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Petrographic characterization and evolution of the Karharbari coals, Talcher Coalfield, Orissa, India

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Abstract In the present study an attempt has been made to carry out the detailed petrographic characterization of the Karharbari coals of Talcher coalfield and to reconstruct the paleoenvironment conditions of coal formation using macerals and microlithtotypes as a tool. For these purposes a large number of samples were collected following the pillar sampling method and were subjected to detailed petrographic study. The petrographic observation shows that these coals are vitrinite rich followed by the liptinite and inertinite group of macerals. On microlithotype scale, these coals shows the dominance of the vitrite followed by clarite, vitrinertite and inertite. The concentration of liptite, clarodurite, duroclarite and vitrinertoliptite are insignificant. The vitrinite reflectance ranks the Karharbari coal as high volatile bituminous 'C' to high volatile 'B' bituminous. Coal petrography based depositional models suggest peat accumulation in forested telmatic swamp. Moreover, during the time of their evolution, there were alternate phases of oxic and anoxic moor conditions with good tissue preservation.

Keywords Petrography · Rank · Evolution · Karharbari · Talcher coalfield

1 Introduction

The Gondwana coals of India are developed mainly along the two sides of a great triangular area whose third side is formed by the northern part of the east coast of Indian peninsula (Fig. 1a). Damodar, Son and Narmada Valleys make the north side of the triangle, whereas the southwestern side runs along to Godavari–Wardha Valley and subsidiary belt run along to Mahanadi Valley (Fig. 1a). The Talcher coalfield is the southeastern part of the Mahanadi Graben. It is detached basin surrounded by Precambrian rocks and occupies an area of over 1800 sq. km. in the Dhenkanal district of Orissa with a small segment lying in the adjoining Sambalpur district.

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The first report on the occurrence of coal from this area dates back to 1937. The first systematic survey of the area was carried out by Blanford et al. (1856). Brief accounts of the geology, structure and coal seams of the basin have been given by Fox (1934), Pascoe (1959), Subramanian (1971), Das and Rath (1974) and Raja Rao (1982). Due to huge coal resources, the basin has attracted the attention of various exploring agencies. As a result the, the Indian Bureau of Mines, the Geological Survey of India, the Central Mine Planning and Design Institute, and the Directorate of Geology, Government of Orissa, initiated the exploration activities in the Talcher coalfield. In the year 1963–1965, Geological Survey of India conducted regional exploration in the coalfield. Presently the Talcher coalfield is exploited by Mahanadi Coalfield Limited, a subsidiary of Coal India Limited. Talcher basin is mainly studied by stratigraphers, sedimentologists and paleontologists, but petrological and geochemical aspects of Talcher coal, however, have not been taken into account so far. Although few reports have been published on the petrographic and geochemical characteristics of Talcher coals

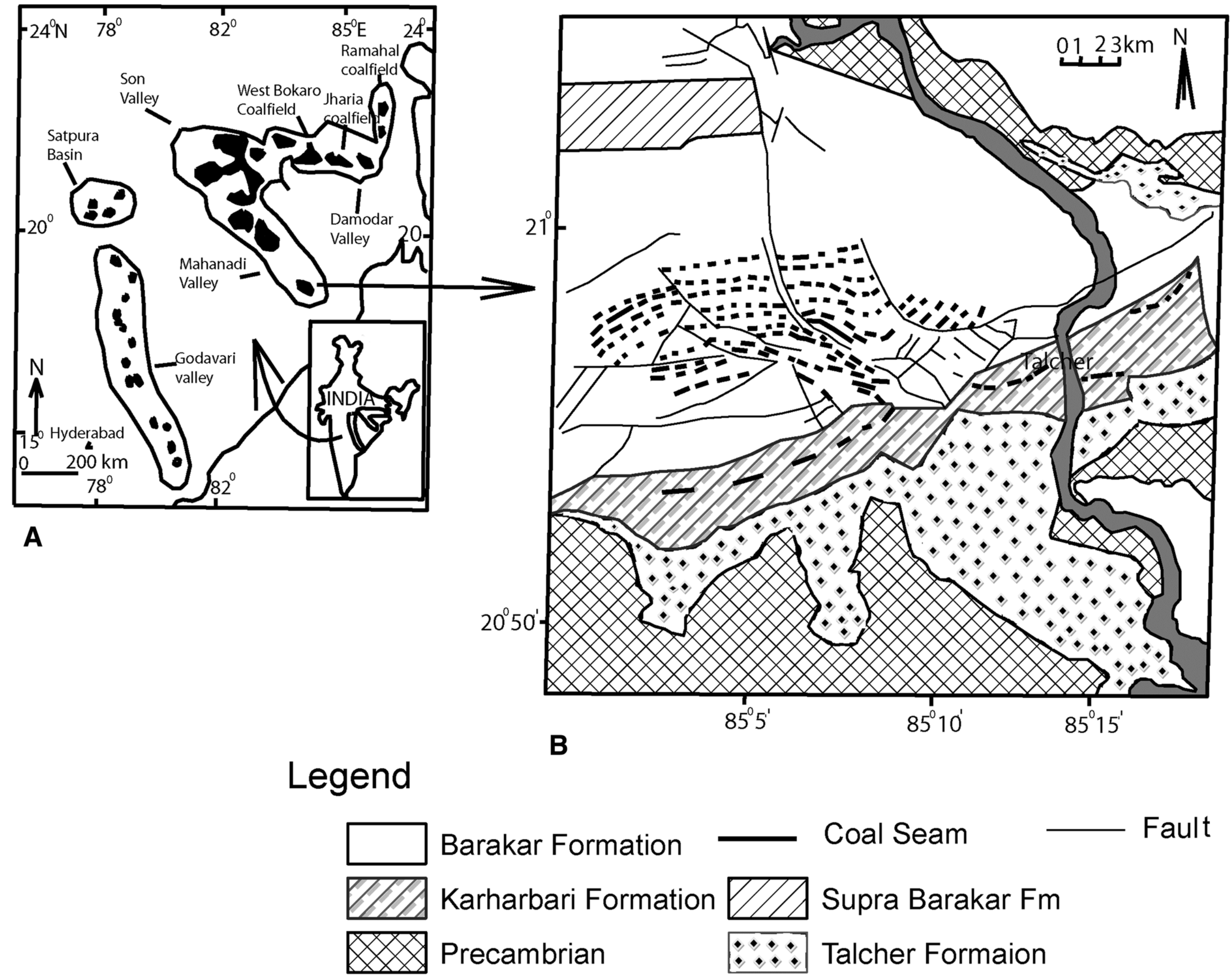

Fig. 1 **a** Location map of Gondwana coal-fields of India. **b** Geological map of Talcher coalfield, Mahanadi valley, Orissa (Raja Rao 1982)

based on sporadic samples, the earlier studies lack the systematic sampling, regional approach and modern techniques. A mention may be the works of Das (1959), Navale (1965, 1966, 1971), Pareek (1955, 1956, 1958, 1963a, b), and Mishra et al. (1998) and Mohanty et al. (2001).

In the Talcher coalfield, coal seams have been reported in the Karharbari and the Barakar formation. In the present study an effort has been made to carry out a detailed petrographic and geochemical study of a large number of coal samples from the Karharbari Formation of the Talcher coalfield aiming to discuss the depositional conditions during accumulation.

2 Geology of the area

The rough outline of the coalfield resembles that of an ellipse. It is flat type of the basin and is bounded on all sides by Archeans. The Gondwana sediments of the investigated area represent a fairly continuous succession of strata comprising a Talcher and Damuda Groups. The sediment rest unconformably on the Precambrian basement comprising granites, gneisses, phyllites and amphibolites (Table 1).

The Precambrian comprises a low ridge and isolated hillock along the boundaries of the basin. In Talcher coalfield, base of Gondwana sediments is marked by a pile of glacial and preglacial deposits. They were originally recognized by Blanford et al. (1856) and have been named Talchir Formation after the type locality. These rocks are well exposed along the southern boundary of the basin. This formation comprises diamictites, sandstone, needle shale, turbidites, rhythmites and varves (Table 1). The Talchir Formation conformably overlain by the Karharbari Formation, which is exposed as a narrow strip both along the southern and northern margins of the basin. Here, the Karharbari Formation has distinct lithological and palynological entity. This formation mainly consists of medium

Table 1 Stratigraphic sequence of Talcher coalfield (Raja Rao 1982)

Age	Formation and lithology
Recent	Alluvium and laterite
Upper Permian–Triassic	Kamthi
	Fine to medium grained sandstone, carbonaceous shale, coal bands with greenish sandstone, pink clays and pebbly sandstones at top (250 m+)
Lower Permian	Barakar
	Medium to coarse grained sandstones, shales, coal seams with oligomictic conglomerate at base (500 m+)
Lower Permian	Karharbari
	Medium to coarse grained sandstones, shales and coal seam (270 m)
Lower Permian	Diamictite, fine to medium grained greenish sandstones, shale, rhythmite, turbidite etc. (170 m+)
Unconformity	
Precambrian	Granite, gneisses, amphibolites, migmatites etc.

to coarse grained sandstone and shale. It also contains the superior quality of coal seam (Fig. 1b). Karharbari Formation is overlain by Barakar Formation, which characterized by a thick and conspicuous conglomerate horizon at the base. The conglomerate is oligomictic in nature and contains well round quartz and quartzite clast of various sizes. The basal conglomerate unit is overlain by a thick sequence (more than 500 m thick.) medium to coarse grained greyish feldspathic sandstone, grey to dark grey shale. The Barakar Formation conformably overlain by a sequence characterized by fine to medium grained, light grey and ferruginous sandstones and shale at the base and a thick succession of pale greenish sandstone with rare shale and pink clay bands, ferruginous coarse grained and pebbly sandstone at the top (Table 1). The formation is designated as Supra Barakar Formation.

3 Method of study

During the present study, coal samples were collected from Derra underground coal mines following the pillar coal sampling method. Coal samples were collected from Karharbari Top seam and Karharbari Bottom seam. Their megascopic characterization was performed by using the scheme proposed by Diessel (1965) and macroscopic seam profiles were constructed. For the microscopic study coal samples were crushed to 18 mesh size (<1 mm size particles). The polished particulate coal mounts were prepared by using cold mounting epoxy resin without pressure. The study was carried out on an advanced petrological microscope equipped with MSP 200 photometry system and fluorescence attachment. The maceral nomenclature applied, followed the ICCP system (1971, 1998, 2001). For the microlithotype analysis, a 20 point Kötter graticule was used. The line to line and point to point distance was maintained 0.4 mm for both maceral and microlithotype analysis. The maceral and microlithotype counting was done simultaneously. The reflectance measurement was carried out as per the ISO standard (ISO 7404-5 1994). For the precise assessment of liptinite and dark vitrinite microscopic examination of macerals was carried out both under the white incident light as well as under blue light excitation. The International Committees for coal Petrology (1971) devised certain rules for the characterization of maceral association. According to which, the minimum dimension of a band to be called a microlithotype, should be 50 × 50 mm, and the 5 % rule. The 5 % rule demonstrates that a microlithotype can have 5 % accessory macerals due to the very fact that neither the monomaceral nor the bimaceral microlithotypes are constituted exclusively of the macerals of one group or two groups respectively. Therefore, they can have 5 % accessory macerals which will have no role in their nomenclature or characterization. ICCP recommendation has been followed during the characterization of microlithotype. All the coal samples were subjected to proximate (BIS 2003) and petrographic analysis.

4 Results

4.1 Macropetrographic characteristics of coal

These coals are banded in nature with vitrain and clarain being the dominant lithotypes. Durain has also been observed only in few coal samples and fusian has also been recorded. In some of the coal samples, pyrite framboids and small nodules have also been found. The scheme proposed by Diessel (1965) for the megascopic characterization of banded coals has been followed in the construction of megascopic seam profiles of Karharbari coals.

In the Karharbari formation, only bright coal, banded bright coal and banded coals have been recorded (Fig. 4).

4.2 Petrographic characteristics of coal

4.2.1 *Rank*

For the determination of rank of the Karharbari coals, the parameters used are volatile matter (d.a.f. basis) and vitrinite reflectance (Ro mean) value. In the Karharbari coals, the volatile matter (d.a.f. basis) ranges from 35.2 to 45.9 %, mean 43.1 % (Table 2) and reflectance of vitrinite (Ro mean) ranges from 0.57 % to 0.69 %, mean 0.59 % (Table 3; Fig. 4). The volatile matter and Ro mean values suggest these coals to range in rank from high volatile bituminous 'C' to 'B'.

4.2.2 *Maceral composition*

All the three group macerals viz. vitrinite, liptinite and inertinite have been recorded. Among the three macerals groups, vitrinite is the most dominant. The macerals of liptinite group have also occurred at moderate concentration, whereas macerals of inertinite group are low in concentration as compared to others two groups.

4.2.2.1 Vitrinite group All the maceral and sub-macerals of vitrinite group have been recorded in these coals. Telovitrinite in general, is the dominant subgroup. Among the telovitrinite subgroup, the concentration of telinite is quite poor while collotelinite occurs at high concentration and dominating over all the macerals of the vitrinite group. Generally it occurs as a thick band (Fig. 2b, c, h). The colour of collotelinite varies from light grey to dark grey. The cavities or cell lumens of the telinite is either filled with collotelinite or mineral matter. After the telovitrinite, the next dominating subgroup is detrovitrinite and represented by vitrodetrinite and collodetrinite (Fig. 2d, h). In the Karharbari coal beyond the collotelinite, next dominating maceral of the vitrinite group is vitrodetrinite. If vitrinite occurs as ground mass (mottled in appearance) of clarite and trimacerite with a colour darker and reflectance lower than the normal collotelinite in the same coal then such maceral is known collodetrinite. Gelovitrinite subgroup is represented by corpogelinite and gelinite. Corpogelinite is characterized by its typical oval to subrounded shape. In occurs occurs mostly as oval bodies as large isolated grains (Fig. 2a), in the form of cluster and also as cell fillings arranged in a definite pattern. The colour has been found to be paler and the reflectance is higher than the associated collotelinite. Gelinite occur as cell and fissure fillings. The colour of this maceral is slightly brighter and reflectance is comparatively higher than that of other vitrinite macerals in the same coal. Pseudovitrinite (more commonly called semi-vitrinite in India) is also present in these coals being characterized by its higher reflectance as compared to the normal collotelinite in the same coal and considered to be a transition stage between vitrinite and semi-fusinite. Some of vitrinite-bands of these coals have shown the fluorescence properties which are low reflecting and comparatively darker grey in colour. Such vitrinite is known as dark vitrinite. The fluorescence of vitrinite has been understood to be due to the presence of adsorped petroleum like substance, generated during the coalification process from liptinite and lipoid substance occurring in association of vitrinite (Teichmüller 1982a, b; Teichmuller and Durand 1983). Oxidation cracks are also recorded in few coals samples and cracks are in places filled with mineral matter (either argillaceous or sulphides). The quantitative distribution of vitrinite group of macerals of the Karharbari coals is given in the Table 4.

4.2.2.2 Liptinite group In the Karharbari coals both primary (structured) and secondary liptinite (unstructured) liptinite macerals have been observed. In these coals, primary liptinite macerals are represented by sporinite, cutinite, resinite, alginite and liptodetrinite whereas secondary liptinitic macerals are represented by fluorinite, exsudatinite and bituminite. Degraded pollen and pollen sacs have

Table 2 Proximate constituents (wt%) of Karharbari coals of Talcher coalfield, Orissa

Proximate constituents	Top seam		Bottom seam	
	Range	Mean	Range	Mean
Dry basis				
Moisture	7.0–8.0	7.9	8.0–10.5	9.0
Ash	10.0–20.0	13.7	5.0–11.3	8.7
Volatile matter	25.5–37.3	33.4	34.1–36.6	35.9
Fixed carbon	39.0–48.5	44.9	43.5–49.5	43.6
Dry ash free basis				
Volatile matter	35.2–45.9	42.6	41.10–45.8	43.6
Fixed carbon	54.2–64.8	57.4	54.21–58.9	56.4

Table 3 Reflectance measurement of Karharbari coals of Talcher coalfield, Orissa

Reflectance values	Top seam		Bottom seam	
	Range	Mean	Range	Mean
Minimum	0.39–0.46	0.4	0.33–0.44	0.37
Mean	0.57–0.69	0.59	0.57–0.61	0.59
Maximum	0.62–0.92	0.81	0.66–0.85	0.78
Standard deviation	0.06–0.11	0.08	0.06–0.09	0.08

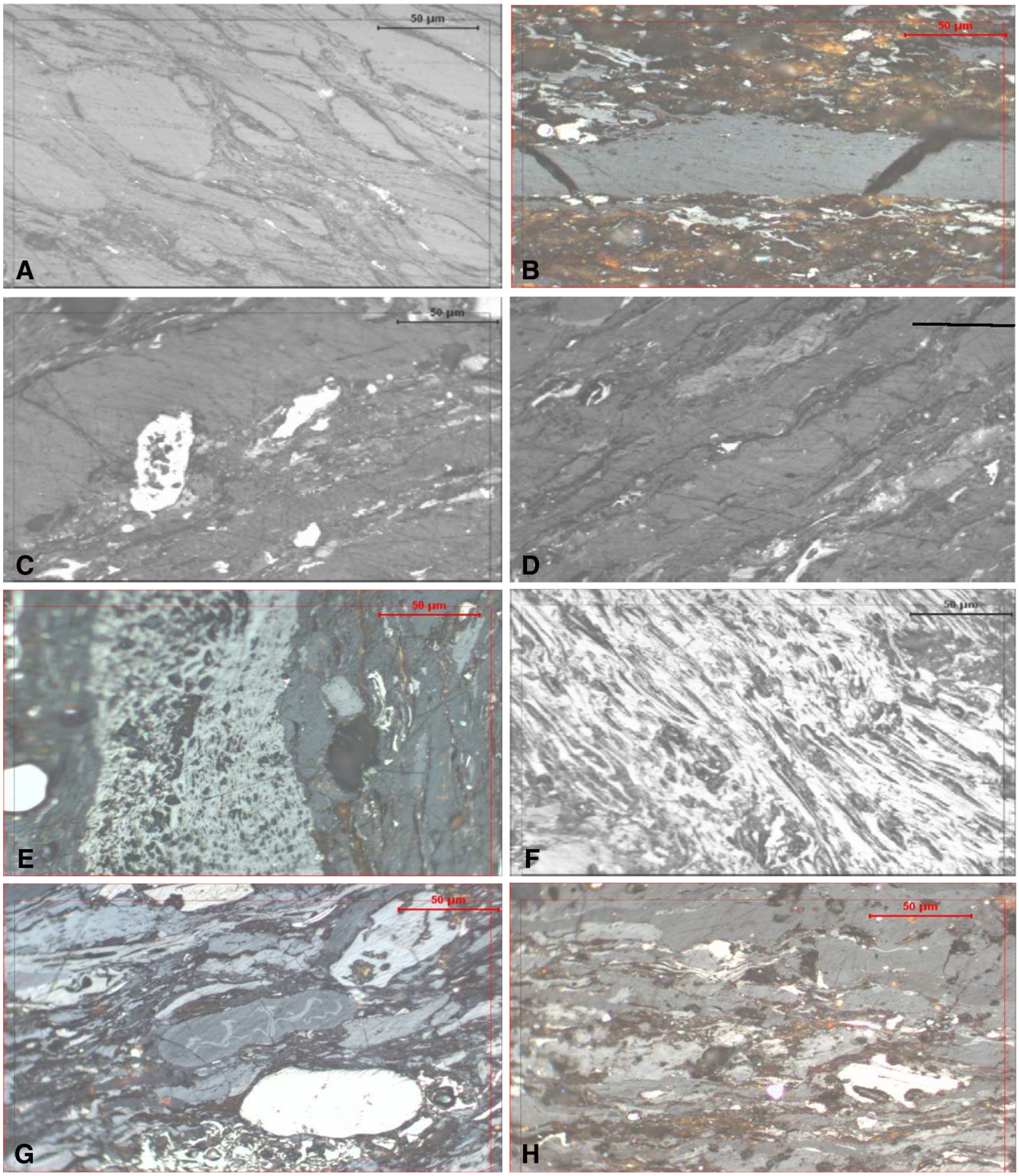

Fig. 2 Photomicrograph under white incident light. **a** Carpogelinite, **b** band of collotelinite, inertodetrinite and carbonate mineral matter, **c** thick band of collotelinite and secretinite, **d** sporinite in the ground mass of collotelinite, **e** collotelinite, semifusinite, resinite and inertodetrinite, **f** fusinite, **g** macrinite, funfinite, **h** collotelinite, vitrodetrinite, inertodetrinite, argillaceous and carbonate mineral matter

also been recorded in the Karharbari coals and counted separately. Among the liptinite group the most dominating maceral is sporinite. In the Karharbari coals, both microspores (microsporinite) and megaspores (megasporinite) have been identified (Fig. 3a–c). The colour of the spores is dark grey to brown under white incident light (Fig. 3d) while in fluorescent mode, the colour of the spores is yellow, turmeric yellow, orange-brown and brown colour (Fig. 3a–d, h). In the megaspore suture lines are quite distinct. The colour of cutinite is similar to sporinite dark grey to grey, but in some places it is paler than the associated sporinite. Thin walled cutinite has been identified in these coals. Resinite is also observed in the Karharbari coals and generally being oval to round in shape (Fig. 3a). In some samples, a thick band of weathered resinite has also been recorded. Resinite is more common in the

Table 4 Maceral and mineral matter composition of Karharbari coals of Talcher coalfield, Orissa

Maceral and mineral matter	Top seam		Bottom seam	
	Range	Mean	Range	Mean
Vitrinite	30.1–51.4 (43.9–62.6)*	39.8 (53.8)	31.6–55.8 (52.4–69.5)	45.5 (61.9)
Telinite	Nil–1.5 (Nil–1.8)	0.33 (0.4)	Nil–2.3 (Nil–3.6)	0.62 (0.9)
Collotelinite	15.2–44.9 (25.0–54.8)	28.4 (37.8)	26.2–51.0 (48.4–63.4)	40.5 (55.1)
Vitrodetrinite	1.5–13.4 (1.83–22.1)	6.2 (8.8)	0.31–1.5(0.4–2.4)	1.07 (1.4)
Collodetrinite	Nil–1.4 (Nil–1.0)	0.59 (0.8)	0.3–1.2 (0.4–1.4)	0.6 (0.8)
Corpogelinite	0.4–2.3 (0.6–2.8)	1.14 (1.6)	0.4–1.7 (0.4–1.9)	0.79 (1.0)
Gelinite	Nil–0.8 (Nil–1.0)	0.4 (0.5)	Nil–0.8 (Nil–1.2)	0.3 (0.4)
Dark vitrinite	Nil–2.3 (Nil–3.0)	0.6 (0.8)	0.4–1.0 (0.6–1.3)	0.7 (0.9)
Pseudovitrinite	0.8–4.6 (1.0–5.5)	2.1 (2.8)	0.4–2.1 (0.4–2.4)	1.2 (1.5)
Liptinite	17.9–29.3 (26.7–43.2)	23.5 (31.9)	11.6–29.1 (16.2–35.1)	22.2 (27.2)
Sporinite	6.2–11.5 (8.2–15.0)	8.7(11.9)	2.9–11.2 (3.7–14)	6.6 (8.3)
Cutinite	0.5–2.5 (0.7–3.1)	1.3 (1.7)	Nil–1.5 (Nil–1.2)	0.7 (0.8)
Resinite	Nil–1.1 (Nil–1.5)	0.5 (0.7)	Nil–0.2 (Nil–0.2)	0.02 (0.02)
Alginite	Nil–0.6 (Nil–0.5)	0.1 (0.2)	Nil–0.7 (Nil–0.9)	0.2 (0.3)
Liptodetrinite	1.4–5.4 (2.3–6.9)	3.1 (4.1)	1.0–3.5 (1.5–4.8)	2.6 (3.2)
Fluorinite	0.7–2.1 (0.8–2.6)	1.1 (1.5)	0.6–3.1 (0.9–4.0)	1.6 (2.1)
Exsudatinite	1.2–6.5 (1.7–11.9)	3.8 (5.2)	3.5–7.4 (3.9–9.6)	5.2 (6.6)
Bituminite	0.2–2.1 (0.3–2.6)	0.9 (1.2)	0.2–2.7 (0.3–3.1)	1.2 (1.5)
Degraded pollen	0.4–5.83(0.6–7.7)	3.0 (4.1)	1.5–5.2 (2.0–6.6)	3.8 (4.8)
Pollen sac	Nil–1.8 (Nil–3.1)	0.9 (1.3)	Nil–1.4 (Nil–1.8)	0.5 (0.6)
Inertinite	5.55–17.2 (6.8–20.7)	10.6 (14.3)	4.5–13.1(5.8–20.6)	8.7 (11.1)
Micrinite	Nil–0.2 (Nil–0.3)	0.02 (0.03)	Nil–0.2 (Nil–0.2)	0.02 (0.03)
Macrinite	Nil–0.4 (Nil–0.4)	0.1 (0.2)	Nil	Nil
Semifusinite	Nil–4.9 (Nil–6.4)	2.5 (3.2)	0.9–3.5 (1.2–4.8)	2.4 (3.0)
Fusinite	0.9–8.4 (1.4–10.1)	3.6 (4.9)	0.9–3.1 (1.2–4.9)	2.38 (3.0)
Secretinite	Nil–2.8 (Nil–3.5)	1.0 (1.4)	0.7–4.0 (0.9–4.8)	1.8 (2.2)
Inertodetrinite	0.7–4.7 (0.9–8.4)	3.28 (4.5)	Nil–5.4 (Nil–8.5)	2.1 (2.8)
Mineral matter	16.63–39.11	26.21	15.16–39.21	20.43
Argillaceous mineral matter	14.3–34.5	21.81	10.1–30.1	17.4
Carbonate mineral matter	1.4–6.4	3.1	0.5–3.9	1.8
Sulphide mineral matter	Nil–4.2	1.3	0.7–3.1	1.3

* Value given in parenthesis is mineral matter free basis

Karharbari top seam as compared to bottom seam. In few samples of the Karharbari coals, alginites is also identified (Fig. 3e). It indicates the marine incursion during the deposition of coals. The alginite can hardly be identified under white incident light. However, it can be better studied in blue irradiation where it shows green, yellow and yellowish- brown colours depending upon the rank of coal. Its fan shaped morphology indicates the pila type of alginite present in the Karharbari coals. Occurrence of acritarch and and ichnofossils have also indicated the marine signature in the basin (Tiwari et al. 1995; Goswami, 2002). Secondary liptinite macerals (unstructured liptinite) have identified at higher concentration indicating that these coals can act as a source rock for the hydrocarbon generation. To support these observations geochemical data are very much essential. Bituminite appears as amorphous, as well as lamellar forms without any definite shape and size occurring as finely dispersed lenses streaks and at places as groundmass for other liptinite maceral (Fig. 3e, h). It shows characteristic orange or brown colour under fluorescence light. Exsudatinite occurs as a crack or fissure fillings in collotelinite and shows black colour under white reflected light and s orange and brownish orange under blue irradiation fluorescence (Fig. 3g). Fluorinite is very common in these coals (Fig. 3h). It is seen as black colour, elongated or lensoid bodies of variable thickness under the

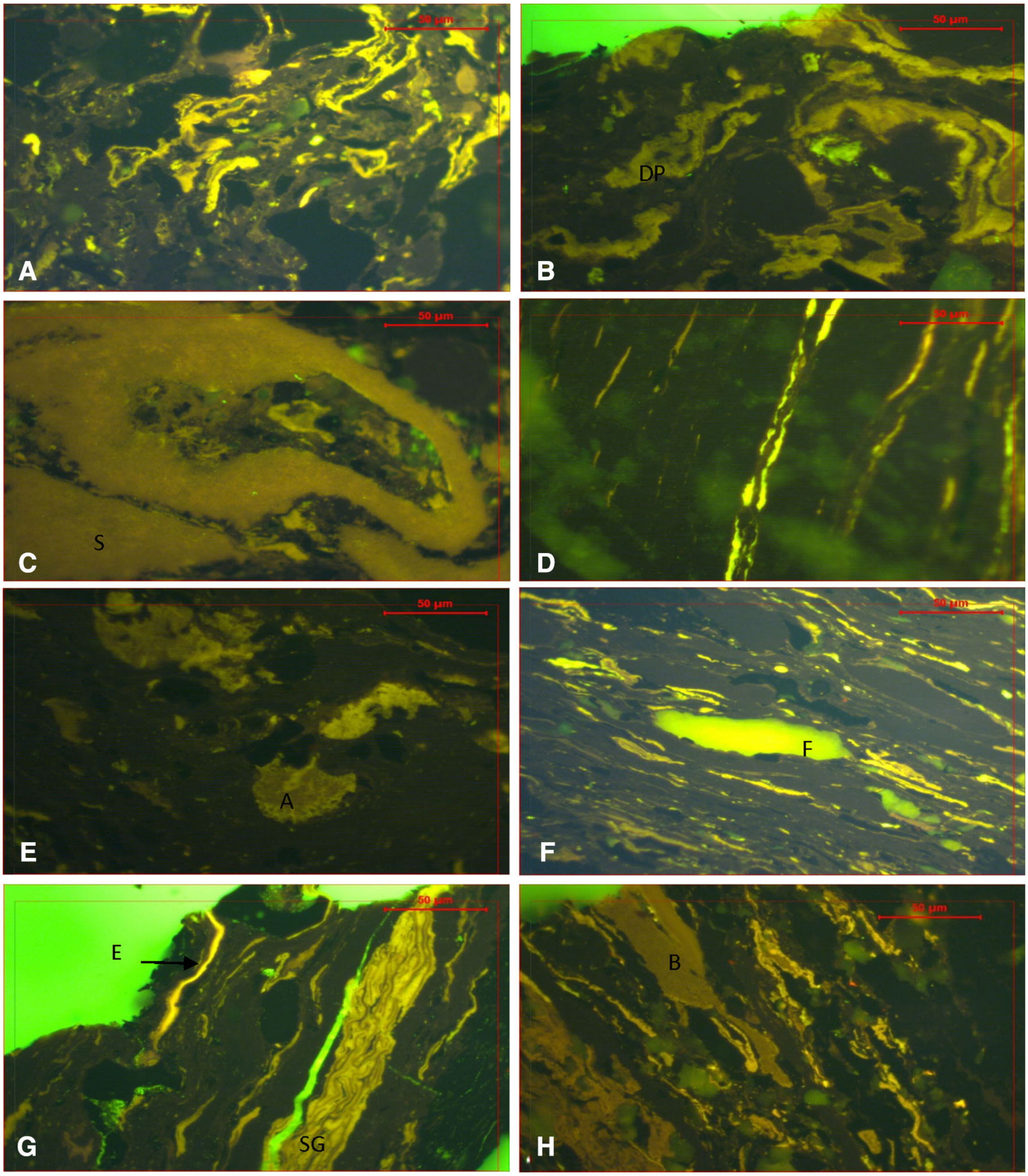

Fig. 3 Photomicrograph of liptinite macerals under fluorescent light. **a** spores, small resin bodies and liptodetrinite, **b** sporinite and degraded pollen (DP), **c** megaspore (S), **d** fluorinite (F) and spore, **e** aliginite (A) and amorphous bituminite, **f** fluorinite, liptodetrinite and spores, **g** exsudatinite (E) and sporangium (SG), **h** amorphous bituminite (B), liptodetrinite and spores

white reflected light. Under the blue excitation, it is greenish yellow to yellow. Liptodetrinite is frequently occurring in these coals (Fig. 3a, d, f, g). The quantitative distribution of liptinite group of macerals of the Karharbari coals is given in the Table 4 and Fig. 4.

4.2.2.3 Inertinite group Inertinite macerals have the same precursors as vitrinite macerals and many of them pass through the same stages of humification except that, before reaching depositional base level below the groundwater table, they are subjected to a period of intensive desiccation and varying degrees of oxidation including partial burning of the accumulated vegetal matter (Gould and Shibaoka 1980). The results are coal constituents which possess relatively high O/C ratios and high reflectance in incident light microscopy because they are rich in aromatic carbon. Most inertinite macerals are relatively brittle and hard, which in incident light microscopy is

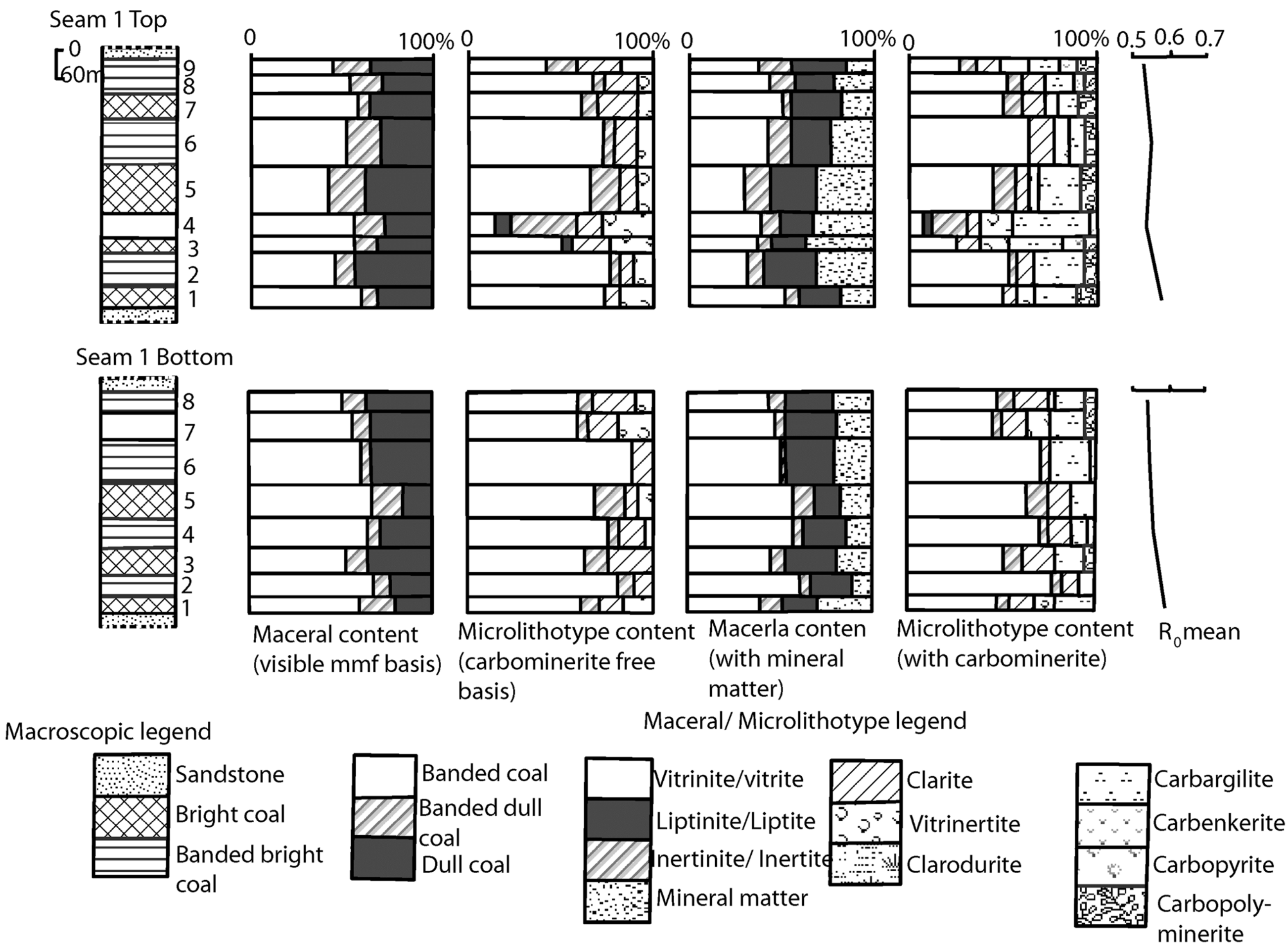

Fig. 4 Macropetrographic section and microscopic seam (maceral and microlithotype) and range of mean vitrinite reflectance (in oil) of Karharbari coals Talcher coal field, Mahanadi valley, Orissa

shown by their tendency to develop polishing relief. Inertinite includes a group of maceral which are characterized by their white to yellowish white colour and high reflectance.

In the coal of Karharbari Formation inertinite occurs at low concentration as compared to the macerals of vitrinite and liptinite groups. All the macerals of this group occur in these coals with significant dominance of fusinite and semifusinite. The macerals of this group include micrinite, macrinite, semifusinite, fusinite, sclerotinite and inertodetrinite.

Fusinite is characterized by a well preserved cellular structure where cell lumens may be open or occupied by mineral matter (carbonate, pyrite and clay) (Fig. 2f). Bogen and sieve structures have also been observed in fusinite. Under white incident light the colour of fusinite is white to yellowish white with high relief and very high reflectance. Both pyrofusinite and degrado fusinite have been recorded. After the fusinite, next dominating maceral of the inertinite group is semifusinite (Fig. 2e). The cell structure of semifusinite is not so well preserved as in the case of fusinite. Its colour lies between light grey to white. In some places, transition from collotelinite to semifusinite has also been observed during the petrographic study. Figure 2e shows the sharp boundary between collotelinite and semifusinite. Marionette has also been observed in these cells. It occurs as rounded to oval bodies. (Figure 2g). The colour is white and reflectance is high close to this fusninte in the same coal. Micrinite has been observed in these coals and it occurs in the form of lenses. It shows white colour and high reflectance. Secretinite has also been recorded in these coals (Fig. 2c). Inertodetrinite is observed only in these coals and it appears to have been derived from crushing of fusinite and semifusinite (Fig. 2c, g, h). The quantitative distribution of inertinite group of macerals of the Karharbari coals is given in the Table 4 and Fig. 4.

4.2.3 *Mineral matter*

The minerals present in these coals includes clay, carbonate, and sulphides. The clay minerals occur as ground mass and also as discrete form, fissure, crack, and cleat fillings and as a infilling of cell lumens of telinite and mainly

Table 5 Microlithotype and carbominerite composition of Karharbari coals of Talcher coalfield, Orissa

Microlithotype & carbominerite	Top Seam		Bottom Seam	
	Range	Mean	Range	Mean
Monomaceral				
Vitrite	7.4–65.6 (41.7–75.8)*	41.7 (59.5)	43.7–76.5 (59.2–89.1)	58.1 (70.7)
Liptite	Nil–3.7 (Nil–4.4)	0.9 (1.6)	Nil–1.0 (Nil–1.3)	0.3 (0.3)
Inertite	Nil–18.5 (Nil–16.7)	7.5 (10.4)	3.4–11.7 (2.3–13.6)	6.7 (8.2)
Bimaceral				
Clarite	3.7–15.1 (5.5–26.1)	9.3 (14.2)	4.9–17.0 (6.3–21.6)	10.7 (13.4)
Vitrinertite	4.1–14.8 (5.3–28.6)	8.6 (13.7)	1.2–11.7 (1.6–15.8)	5.1 (6.6)
Trimaceral				
Duroclarite	Nil–1.5 (Nil–1.8)	0.4 (0.6)	Nil–1.1 (Nil–1.4)	0.4 (0.5)
Clarodurite	Nil	Nil	Nil–1.1 (Nil–1.4)	0.2 (0.3)
Vitrinertoliptite	Nil	Nil	Nil–1.1 (Nil–1.4)	0.2 (0.3)
Carbominerite				
Carbargilite	5.5–35.4	22.6	4.8–19.4	12.6
Carbankerite	1.4–10.4	3.6	0.4–1.9	1.2
Carbopyrite	Nil–5.3	2.1	0.6–3.9	1.9
Carbopolyminerite	Nil–10.5	4.3	0.8–7.7	2.7

* Value given in parenthesis is carbominerite free basis

detrital in orgin. Sulfide occurs in the form of pyrite as disseminated pyrite, discrete grains and infillings of fissures and cracks. Pyrite particles of <1 mm size have been identified as disseminated or submicron pyrite. In the coals it occurs mostly as sporadically distributed particles in the organic ground mass. This form of pyrite originates during hummification process and thus characterized genetically as syngenetic (Reyes-Navarro and Davis 1976; Renton 1979). The discrete grain of pyrite is characterized as a epigenetic origin, which comes into being through ingress of ferruginous solutions at the later stages of coal formation, particularly after partial compaction (Neavel 1966). Fissure and crack filling form of the pyrites are very common in these coals and occurrence of these pyrite forms are described to be of epigenetic origin (Renton, 1979). In one or two samples, framboidal pyrite has also been observed. Although mechanism of the development of framboid is yet to be understood; Kizilstein and Trufanov (1968), Kizilstein and Minaeva (1972), Skripchenko and Berberian (1975), and Reyes-Navarro and Davis (1976) have shown that this type of pyrite is produced by bacteria in anaerobic settings and which may be considered as marine signature. The carbonates occur as ground mass, as strings and also as a cavity and fissure fillings. At few places it has impregnated over the macerals. Carbonate minerals are mainly syngenetic in origin. The concentration of different type of mineral matters in the Karharbari coals is given in the Table 4 and Fig. 4.

4.2.4 Microlithotype and carbominerite

Among microlithotype group, the most dominating is monomaceral followed by bimaceral and trimaceral. The microlithotype analysis shows the dominance of vitrite, clarite, vitrinertite and inertite. Monomaceral microlithotype group is represented by the vitrite, liptite and inertite whereas bimaceral microlithotype group is represented by the clarite and vitrinertite. Trimaceral group has been seen only a few samples. The mineral matter has also been identified in terms of carbominerites. The carbominerite has been characterized as carbargilite, carbankerite, carbopyrite and carbopolyminerite (Mackowsky 1982). The most dominating carbominerite in the Karharbari coals is the carbargillite and which followed by the carbankerite, carbopyrite and carbopolyminerite. The concentration range of the different microlithtypes is given in the Table 5 and Fig. 4.

5 Discussions

Advancement of coal petrographic techniques offers extended parameters which can retrieve the archived records of the evolutionary path of coals. The qualitative and quantitative occurrence of microscopic codes which are to be decoded to interpret the nature and type of plant community, depositional milieu, dynamics of surface and

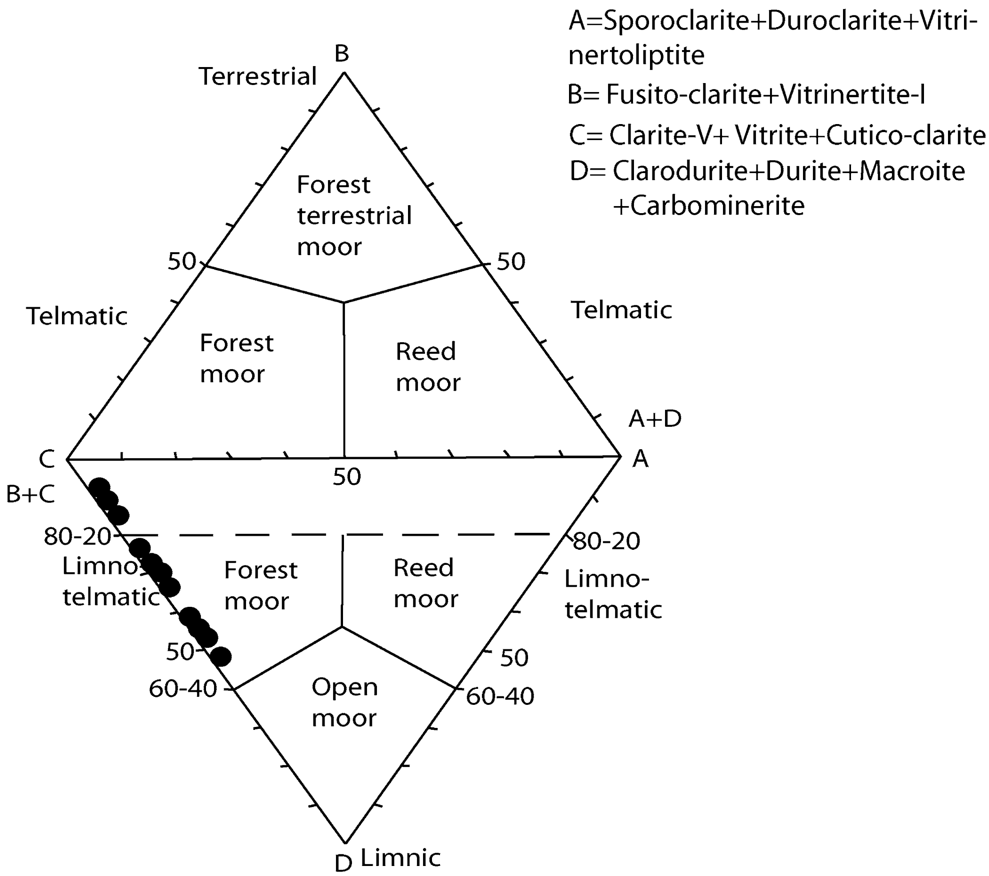

Fig. 5 Microlithotype composition of Karharbari coals plotted on a facies diagram proposed by Hacquebard and Donaldson (1969) and modified by Marchionni (1980)

underground waters, paleogeography and paleoclimate of a coal deposit. The coal petrologists who have significant contribution in this field are: Krausel (1961), Cohen and Spackman (1972), Smyth (1979, 1980, 1984); Teichmüller and Teichmüller (1975); Teichmuller and Teichmuller (1982); Styan and Bustin (1983), Harvey and Dillon (1985), Diessel (1986), Cohen et al. (1987), Hunt (1989), Hunt and Smyth (1989), Calder et al. (1991), Grady et al. (1993), Shearer and Clarkson (1998), Hawke et al. (1999), Duan et al. (2011), Deng and Sun (2011), Lin and Tian (2011), Singh and Singh (1996, 2000), Singh et al. (2010a, b, 2012a, b, 2013) and Suárez-Ruiz et al. (2012).

Coal facies is a function of the type of peat forming flora. The flora in a given geological milieu are controlled by climate, ground water table, nutrient supply and chemistry of water (marine influence). The ground water is the most important factor which determines not only the type of vegetation but also controls the redox potential (oxic to anoxic) and thereby the mode of preservation of plant litter or intensity of humification process. A peat accumulating system can be distinguished in coastal lowland and freshwater peat land (Diessel 1992). The coastal low land is protected by sand bars or barrier beaches, close to tidal influences and grade into marine-influenced to freshwater mires. The fresh water peatlands are inland mire, having no connection to sea, including upper delta and alluvial plain swamps, marshes and bogs. Peat may form in forest swamps from various plant associations, or in marshes with herbaceous vegetation (sedges and grasses) or in open swamps with predominantly submerged and floating plants or in raised bog with mosses or shrubs or trees. Several coal geologists made significant contributions towards the depositional system, mention may be the name of Amijaya and Littke (2005), Marques (2002), Sebag et al. (2006), and Silva et al. (2008). For retrieving the type of Karharbari coal facies, petrography based model proposed by Hacquebard and Donaldson (1969), Diessel (1986), Calder et al. (1991), Mukhopadhyay (1986), Singh and Singh (1996) and Singh et al. (2013) have been used.

The microlithotype composition of the Karharbari coal in a facies model proposed by Hacquebard and Donaldson (1969) suggests that this coals was evolved from the forest mire (Fig. 5). Hacquebard and Donaldson (1969) have shown that the quality and quantity of flora are controlled by water depth conditions of the peat mires, which also

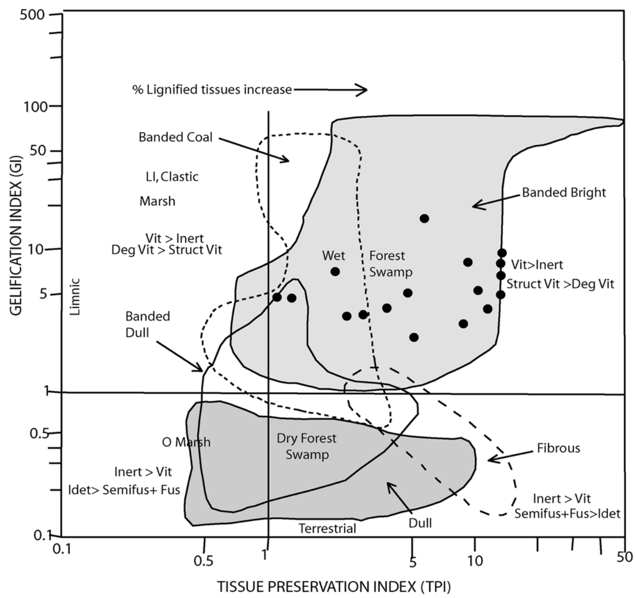

Fig. 6 Coal facies deciphered from gelification index (GI) and tissue preparation index (TPI) in relation to depositional setting and type of mire for Karharbari coals, Mahanadi valley, Orissa (after Diessel 1986 and modified by Kalkreuth et al. 1991). *LI* limited influx, *O MARSH* open marsh, *VIT* vitrinite, *INERT* inertinite, *SEMIFUS* semifusinite, *FUS* fusinite, *IDET* inertoderinite, *STRUCT* structured, *DEG* degraded

regulates the mode of preservation and thereby quantitative distribution of macerals and microlithotypes. Therefore, the microlithotype composition of Karharbari coal suggests the evolution of these coals via forest moors. In order to substantiate the above contemplation a facies model designed by Diessel (1986) has been tested for these coals. Diessel has formulated two parameters—gelification index (GI) and tissue preservation index (PI), for retrieving the paleofacies and has interpreted the depositional setting based on these GI and TPI index have been calculated according to the given formulae:

$$\mathrm{GI} = \frac{\text{Vitrinite} + \text{Macrinite}}{\text{Semifusinite} + \text{Fusinite} + \text{Inertodetrinite}}$$

$$\mathrm{TPI} = \frac{\text{Telinite} + \text{Collotelinite} + \text{Semifusinite} + \text{Fusinite}}{\text{Collodetrinite} + \text{Macrinite} + \text{Inertodetrinite}}$$

This model was further addressed by Lamberson et al. (1991), Alkonde et al. (1992) and Diessel (1992). The TPI is the measure of the degree of tissue decomposition and the ratio of the woody plants in the original peat forming plant congregation. Further, the ratio of tissue-derived structured macerals versus tissue-derived unstructured macerals is a scale to quantify the degree of humification suffered by maceral precursor and also to measure the proportion of wood matter contributed to the gamut of peat. In addition, low TPI gives two different clues either the dominance of herbaceous plants in the swamp or an intense humification process leading to extensive destruction of plant tissues (Diessel 1992). On the other hand, high TPI suggests the presence of well-preserved plant tissue (telinite, fusinite and semifusinite), a high proportion of arboreal vegetation (telinite, collotelinite, fusinite and semifusinite) and aerobic condition.

The GI scales the intensity and time of wet condition (Diessel 1992). It decreases with the increase of oxidation. Further, a high GI and TPI point to a meagre aerobic decomposition (Lamberson et al. 1991). In case of Karharbari coal, the GI and TPI values are moderately high. The GI and TPI values of Karharbari coal in this model (Fig. 6) indicates that these coals have evolved under telmatic conditions and wet forest swamp.

A facies model of Calder et al. (1991) is also used, which is based on the ground water index (GWI) and vegetation index (VI). In fact, this model is very similar to GI and TPI indices of Diessel (1986). The parameters used in the reconstruction of peat lands are the degree of ground water influence, relative rainfall (Kalkreuth et al. 1991; Ligouis and Doubinger 1991), changes in ground water level in the mire (Peatland = marsh + swamp), vegetation, mineral matter content and degree of preservation of maceral precursor (Calder et al. 1991). The GWI and VI are calculated as under:

$$\mathrm{GWI} = \frac{\text{Gelinite} + \text{Corpogelinite} + \text{Clay mineral} + \text{quartz} + \text{Vitrodetrinite}}{\text{Telinite} + \text{Collotelinite} + \text{Collodterinite}}$$

$$\mathrm{VI} = \frac{\text{Telinite} + \text{Collotelinite} + \text{Fusinite} + \text{Semifusinite} + \text{Suberinite} + \text{Resinite}}{\text{Collodterinite} + \text{Inertodetrinite} + \text{Alginite} + \text{Liptodetrinite} + \text{Sporinite} + \text{Cutinite}}$$

Based on GWI and VI index, Calder et al. (1991) retrieved major mire paleoenvironments- such as limnic (open water marsh), swamp, fen and bog (Fig. 7) representing rheotrophic and ombrotrophic hydrological conditions. The GWI and VI values of Karharbari coals suggest the deposition of peat in swamp forest, mostly under rheotrophic to mesobrotrophic hydrological conditions, but few plots also lying in the ombrotrophic zone (Fig. 7).

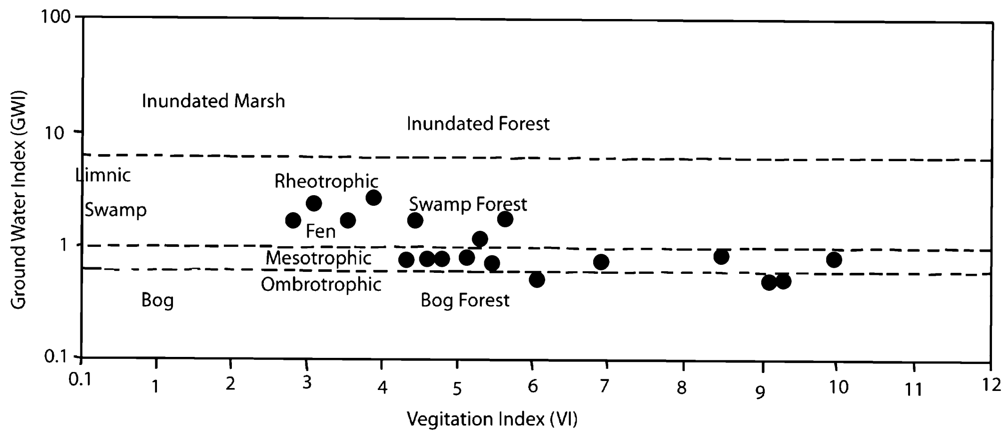

Fig. 7 Karharbari coals, Talcher coalfield, Mahanadi valley, Orissa, GWI versus VI Paleoenvironment diagram (modified after Calder et al. 1991)

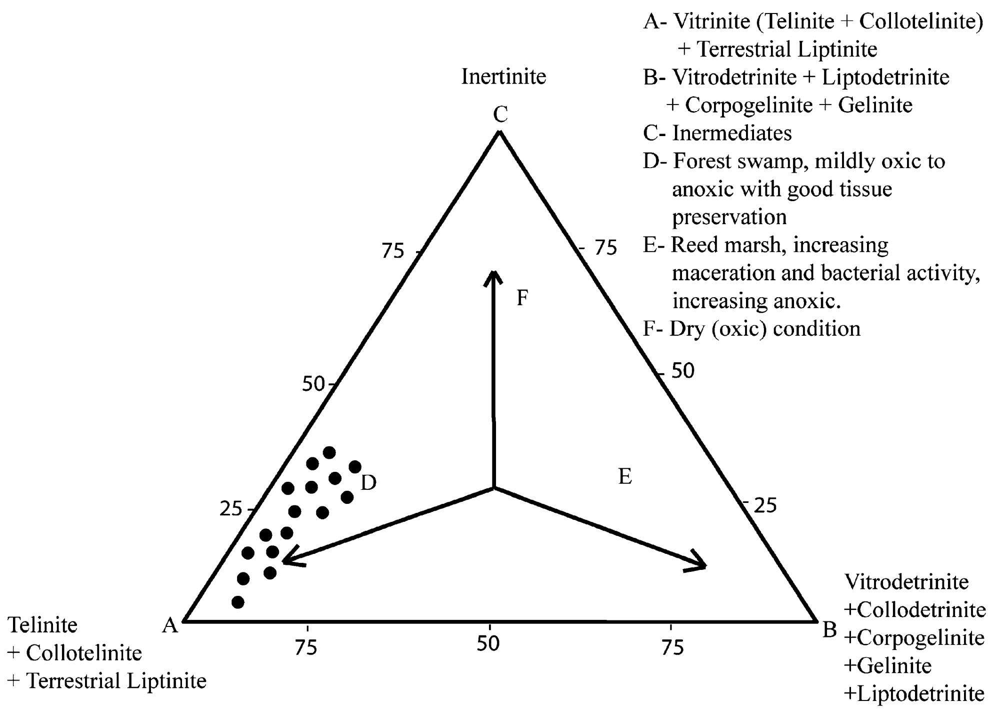

Fig. 8 Ternary diagram illustrating facies critical maceral association in Karharbari coals, Talcher coalfields, Mahanadi valley, Orissa and suggested peat forming environment (modified from Mukhopadhyay 1986)

A facies model proposed by Mukhopadhyay (1986) has also been used for the Karharbari coals based on the maceral composition. In this model (Fig. 8), plots of Karharbari coals indicate again their origin by forest swamp under mildly oxic to anoxic conditions with good tissue preservation.

A facies model proposed by Singh and Singh (1996) has been applied which is based on the maceral and mineral matter content. In this model more emphasis has been given in the quantitative occurrence of mineral matter in coal because it directly relates to the influx of surface water cover in swamps. The plots of Karharbari coal in this model suggest that these coals was deposited in alternating oxic and anoxic mire (Fig. 9) It is indicative of fluctuating water cover in the basin.

Yet another facies model based on Microlithotype has also been used (Singh et al. 2013) to infer the paleodepositional conditions of coals. Three parameters (A, B and C) have been taken into considerations which are as under:

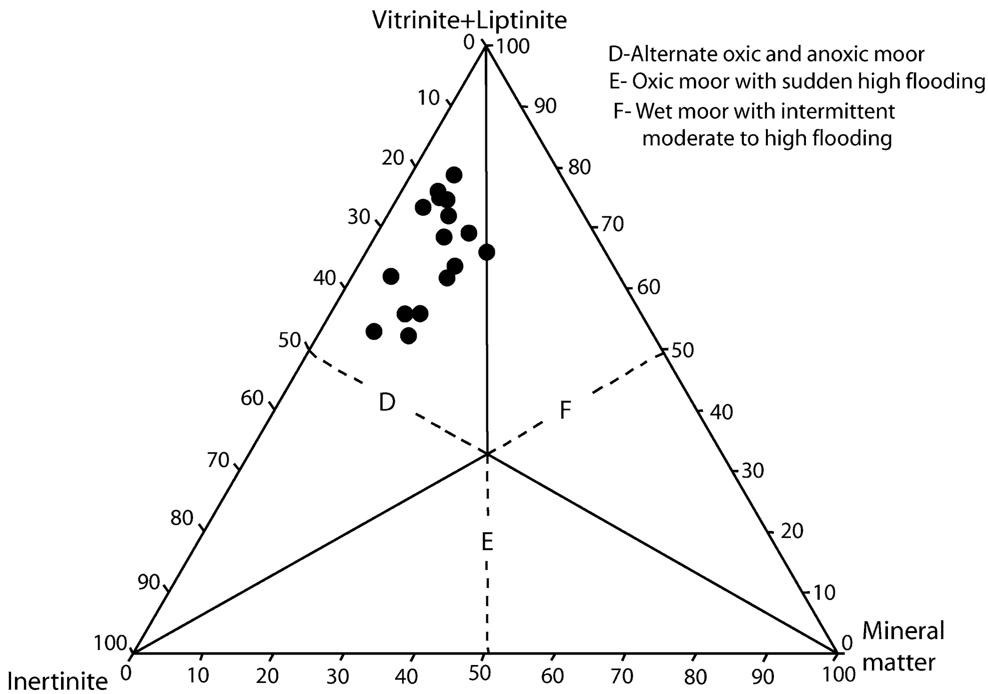

Fig. 9 Depositional conditions of coals based on maceral and mineral matter content (after Singh and Singh 1996)

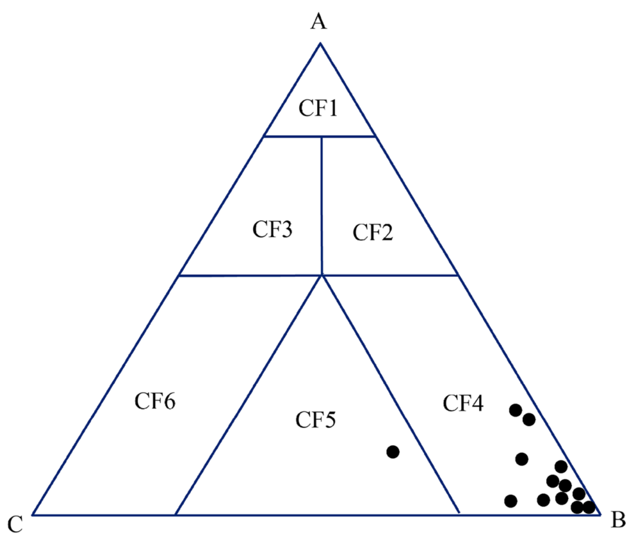

Fig. 10 Coal facies based on microlithotype composition of Karharbari coals form the Talcher coalfields, Mahanadi valley Orissa, *CF1* deep water facies characterized by organic mud rich liptinite, *CF2* open water with dominance of sub aquatic plants, *CF3* forest swam with sudden eustatic change, *CR4* forest reed swamp, *CF5* forest swamp, *CF6* mass swamp with extremely dry conditions (Singh et al. 2013)

A = Liptite + Clarite (L) + Vitrinertoliptite + Durite (L)

B = Vitrite + Clarite(V) + Vitrinertite (V) + Duroclarite

C = Inertite + Durite (I) + Clarodurite + Vitrinertite (I)

The types of facies delineated are:

CF1 Deep water facies, characterized by organic mud, rich in liptinites
CF2 Open water with dominance of subaquatic plants
CF3 Forest swamp with sudden eustatic changes
CF4 Forest to reed swamp
CF5 Forest swamp
CF6 Moss swamp with extremely dry conditions

The plots of Karharbari coal, on this model, suggest the development of forest facies (Fig. 10).

6 Conclusions

Petrographic study of the Karharbari coal shows that these coals are vitrinite rich, followed by liptinite and inertinite. Secondary liptinite macerals are observed in significant amount. The microlithotype analysis shows the dominance of vitrite followed by vitrinertite, clarite and inertite. The vitrinite reflectance (Ro) and volatile matter (d.a.f) values rank the Karharbari coal as high volatile bituminous ‘C’ to ‘B’. The microscopic constituents of Karharbari coal indicate peat accumulation in the forest mire under fluctuating oxic to anoxic conditions with good tissue preservation.

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