswamy (1985), Ahmed and Bharali (1985), Singh (1989), Mishra (1992), Chandra and Behra (1992), Ahmed and Rahim (1996), Mishra and Ghosh (1996) and Rajarathnam et al. (1996). Subsequently, Singh and Singh (2000) made a detailed study on petrographic and geochemical characteristics of these coals. The comparative distribution of macerals in the Meghalaya coals of Platform basin is shown in Fig. 3d. Meghalaya coals are petrographically rich in vitrinite with subordinated concentration of liptinite and inertinite. The mineral matter content is moderately high (Singh and Singh, 2000). Vitrinite varies from 45.0 to 92.9%. Collotelinite is the chief constituent of vitrinite accounting for nearly 95% of it followed successively by corpogelinite, collodetrinite and gelinite. Telinite rarely occurs in Meghalaya coals but their cell lumens are often filled with resinite, gelinite or phlobaphinite. Singh and Singh (2000) have observed phlobaphinite as infillings in the telinite in Langrin coals. In general the vitrinite of Garo hill coals is darker in color compared to the vitrinite of Khasi hill coals. The mineral matter generally occupies the cracks, fissures or cavities. At a few places the collotelinite is converted into pseudovitrinite showing slightly higher reflectance than the surrounding collotelinite (Singh and Singh, 2000). Similarly dark vitrinite has also been noticed which is characterized by darker color and relatively low reflectance than the vitrinite reflectance of same coal. The dark vitrinite is further characterized by orange to brown fluorescence due to impregnation by bituminous substances. The liptinites in the Meghalayan coals include sporinite (both microspores and megaspores), cutinite (commonly tenuicutinite), resinite, suberinite, alginate and liptodetrinite. The resinite, under fluorescent light, shows brilliant yellow to yellowish brown color and ranges in size from 0.06 to 84 mm. Suberinite occurs as bands of variable thickness. Both *Pila* and *Reinschia* algae occur in these coals but are more common in the Garo hill coals. They show brilliant yellow fluorescent color. Singh and Singh (2000) also observed bituminite, fluorinite and exsudatinite. The total liptinite ranges from 6.5 to 53.1 %. Though inertinite occurs in small concentration but all the macerals of this group occur in Meghalayan coals. Some fusinite bands show bogen and sieve-structure. While the former occurs as collapsed empty cell lumens due to compression, the latter depicts uncompressed cell lumens infilled with mineral matter. Funginite is a frequently occurring inertinite maceral in these coals which is oval to elliptical in shape. Fungal spores or telutospores having single, double, triple and multi celled features frequently occur. The inertinite group of macerals ranges from 0.0 to 13.8 %. Mineral matter in form of clay carbonates and sulphides occur in appreciable amount. Clay dominates over the others and occurs as groundmass, and also as infillings in cracks, fissures and cleats. Several forms of pyrite are seen to occur like massive replacement, fissure fillings, blebs, discrete grains, disseminated particles and framboidal bodies while carbonate occurs as groundmass and stringers, and also in fissures.

Northwest Himalayan Coals

The coals of NW Himalaya are rich in vitrinite while inertinite and liptinite occur in subordinated amount. They have variable concentration of mineral matter but their sulphide content is relatively higher when compared with the Gondwana coals because of marine influence (Singh and Singh 1995).The chemical constituents of Jammu coals as determined by Pareek (1983) reveals that these coals have a low moisture, volatile matter, ash yield and high fixed carbon content; they are low volatile bituminous to semi anthracite in rank.

The comparative distribution of macerals in the Jammu coals is shown in figures 3a, b & c. In all the three coalfields viz. Kalakot, Metka and Mahogala, the coals are dominantly rich in vitrinite which varies (in mmf basis) from 67.1-86.2% in Kalakot, from 84-93.1% in Metka and from 80.8-92.2 % in Mahogala (Singh and Singh, 1995b, 1996a; Singh et al. 2009). This group is mainly contributed by telovitrinite subgroup. Inertinite is the second in dominance which varies from 12.8-31.5% in Kalakot, from 5.8-14.8% in Metka and from7-18.7% in Mahogala coals on mmf basis. These coals, however, have very low liptinite content which varies from 0.6-2.3% in Kalakot, from 0.7-2.1% in Metka and from 0.3-2.5% in Mahogala coals (mmf basis). The mineral matter is moderate in amount with an average of 13.3% in Kalakot, 15.5% in Metka and 25.6% in Mahogala (Singh and Singh, 1995b). These coals have a low moisture content (<2%) while ash yield is moderate (~17-20%). However, they are enriched in fixed carbon (82-83% on daf basis) and their elemental carbon is very high (90-92% on daf basis) (Singh and Singh, 1996).

DISCUSSION

Paleodepositional Environment of Tertiary Himalayan Basins of India

Understanding the peat forming environment has always been a challenging one because of the complexity of the processes involved during the period of peat growth (Dai et al., 2019). It is further modified by the external sedimentary environment and subsequent alterations. Peat accumulation may take place in coastal-low lands or it may have fresh-water mire (Diessel, 1992). The coastal peats may grade into both, sometimes affected by tidal influence and may also get fresh water terrestrial input. Coal petrography has widely been used to decipher the paleodepositional environment of the paleomires. Plants are very sensitive and react to the changing environmental conditions which are also recorded in the petrographic study (Teichmuller and Teichmuller, 1975; Styan and Bustin, 1983; Singh and Singh, 1996). Comprehensive account is provided by Tailor et al. (1998), Suárez-Ruiz et al. (2012) and Suárez-RuizJohn Crelling (2008). Several petrography based facies models are being used by researchers to understand the paleodepositional environments (Singh and Singh 1996b, Singh et al., 2003, 2010a,b, 2011, 2012a,b,c, 2014, 2016, 2017a, b, c, d, 2019; Cohen et al., 1987; Hawke et al., 1999; Naik et al., 2016; Rajak et al., 2019).

Evolution of Foredeep Coal Bearing Sequences

Biswas et al. (1993) believe that the coal bearing sequences of Assam, Arunachal and Nagaland were formed in the foredeep which evolved as a result of drifting of Indian plate towards the northeast during Cretaceous period. This was followed by collision of Indian plate with Burmese plate and subduction at the Indian plate margin. This movement resulted into the development of foredeep which is tectonically active and rapidly subsiding basin. Consequently, a number of complex thrusts and folds came into existence.

Oligocene period is marked by the existence of brackish water condition and stratigraphic succession of Barail Group developed. The basin suffered uplifting during Baragolai and Tikak Parbat sedimentation followed by shallowing of the basin which transformed the larger part of upper Assam into land area. Gradually a prograding delta complex emerged as a result of sea regression. Soon back water swamps and lagoons began to develop. Teichmuller and Teichmuller (1975) believed that the Tertiary swamps had dominance of angiospermic plants worldover and at the same time the Tertiary flora was diverse. Venkatchala et al. (1988) reported pollen grains of Sonneratia, Barringtonia and Rhizophora in addition to coastal and terrestrial angiosperms from the Paleocene and Oligocene sequences of Upper Assam region. Resins commonly occur in these coals which indicate their derivation from conifers grown in temperate conditions. Some studies have used petrography based models to decipher paleoenvironmental conditions. Coals with rich vitrinite content and a low semifusinite ratio indicate their development in foreland basin (Singh et al., 2013). Further, high gelification and tissue preservation indices of these coals favour the peat growth in telmatic condition under prolong wet environment (Fig 5). Similar observations were also made by Mishra and Ghosh (1996) who noticed the evidence of forest swamps and marshy environment. The ground water and vegetation indices of these coals are indicative of bog forest developed

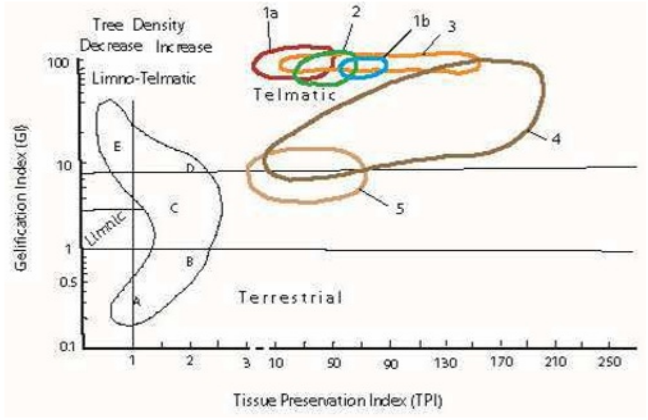

Fig. 5. Facies diagram of Himalayan coal bearing sequences as revealed from Gelification and Tissue Preservation Indices and their relation with the depositional setting and mire (after Diessel, 1986). A - Dry Forest Swamp, B - coal deposited in piedmont swamp, C - coal deposited in upper delta plain, D - wet forest swamp, E - coal deposited in lower delta plain; 1a - Borjan coal of Nagaland, 1b - Tiru valley coal of Nagaland, 2 - Namchik-Namphuk coal of Arunachal Pradesh, 3 - Makum & Dilli-Jeypore coal of Assam, 4 - Meghalayan coal, 5 - Jammu coal (1a, 2, & 3 data replotted from Singh et al., 2013; 1b data replotted from Singh et al., 2012; 4 data replotted from Singh and Singh, 2000; 5 data replotted from Singh and Singh, 1995)

in mesotrophic to ombrotrophic hydrological conditions (Singh et al., 2013). While working on the Tiru valley coals of Nagaland, Singh et al. (2012a) observed variable clastic mineral content which relates to water influx in the basin especially at the time of flooding. Thus, water table kept fluctuating throughout the period of peat growth. Their study also indicates wet-forest having intermittent moderate to high flooding of the paleomires of foreland basin. Sulphur rich content of these coals reveals their association with brackish water or marine sediments.

Evolution of Meghalayan Coals of Platform Basin

The coal facies development in Meghalaya is typical of platform areas. Here Lakadong Formation is the coal bearing one which is formed in consequence of intermittent transgressions and regressions during Eocene. The Vegetation is believed to be mangrove rich angiosperms that grew insitu under the tropical humid climatic condition in estuaries, lagoons and inland bays and (Raja Rao, 1981). Singh and Singh (2000) believe that in Garo hills the coal seams developed in reed to open water swamps with telmatic to limnic conditions. Further, the coal seams of Khasi hills developed in the forest swamps with telmatic to limno-telmatic conditions (Fig 5). Presence of single, double and triple celled telutospores suggests a typical angiospermic Tertiary flora and the development of peat took place under prolong wet condition as revealed by high GI and TPI values while high tree density prevailed in the mire. They also observed large size resins from these coals and suggested a prolific growth of conifers in the swamps.

It is believed that during Eocene period there were intermittent marine transgressions and regressions and the mangrove rich angiosperms grew under humid tropical condition along inland bays, estuaries and lagoons. Presence of single celled and three celled telutospores also indicates the angiospermic flora for Meghalaya coals. This is indicated in the formation of thin beds of coal (0.3-2.0 m) because of shifting of distributary channels (Raja Rao, 1981; Singh and Singh, 2000). Petrography based models indicate terrestrial input for coals of Mawlong-Shella, Langrin, Cherrapunji, Bapung and Laitryngew while reed-moor and open-moor facies especially for West Daranggiri and Siju coals of Garo Hills (Singh and Singh, 2000).

Evolution of Jammu Coals

Singh (1970) worked on the foraminiferal records of Subathu Formation and believed that their sediments got deposited in neritic environment. The lower part of this Group has coal bearing sequences. Based on mammalian fossil record, Khan (1973) opined that the Subathu sequences deposited in a shallow marine environment while the overlying Murree Group formed under brackish-water environment with intermittent flux of fresh water. Singh and Singh (1995b) reported the occurrence of one, two- and three- celled telutospore having typical Tertiary floral assemblage and they showed a possibility of angiosperm flora contributing to the mires of the Jammu coals. Singh and Andotra (2000) and Singh (2012) have suggested that the Subathu Formation is largely comprised of barrier-lagoon and tidal cycles. They have suggested that the coal have developed within the swamps adjacent to lagoons. Singh (2003) interpreted a regional unconformity at the site of the fore bulge represented by the impure bauxite above the Precambrian Sirban Limestone. Intense weathering under the hot and humid climate near the equator resulted lateritization/ bauxitization (Singh et al., 2005; 2009).This was followed by a transgression associated with tropical humid climatic conditions that resulted into luxuriant floral growth and subsequent development of forest swamps (Fig 5). Coal petrological study further reveals that Jammu coals evolved from forest moor under limno-telmatic depositional condition. Here undisturbed peat grew in-situ and there was intermittent sub aqautic sedimentation. Petrographic study further supports high tree density under telmatic environment and prevalence of high gelification index which indicates a continuous influx of calcium rich sea water into the peat swamps. Singh and Singh (1995b) have opined that the Kalakot was a shallower basin while Mahogala was a deeper one while coals of Metka were subjected to an intermediate depth. Based on floral study of the lignite deposits of Kashmir valley, tropical to sub-temperate paleoenvironmental condition is suggested by Tripathi (1987).

Thermal Maturity and Coalification

Coalification is a transformational process where coal undergoes systematic physical and chemical changes that result in peat to meta-anthracite formation with increasing maturation. Diagenesis and catagenesis are the main physico-chemical processes, and a number of factors such as paleodepositional environment, depth of burial leading to lithostatic pressure, temperature, duration of heating and tectonic activities are involved in the process. High regional coalification level is marked by an enhanced vitrinite reflectance. This is attributed to tectonic activity in the Himalayan terrain that led to increased pressure and temperature. The coal bearing horizons in Himalaya experienced multistage tectonic deformations those are variable in different parts. The tectonic framework of the coalfields differs in western region (Jammu) from the eastern region (Assam, Meghalaya, Arunachal and Nagaland). The tectonic-thermal evolution of the coal bearing horizons invariably accelerated the coalification process. It is interesting to learn that during the same period, the coalification processes were also undergoing in the other parts of the country especially in western and southern margins of peninsular India. In these regions only lignitous rank could be attained by the coal bearing sequences. The reflectance values of Jammu coals are significantly higher than those of peninsular lignites of western India. Even within Himalayan belt, the reflectance values of coals in the eastern states are relatively lower than that in the western state of Jammu and Kashmir which has been substantiated in various studies. Chandra and Chakrabarty (1989) believed that Metka, Kalakot and Mahogala coals of Jammu are of semi-bituminous to carbonaceous rank of Seyler while petrographically they reveal semi-anthracite character. Based on the relation between R_{omax} and volatile matter, they observed a gradual change in volatile matter. Singh and Singh (1993) have assigned the rank of the Jammu coals as low-volatile bituminous based on their Ro max values (1.84 to 1.93%). As per Kotter (1960) scheme of rank determination, the Jammu coals vary between low volatile bituminous and semi-anthracite. Further, they have noticed local variation in the rank and attributed it to tectonic stress. The coals of foreland basin of north-eastern India possess vitrinite reflectance (R_{om}) from 0.39 to 0.61 % which assigns them sub-bituminous-C to high volatile bituminous-C rank as per German (DIN) and North American (ASTM) scheme (Singh et al., 2013). While Tiru valley coals of Nagaland studied by Singh et al. (2012a) found their place in sub-bituminous to bituminous-D rank as per ISO-11760 (2005). The Platform type coals of Meghalaya have volatile matter (38.5 to 70.0%) and vitrinite reflectance (R_{om}) values (0.38 to 0.68%) which place them in sub-bituminous-C to high volatile bituminous-C rank (Singh and Singh, 2000). Vitrinite reflectance (VRr %) in the Foreland basin coals of Assam (Makum and Dilli-Jeypore coal), Arunachal (Namchik-Namphuk coal) and Nagaland (Borjan and Tiru Valley coal), Jammu (Metka and Mahogala coal) and the Platform basin coals of Meghalaya (West Daranggiri, Siju, Langrin, Mawlong-Shella, Cherrapunji, Laitryngew, Bapung coals) is shown in Figs. 6a,b. Thus the coal bearing basins of Himalaya underwent a complicated geological evolution than their counterparts in Peninsular India.

Coal Development and Paleogeography

Extensive coal deposits are seen in the tropical climatic zones where warm and humid conditions prevail and favour plant growth and subsequent peat formation (Esterle and Ferm, 1994; Taylor et al., 1998), though, coals are also reported from temperate and cold regions. This could be because peat-forming vegetation in these warm and humid zones is woody and arborescent. This is a better analogue for the palaeopeat-forming vegetation grown during the Carboniferous, Cretaceous and Tertiary periods (Esterle & Ferm, 1994). The

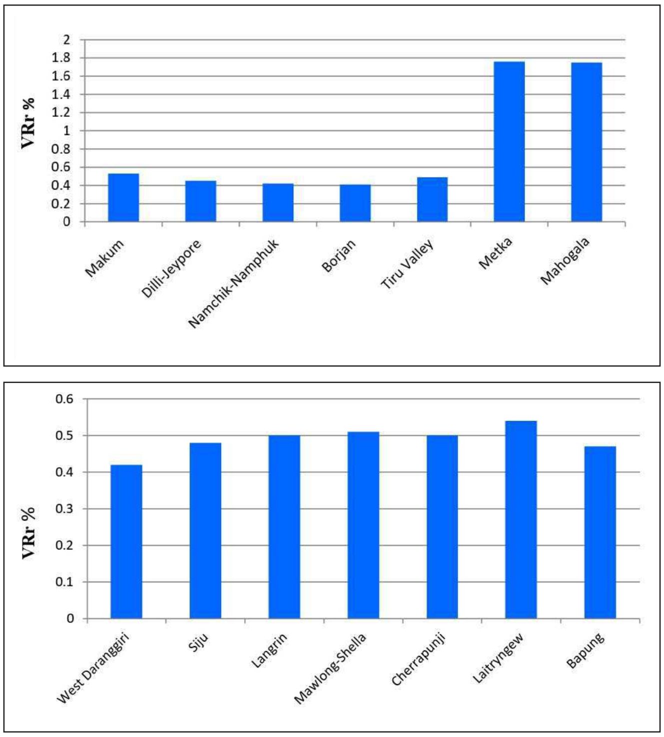

Fig. 6. (a) Vitrinite reflectance (VRr %) in the Foreland basin coals of Assam (Makum and Dilli-Jeypore coal), Arunachal (Namchik-Namphuk coal) and Nagaland (Borjan and Tiru Valley coal), Jammu (Metka and Mahogala coal). **(b)** Vitrinite reflectance (VRr %) in the Platform basin coals of Meghalaya (West Daranggiri, Siju, Langrin, Mawlong-Shella, Cherrapunji, Laitryngew, Bapung coals).

characteristics of the late Paleocene coals of Jammu indicate their formation in a humid tropical climate which led to the growth of plants in the swamps around lagoons where groundwater maintained the wetness (Singh et al., 2009). These coals of the western Himalayan foreland basin are vitrinite rich and were formed in tropical climate where most of the plant fibres were converted into peat. During the late Paleocene the northern part of the Indian landmass was in the northern hemisphere.

As the coal developed at two distinct stratigraphic levels in the eastern Himalaya (NE India), we envisage similar situations twice when the coal developed. Probably, the Eocene coals developed when the NE India was in humid tropical zone in the southern hemisphere and the Oligocene coals developed when the NE India was in the humid tropical zone in the northern hemisphere during northward drift of India. Thus, the similar conditions prevailed during late Paleocene in the northwest India, and during Eocene and Oligocene in the northeast India as a result of the latitudinal-shift related climatic change.

India-Asia Collision and Formation of Coal

During Cenozoic period, India moved towards north with a rapid reduction in velocity at ~ 55 Ma in the western part due to collision of the Indian plate with the Asian plate that was diachronous and eastern part of India collided ~ 10 Ma later than the western part (Klootwijk et al., 1992). At this time (ca 55 Ma), part of northwestern India moved and entered the northern hemisphere having a steady northward movement of 5 to 10 cm year. Consequently, the collision led to the buckling and tectonic uplift of the Himalaya which gave rise to the development of Himalayan foreland basin in the fold-thrust belt. This substantially changed oceanic and atmospheric circulation (Cerling, 1997; Singh & Lee, 2007). Coals of the western Himalaya are supposed to be the initial deposits formed from peats developed in a swamp in the foreland basin associated with a major transgression. Before the coal formation, the evidences of growth fault and forebulge are found by Singh (2003) in the western Himalaya (Fig. 7). Thus, the western Himalayan coals are the true representative of the foreland basin where rank of coal is high (Fig. 6a) due to tectonic activities. The Eocene coals of the eastern Himalaya developed in platform basin due to intermittent transgression and regression and the area was lacking much tectonic activities. Hence, the coalification was governed by the depth of burial mainly. In the higher-up the Oligocene coals developed in the foreland basin that formed later in the eastern Himalaya after the collision in the eastern part. The foreland basin coals are more mature than the platform coals here due to tectonic activities in the basin. Also, appreciable amount of mineral matter is present in the platform basin coals occurring in form of clays, carbonates and sulphides due to mixing of organic and inorganic matter. The differences in the late Paleocene coals of the northwest India, and Eocene and Oligocene coals of the northeast India in terms of maturity and rank are due to the diachronous timing of collision of the Indian plate with the Asian plate and related tectonics that happened in late Paleocene in the western Himalaya and Oligocene in the eastern Himalaya.

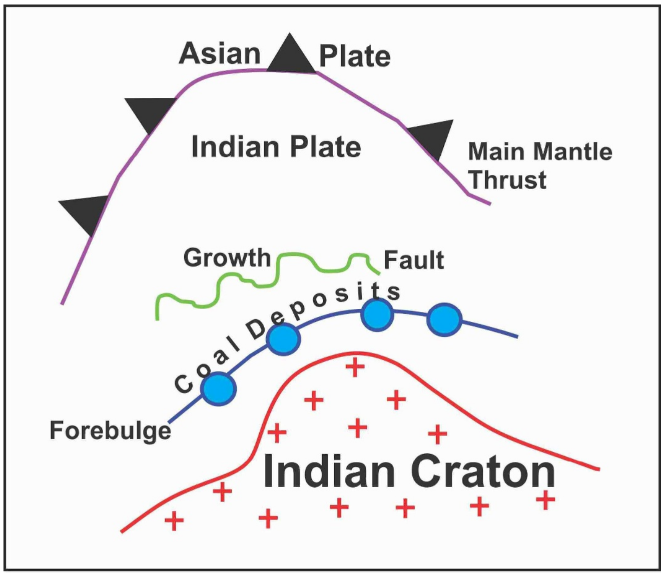

Fig. 7. Configuration of the Himalayan foreland basin between the Himalayan orogen and the Indian Craton (after Singh, 2003). Also shown are the coal deposits in the foreland basin.

CONCLUSIONS

1. The coal bearing sequences of Meghalaya are developed in a platform basin, while coal bearing sequences in upper Assam, Arunachal Pradesh and Nagaland forming a linear belt have developed in a foreland basin in eastern Himalaya. In western Himalaya, the main coal deposits of Jammu occur along a linear belt forming a part of the western Himalayan foreland basin.
2. The coals of the eastern Himalayan foreland basin are rich in vitrinite while liptinite and inertinite occur in subordinated amounts. Some coals (Makum and Namchil-Namphuk) have developed caking properties. The coals of platform in the eastern Himalaya, having vitrinite as dominant maceral group, also have pseudovitrinite and saprovitrinite; the latter shows brown fluorescence due to impregnation of bituminous substance especially in Garo hill coals. Like eastern Himalayan coals, the coals of Jammu in western Himalaya are also rich in vitrinite group of macerals while inertinite and liptinite occur in low concentrations.
3. The coal bearing sequences of platform basin (Meghalaya) indicate intermittent transgression and regression during Eocene period. The presence of single and triple celled telutospores suggests mangrove rich angiosperm that grew in tropical humid climate and the occurrence of large size resins suggests growth of conifers. The coals of foreland basin in eastern Himalaya evolved in a prograding delta that emerged due to regression of sea and subsequently angiospermic flora grew in dominance which appeared in form of coal bearing sequences. Bog forest developed in mesotrophic to ombrotrophic hydrological conditions here. The coal bearing sequences of western Himalaya evolved under shallow marine environment where Tertiary angiospermic flora grew.
4. The western Himalayan coals are low volatile bituminous in rank and the coals of eastern Himalaya varies from sub-bituminous to high volatile bituminous C/ bituminous D in rank. The differences in the rates of coalification observed in the western and eastern Himalayan coals may be linked to the differences in tectonic activities, basin development and differences in the collision ages in the western and the eastern Himalaya.

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