Panandhro lignite from Kutch (Gujarat), India : Petrological nature, genesis, rank and sedimentation

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Biopetrological investigation of four lignite seams and associated sediments of Lower Eocene (Ypresian) age from Panandhro Lignite field, district Kutch, Gujarat reveals that the lignite seams, under normal reflected light, are rich in huminite macerals with subordinate amounts of liptinite and inertinite macerals. Associated mineral matter (early diagenetic pyrite, calcite, clay and quartz) are low to moderately high. Under blue light excitation, they have quite high liptinite macerals formed chiefly of liptodetrinite and resinite. Fluorinite is sporadic and exsudatinite is rare. Alginite (*Botryococcus* and *Pleurocapsa*) are common to frequent. The rank of the lignite seams and associated sediments varies between R_o max. 0.43 to 0.44 per cent probably in response to persistently low geothermal gradient since Eocene and also shallow depth of burial. The lignite seams were formed mainly from autochthonous mangrove-mixed angiospermous forest vegetation with prolific undergrowths growing under humid tropical climate. Nonperennial herbs and shrubs, especially the pteridophytes, were mostly responsible for the formation of *in situ* inertinite macerals during dry periods and/or periodic lowering of water table. The peat accumulation for Seam Nos. 1, 2 and 4 took place under highly anaerobic and elevated pH (> 6) conditions of the swamp water which favoured precipitation of high amount of syngenetic pyrite and calcite. With the result vegetal matter were subjected to high microbial degradation and a fair amount of plant-derived mineral matter were released *in situ* for incorporation in the ancient peat. On the other hand, formation of Seam No. 3 was from a peat that accumulated under conditions favourable for vegetal preservation with relatively low pH of the swamp water. Its higher pyrite content is the result of leaching from the overlying highly pyriteous grey shales. It has been presumed that minor parting bands associated with lignite seams were formed *in situ* from severe degradation of organic matter The formation of authigenic partings caused splitting of a single basal seam into three separate ones which may be considered as parts of as a single composite seam. The lignite seams were formed in a lagoon from rheotrophic peat swamp near the then existing shore-line; the brackish water influence appears to have been significant.

The petrographic composition suggests that the lignite Seam Nos. 1 and 4 can be utilized better for the manufacture of organic chemicals, and the high amount of pyrite in lignite seams and associated sediments can be used for the production of sulphuric acid or even fertilizers.

Key-words—Petrology, Lignite genesis, Palaeoenvironment, Panandhro Lignitefield (India).

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सारॉंश

भारत में कच्छ (गुजरात) से पनान्धो लगुड़ांगार : शैलिकीय प्रकृति, उत्पत्ति, कोटि एवं अवसादन

बसन्त कुमार मिश्रा एवं गरुड़ कृष्ण बिन्दिग नवले

गुजरात में कच्छ जनपद के पनान्धो लगुड़ांगार-क्षेत्र से अधरि आदिनूतन (इप्रेसिअन) की चार सीमों तथा इनसे सहयुक्त अवसादों के जैवशैलिकीय अन्वेषण से व्यक्त होता है कि सामान्य परावर्तित प्रकाश में इनमें लिप्टीनाइट एवं इनर्टीनाइट मेसीरलों की कम मात्रा के साथ-साथ ह्यूमीनाइट की प्रचुर मात्रा है। इन मेसीरलों से सहयुक्त खनिज पदार्थों की भी निम्न तथा कुछ अच्छी मात्रा विद्यमान है। नीले प्रकाश में इनमें मुख्यतया लिप्टोडिट्रीनाइट एवं रेज़ीनाइट से बने लिप्टीनाइट की अत्याधिक मात्रा प्रेक्षित की गई है। फ्लोरीनाइट यत्र-तत्र बिखरा सा है जबकि एक्सूडेटिनाइट अत्यन्त कम है। ऐल्जिनाइट (**बॉट्रीओकॉकस** एवं **प्लूरोकैप्सा**) सामान्य अथवा काफ़ी अच्छी संख्या में मिलते हैं। लगुड़ांगार सीमों एवं सहयुक्त अवसादों की कोटि की अधिकतम परावर्तनशीलता 0.43 से 0.44 प्रतिशत तक प्रेक्षित की गई है ऐसा सम्भवतया आदिनूतन युग से लगातार निम्न भूतापीय प्रवणता तथा छिछले शवाधान के

फलस्वरूप हुआ है। ये सीमें आर्द्र उष्णकटिबन्धीय जलवायु में मुख्यतया स्वस्थानिक मैंग्रोव मिश्रित आवृतबीजी वनों से जिनमें कि अत्याधिक झाड़ियाँ आदि विद्यमान थीं, बनी हैं। शुष्क परिस्थितियों में विद्यमान अल्प-बहुवर्षजीवी शाकीय एवं झाड़ीदार पौधों, मुख्यतया टेरीडोफ़ाइटी पौधों, से स्वस्थानिक इनर्टीनाइट मेसीरल बने हैं। सीम 1, 2 और 4 में पीट का निक्षेपण अत्याधिक अवायवीय तथा पी-एँच० > 6 जैसी परिस्थितियों में हुआ है जिसके कारण इनमें सहजनित पाइराइट एवं केल्साइट की बहुत अधिक मात्रा विद्यमान है और यही कारण है कि वनस्पतिक पदार्थ का अत्यन्त जीवाणविक ह्रास हुआ है तथा इन सीमों में पौधों से व्युत्पादित खनिज पदार्थ बन गये हैं। इसके विपरीत सीम 3 एक ऐसी पीट से बनी है जो अपेक्षाकृत कम पी-एँच० वाली अनुकूल परिस्थितियों, जिनमें कि वनस्पतिक सामग्री का परिरक्षण संभव था, संग्रथित हुई थी। इसमें पाई जाने वाली पाइराइट की अधिक मात्रा इस सीम के ऊपर विद्यमान पाइराइट से भरपूर शैलों से बह कर आने के कारण है। ऐसा अनुमान है कि लगुडांगार सीमों से सहयुक्त छोटी-छोटी पट्टियाँ कार्बनिक पदार्थ के अत्याधिक ह्रासित होने के कारण उसी स्थान पर बन गई हैं। तत्रजनिक पट्टीयों के बन जाने के कारण आधारी सीम तीन अलग-अलग सीमों में बँट गई है। लगुडांगार सीमों की उत्पत्ति तत्कालीन समुद्र के समीपस्थ धारानुवर्ती कछारी पीट से एक समुद्रताल में हुई थी। शैलिकीय संरचना के आधार पर सीम 1 एवं 4 का अच्छा उपयोग कार्बनिक रसायनों के बनाने में किया जा सकता है तथा सीमों एवं सहयुक्त अवसादों में विद्यमान पाइराइट की अधिक मात्रा का उपयोग गंधक का अम्ल एवं खाद बनाने में किया जा सकता है।

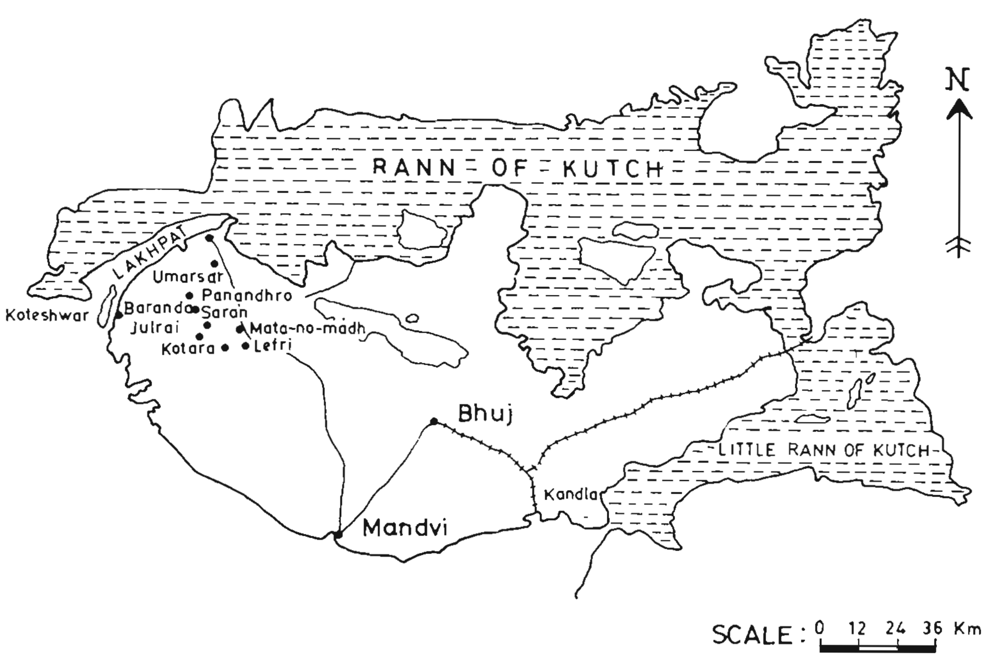
INDIA has about 2,350 million tonnes of exploitable lignite reserve (Gowrisankaran *et al.*, 1987). The lignite deposits are associated with Tertiary and Quaternary sediments ranging in age from Palaeocene to Pliocene-Pleistocene Epochs located in northern (Kashmir), southern (Tamil Nadu) and western (Rajasthan and Gujarat) parts of India. In the states of Rajasthan and Gujarat in western India, the lignite deposits are distributed widely in small isolated patches in contrast to the lignite deposits of Kashmir (Nichahoma) and Tamil Nadu (Neyveli) which are quite extensive. Nevertheless, these deposits are significant for the power hungry states of Rajasthan and Gujarat in view of their economic and fuel potential.

The Panandhro Lignitefield (23°41′ : 68°45′) in the Kutch District of Gujarat is the second largest lignite deposit of India after the Neyveli Lignitefield of Tamil Nadu (Text-fig. 1). It has a geological reserve of 95-100 million tonnes out of the total 220 million tonnes estimated for the state.

Petrographic data particularly on western Indian lignites are only few and limited. Pareek (1984) provided a brief comparative morpho-petrographic account of Panandhro and Palana (Bikaner District of Rajasthan) lignites. The present study deals in detail with the quantitative petrographic, rank and fluorescence characteristics of the lignite seams from the open-cast quarry of Panandhro Lignitefield in order to ascertain their genesis, type of source material and potential for economic utilization.

GENERAL GEOLOGY AND LITHOSTRATIGRAPHY

The Panandhro Lignitefield represents a valley base surrounded by semicircular hills formed by traps. The field is practically devoid of vegetation and falls under semi-arid climatic belt of India. The



Text-figure 1—A map showing main lignite fields of Kutch, Gujarat.

Tertiary basin of Kutch is a pericratonic shelf basin with a thin cover of sediments developed over the palaeotrappean country. The Tertiary sediments including the lignite deposit are disposed as a plunging syncline in an elliptical shaped basin with trap edges. The basin deepens towards NNE coinciding with the axis of the fold.

The lithostratigraphic classification of the Tertiary sequence in Kutch by Biswas and Raju (1971, 1973), based on studies mostly in southeastern part, was found unsuitable for the sediments exposed in the northwestern part by Saraswati and Banerjee (1984). They proposed another lithostratigraphic classification by recognizing five lithostratigraphic units as follows (given partly up to Middle Eocene):

Northwestern Kutch (Saraswati & Banerjee, 1984)			Southeastern Kutch (Biswas & Raju, 1973)
FORMATION	MEMBER	LITHOLOGY	
Kapurasi Formation (Mid. Eocene)	Foraminiferal Limestone (29.0-87.0 m)	White or buff, soft limestone packed with foraminifera	Fulra Limestone & a part of Harudi Formation (Mid. Eocene Lutetian)
	Argillaceous Limestone (1.0-2.6 m)	Greenish to brownish glauconitic (agrill.) limestone	
Panandhro Formation (Palaeocene to Early Eocene)	Gypseous Shale (1.0-4.5 m)	Grey to brownish gypseous shale, thin impersistent bands of coquina & limestone in the basal part	A part of Harudi, Naredi (Early Eocene-Ypresian) & Matanomadh (Palaeocene) Formations
	Carbonaceous Shale (12.5 m)	Dark grey carbonaceous shale with lignite beds, sandstone & mottled clays	
..........Unconformity..........			
Deccan Trap (Upp. Cretaceous to Palaeocene)		Basalt & residual laterite	

The Tertiary sediments in the area between Karanpur in northeast and Guvar in the southwest are exposed in two broad crescent-shaped belts converging at a central point eastwards near Fulra (Text-fig. 2, after Saraswati & Banerjee, 1984). The Deccan Traps (Upper Cretaceous-Palaeocene) are the basement rocks and are exposed as discontinuous patches in the south of Panandhro and north of Fulra lying west of Umarsar and Pranpura. The Tertiary strata are normally gentle dipping (2°-5°) towards north-north-east and north-east in the northern and north-north-west to north-west in the western parts. In the northeast near Lakhpat the beds show higher dips varying between 10°-20° and 60°-70° at Kapurasi due to faulting. The Tertiary sediments in the northwestern Kutch consist chiefly of carbonate rocks with lower part being shaly and the upper sandy in nature. The trap margins are covered with fine trap-derived sediments or trap-wash.

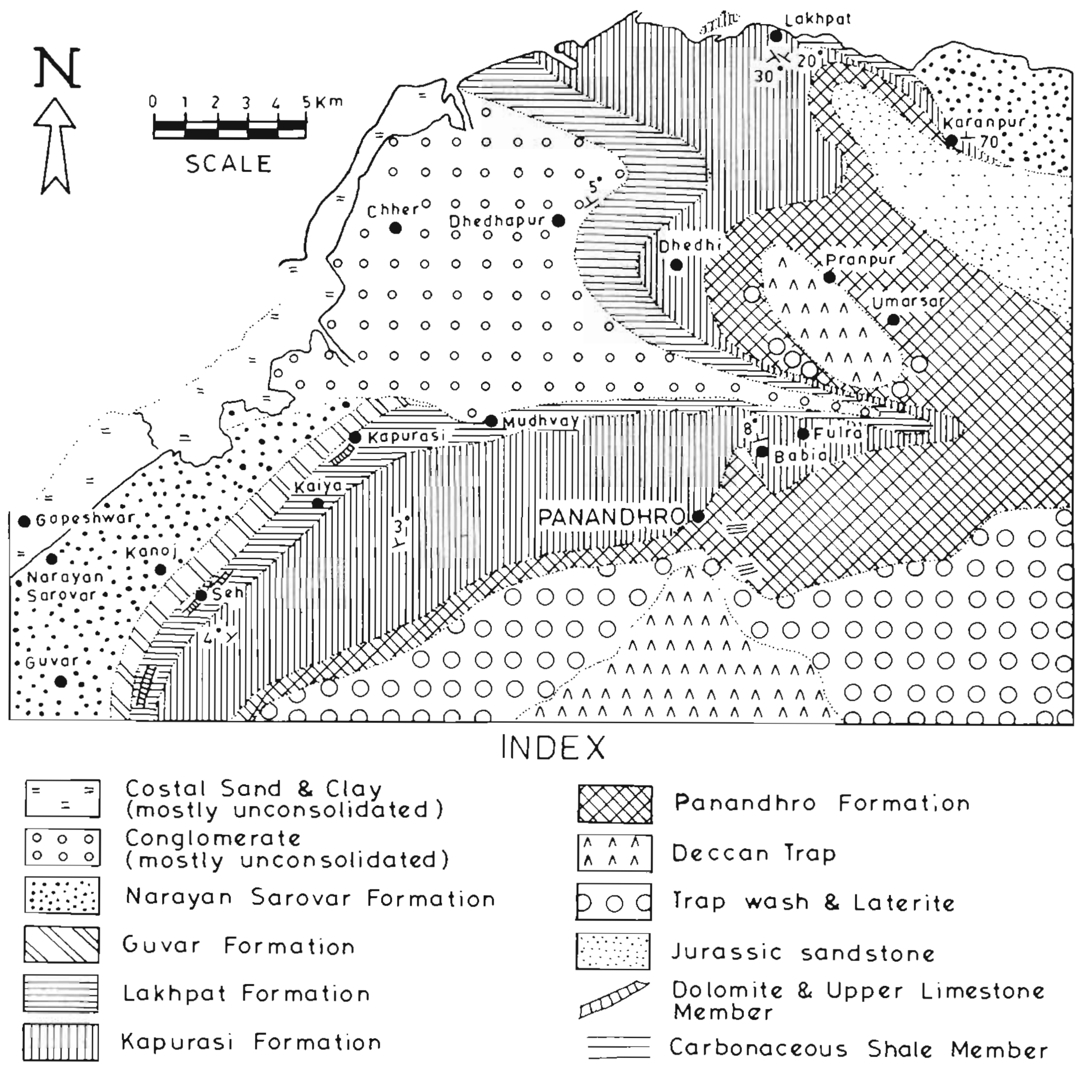
In Panandhro, the Lower Eocene (Ypresian) lignite deposit is associated with the lower member (Carbonaceous Shale Member) of the Panandhro Formation (Biswas & Raju, 1971; Saraswati & Banerji, 1984). The sedimentary sequence and lignite seam sections exposed in the Panandhro Lignite Quarry given by Gujarat Mineral Development Corporation are as follows:

Lithological Sequence

Red-ochre shale with gypsum pockets and blades	4.00 m
Yellow shale	2.00 m
Grey shale with bands of yellow shale	1.40-2.00 m
Calcareous sandstones with bands of grey shale containing ferruginous nodules	1.00 m
Grey carbonaceous shale	0.15 m
Brownish weathered sandstone	0.30 m
Lignite seam	10.45 m

Lignite Seam Section

Lignitic shale	0.30 m
Weathered lignite	1.00 m
Lignite with thin lenticular beds of clay	0.30 m
Resin-rich band	0.25 m
Lignite with resin-rich bands up to 2.0 cm thick at intervals of 1.0 m	3.00 m
Grey carbonaceous shale	0.60 m
Dull grey non-banded lignite with resin-rich bands containing siderite and pyrite	1.50 m
Carbonaceous shale with fractures and joints infilled with yellowish sulphurous spongy material	0.15 m
Dull, compact non-fragile lignite with sulphurous encrustations and white powdery matter (?marcasite and pyrite)	1.00 m
Resin-rich lignite	0.20 m
Dull, compact lignite	0.60 m



Text-figure 2—A geological map of north-western Kutch, Gujarat (after Saraswati & Banerjee, 1984).

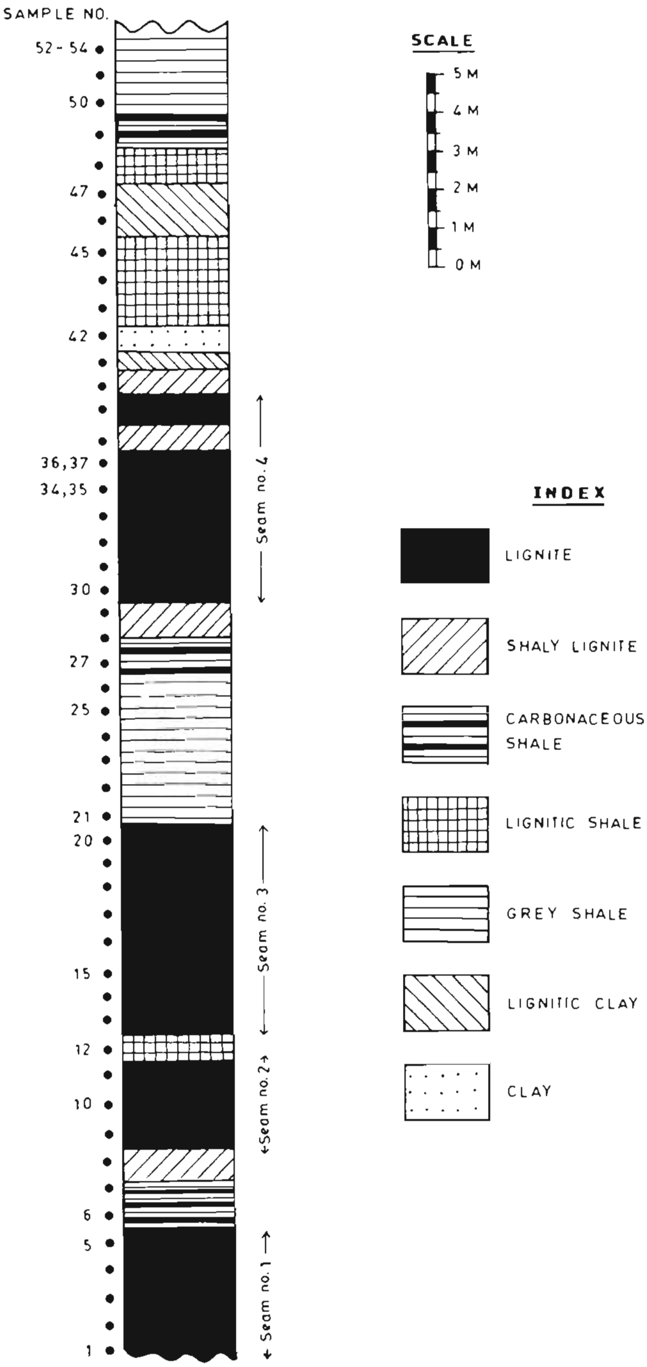
Resin-rich band	0.30 m
Dull, compact lignite	0.15 m
Resin-rich band	0.20 m
Friable, weathered lignite	1.00 m

In general, there are two workable lignite seams separated by grey shale, carbonaceous shale and clay beds. The maximum thickness of the lower seam is approximately 4.0 m whereas the upper seam may be as thick as 23.0 m with minor shale and clay intercalations. However, lateral digitations cause splitting of the seams and the number of seams may vary between 2 to 5 (Nadhamuni, 1976). In the present section four lignite seams (1-4 in ascending order) have been encountered (Text-fig. 3).

SAMPLE PREPARATION AND METHODOLOGY

Of the four lignite seams in the Quarry Section (Text-fig. 3), the bottom most seam (Seam no. 1 : sample nos. 1-5) is overlain by nearly 2.0 m thick carbonaceous shale and shaly lignite beds preceding Seam no. 2 which (> 2.0 m thick; sample nos. 9-11) is separated by a < 1.0 m thick lignitic shale bed from seam no. 3. Seam no. 3 (± 6.0 m thick; sample nos. 13-20) is overlain by a 4.0 m thick grey shale parting followed by carbonaceous shale and shaly lignite beds which merge upwards into Seam no. 4 (Sample nos. 30-37, 39). Seam no. 4 in its upper most part is punctuated and overlain by shaly lignite, lignitic clay, clay, lignitic shale, carbonaceous shale and grey shale beds.

In all, fiftyfour samples were collected in ascending order by a colleague (Dr RK Kar—for palynological study) approximately at an interval of 0.75 m from the lignite quarry. Sample nos. 35, 36, 53 and 54 were collected laterally and thus not used in the present study. The samples were crushed (grain size between ± 1-2 mm excluding fines) and



Text-figure 3—A litholog showing lignite seams and associated sediments along with the position of samples.

50 particulate pellets were prepared by cold embedding in epoxy. Biopetrological study and reflectance measurements were carried out following I.C.C.P. (1971) procedures on MPV-1. Fluorescence study, under incident blue light excitation, was done on Leitz MPV-3 using 150 watt Xenon lamp and oil immersion objectives (NPL Flutar 25 and 40) with high numerical aperture. The descriptive terminology for fluorescing macerals is given by Stach *et al.* (1982).

MEGASCOPIC CHARACTER

The Panandhro lignite is dark brown in colour with amorphous texture and sparingly banded in nature. According to Pareek (1984) the lignite is compact when fresh but becomes brittle and disintegrates on exposure to air. Thin lenticular bands of carbonaceous shale occur, at places, in the lignite seams. Specks, globules, lenses and bands of yellow and red coloured resins occur at intervals through out the seam. Pyrite is frequent in the seams as specks and granules, whereas associated sediments have pyrite nodules and nuggets also.

PETROLOGICAL CHARACTER

Under Normal Incident Light

Lignite and non-lignite samples have high proportion of huminite macerals formed mainly by attrinite and densinite. Maceral ulminite (ulmo-textinite and texto-ulminite) is significant in lignite seams only. Corpohuminite is common and textinite is sporadic to rare. Resinite is the commonest liptinite maceral followed by sporinite, cutinite and suberinite. Main inertinite macerals are semifusinite, inertodetrinite and sclerotinite. Associated mineral matter are moderate to high in amount constituted by clay, quartz, pyrite and calcite.

Huminite Group

Humotelinite and humodetrinite macerals exhibit granular or spongy texture and a fraction of them is distinctly low reflecting and greyer in appearance than normal ones. This low reflecting huminite has been, for convenience, termed as 'grey huminite'. Lignite seams, in general, have high proportion of humodetrinite (14.0-47.4%) and humotelinite (4.2-50.8%) macerals (Table 1; Text-fig. 4). Seam no. 3 has highest average contents of total huminite and humotelinite macerals (67.2% and 31.9%) followed by Seam nos. 2, 1 and 4 (64.5 and 15.5%, 51.8 and 13.6%, 40.7 and 8.2% respectively). Shaly lignite, carbonaceous shale, lignitic shale, lignitic clay, grey shale and clay samples mainly have humodetrinite macerals which show progressive decrease with the increase of mineral matter content.

Table 1—Composition of macerals and mineral matter (under normal reflected light) in the lignite seams (1-4) and associated sediments from Panandhro lignitefield, Kutch

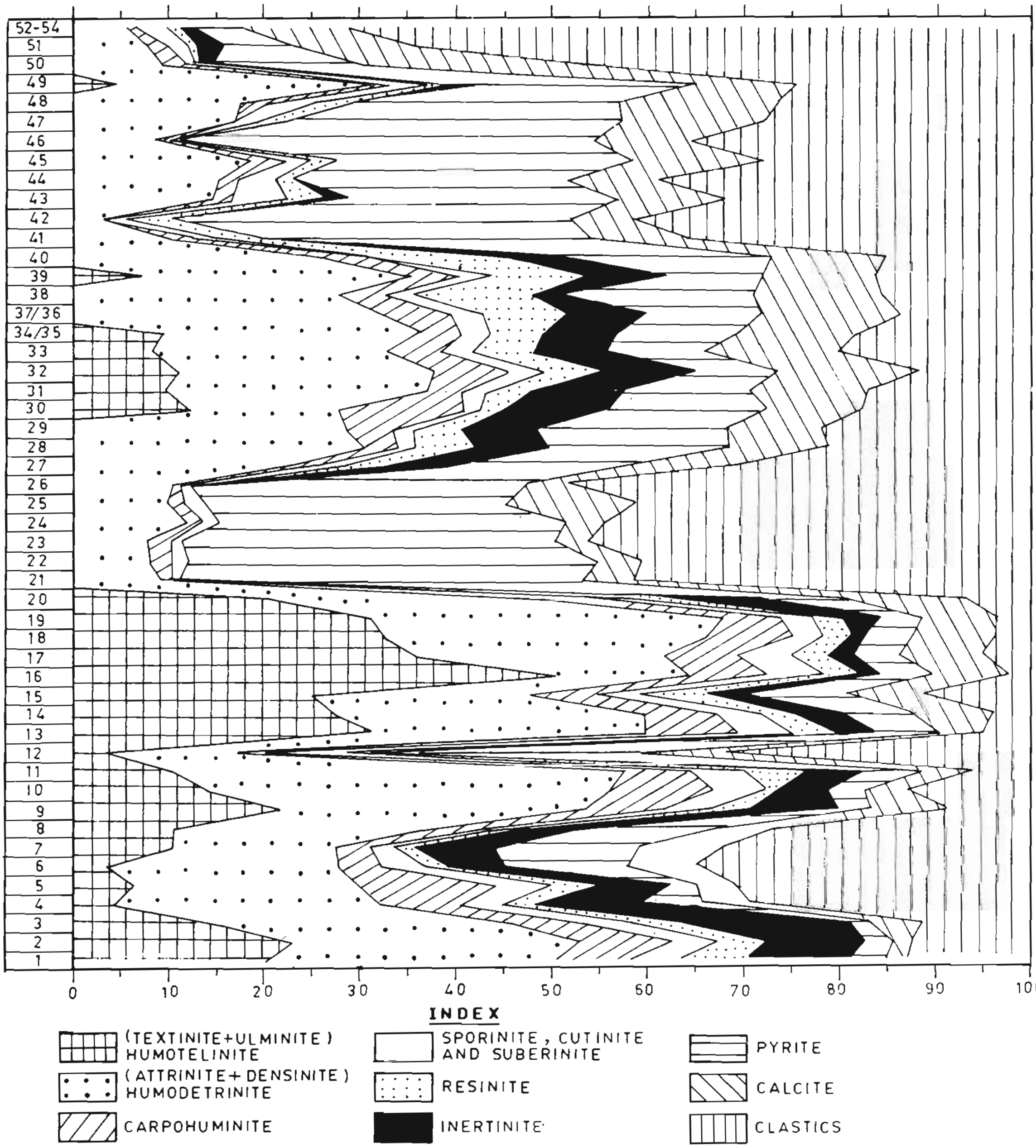
Lithology of samples	Seam 1	Seam 2	Seam 3	Seam 4	Shaly lignite (8,28,29, 38,40)	Carbonaceous shale (6,7,27, 49)	Lignitic shale (12,43-45,48)	Lignitic clay (41,46, 47)	Grey shale (21-26, 50-52)	Clay (42)
Maceral Composition (volume %) under normal reflected light										
Humotelinite (Textinite + Ulminite)	4.2-23.0 (13.6)	10.4-21.8 (15.5)	20.6-50.8 (31.9)	0-12.0 (8.2)	0-10.6 (2.2)	3.4-10.4 (4.6)	0-3.2 (0.6)	—	—	—
Humodetrinite (Attrinite + Densinite)	28.2-32.0 (30.3)	32.0-47.4 (40.5)	14.0-37.0 (27.9)	15.8-32.2 (25.8)	26.2-30.6 (27.9)	17.2-26.8 (22.8)	14.4-18.8 (16.2)	8.6-16.8 (11.8)	4.4-12.0 (8.5)	3.0
Humocollinite (Gelinite + Carpo huminite)	6.8-9.8 (7.9)	7.0-10.6 (8.5)	4.8 9.4 (7.4)	4.2-13.0 (6.7)	3.4-6.4 (4.7)	2.4-4.6 (3.5)	2.2-3.6 (2.7)	0-2.6 (1.4)	1.2-2.6 (0.9)	—
Total Huminite	40.4-62.8 (51.8)	61.8-67.0 (64.5)	53.8-75.4 (67.2)	38.2-45.4 (40.7)	30.6-43.6 (34.8)	24.6-34.2 (30.9)	16.8-22.4 (19.5)	10.0-16.8 (13.2)	5.6-12.0 (9.4)	3.0
Sporinite	3.6-5.6 (4.5)	3.8-4.8 (4.2)	2.0-4.2 (3.0)	1.8-3.2 (2.6)	0.2-2.2 (1.6)	2.0-3.2 (2.5)	1.4-2.8 (2.3)	0.8-2.0 (1.3)	0.4-2.2 (1.3)	1.4
Cutinite + Suberinite	0.-1.2 (0.7)	0.4-1.8 (1.3)	0.2-3.0 (1.5)	0-1.2 (0.5)	0-0.8 (0.4)	0.2-2.0 (1.1)	1.0-3.2 (1.8)	0-1.0 (0.6)	0-2.0 (0.4)	1.0
Resinite + Secondary Liptinite	3.6-6.8 (5.3)	1.4-6.8 (3.9)	3.0-6.8 (4.2)	2.2-10.2 (6.4)	1.2-13.8 (7.5)	2.0-4.6 (2.9)	1.6-5.2 (3.5)	0-5.6 (2.6)	0.6-2.2 (1.3)	4.6
Total Liptinite	8.0-12.2 (10.5)	7.0-12.0 (9.3)	6.0-11.2 (8.7)	4.0-14.6 (9.5)	3.4-14.8 (9.5)	4.4-7.8 (6.5)	5.2-10.2 (7.6)	1.2-7.4 (4.5)	1.4-5.0 (3.0)	7.0
Semifusinite + Fusinite	6.4-13.8 (8.9)	1.8-4.8 (3.2)	0.8-5.4 (2.5)	2.8-8.0 (5.3)	1.8-6.0 (3.5)	1.8-4.4 (3.6)	0-1.4 (0.5)	—	0-1.8 (0.3)	—
Inertodetrinite + Macrinite + Micrinite	0-1.8 (1.1)	1.0-3.2 (2.0)	0.2-6 (1.1)	0.8-4.0 (2.6)	0.8-3.6 (2.0)	0.6-2.6 (1.5)	0-1.6 (0.45)	—	0-0.8 (0.3)	—
Sclerotinite	0.8-1.6 (1.2)	1.2-2.0 (1.4)	0-1.0 (0.4)	0.6-1.6 (1.0)	0-1.4 (0.5)	0.4-1.8 (0.9)	0-0.2 (0.04)	—	0-0.4 (0.08)	—
Total Inertinite	7.4-17.0 (11.2)	4.8-9.2 (6.7)	2.0-8.4 (4.0)	7.6-11.2 (8.9)	3.0-8.0 (6.0)	3.0-8.4 (6.0)	0-3.0 (1.0)	— —	0-2.8 (0.7)	—
Pyrite	2.0-6.8 (3.4)	3.4-6.2 (4.5)	4.2-10.8 (6.6)	8.2-16.4 (11.8)	13.0-20.4 (18.6)	12.6-22.4 (17.3)	26.8-30.8 (28.4)	35.4-43.6 (37.7)	4.7-42.6 (28.3)	42.0
Calcite	2.0-5.4 (3.5)	4.4-8.0 (5.9)	4.6-12.8 (8.4)	9.8-14.8 (12.9)	6.0-12.0 (10.3)	7.2-10.4 (9.2)	9.4-16.6 (12.1)	6.6-14.6 (11.6)	3.6-23.2 (9.4)	6.6
Clastic Minerals	11.2-30.8 (19.6)	5.6-13.0 (9.1)	2.2-11.2 (5.1)	11.8-20.0 (16.3)	16.4-26.6 (20.8)	23.4-34.8 (29.9)	26.4-39.2 (31.4)	28.2-35.6 (33.0)	40.2-71.1 (49.2)	41.4
Total Mineral Matter	17.2-40.8 (26.5)	17.2-21.2 (19.5)	15.4-30.0 (20.1)	34.8-44.2 (41.0)	46.4-51.6 (49.7)	54.6-60.6 (56.4)	68.2-77.2 (71.9)	78.2-88.8 (82.3)	81.8-89.6 (86.9)	90.0
R_o max %	0.43-0.46 (0.44)	0.43 —	0.41-0.44 (0.43)	0.42-0.46 (0.43)	0.42-0.44 (0.43)	0.43-0.45 (0.44)	0.43-0.45 (0.44)	0.44-0.45 (0.44)	0.42-0.47 (0.44)	0.44

Liptinite Group

The main liptinite macerals in the samples from Panandhro, in order of decreasing abundance, are resinite, sporinite, cutinite and suberinite. Secondary liptinites are rare (for details refer Misra, 1991). Liptinite contents of lignite seams (4.0-14.6%) and shaly lignite (3.4-14.8%) are almost identical. Rest of the sediments contain relatively lower proportions of liptinite macerals (Table 1).

Inertinite Group

Semifusinite, inertodetrinite and sclerotinite are the main inertinite macerals recorded. Fusinite is usually absent (in 14 out of 23 lignite samples) or rare (0.2-1.8% in 7 lignite samples), however, occasionally it is significant (2.4 and 5.2% in sample nos. 3 and 20) in a few samples. In general, rank and degrado-semifusinite/fusinite have been recorded



Text-figure 4—A cumulative frequency diagram of macerals and mineral matter in the samples of lignite seams and associated sediments from Panandhro Lignitefield (from analysis under normal reflected light).

with poor structural preservation. Homogeneous (gelified) inertinite fragments are also common. Macrinite (0.2-1.8%) and micrinite (0.2-1.0%) are sporadic. Inertinite content is usually high in the basal parts of the lignite seams (Text-fig. 4). Seam no. 1 records highest average amount of total inertinite (11.2%) progressively decreasing up to Seam no. 3 to increase again in Seam no. 4 (Table 1).

Mineral matter

Clastic minerals (clay and quartz), syngenetic pyrite and calcite are the mineral matter recorded presently. Clastic minerals occur in lumps, bands, filled in lumens of inertinite (occasionally) and huminite macerals and randomly dispersed in attrinite and densinite. It is also associated with pyrite which occurs as framboids, crystals and granules. Framboids are either solitary, in bands, aggregates or in large mass forming crusts. Crystalline pyrite are, especially common in non-lignite samples. Individual pyrite crystals are triangular in polished sections representing faces of octahedron. Octahedral crystals are also seen. They show loose granular texture and are frequently twinned. The mineral is commonly associated with liptinite macerals also. Calcite occurs mostly as concretions, however, crack-filling calcite is also present.

Non-lignite samples are moderately to highly pyriteous with distinctly low calcite content (Table 1). In lignite seams calcite content is always higher than pyrite. Both of them together constitute 53.3 to 74.6 per cent of the total mineral matter content in lignite seams and shaly lignite beds except in Seam no. 1 which has appreciably high amount of clastics (74.0% of the total mineral matter).

Under blue light excitation

The macerals alginite and liptodetrinite are additionally recorded under blue light excitation. Record of alginite, liptodetrinite and increase in the proportion of cutinite were found to be at the expense of argillaceous matter and calcite. Whereas, certain fraction of calcite and sporinite proved to be compressed cell-filling and discrete resinite bodies and thus added to the resinite content. Evidently, amounts of sporinite, calcite and argillaceous matter, especially in lignite seams and shaly lignite beds, appear to be over-represented in the analysis under normal reflected light (Table 1).

Huminite Group

In the samples from Panandhro only weakly reflecting huminite with spongy texture (grey huminite) fluoresces with dark reddish brown or brown colour. 'Grey huminite' is also characterized with very small granules (1.0 to few microns in size) of some fluorescing material, probably yellowish orange to brown coloured resin droplets, embedded in huminite groundmass. The fluorescing huminite varying between 0.7 to 17.0 per cent is restricted in Seam nos. 1 to 3 and in low proportions (0-2.4%) in a few samples of shaly lignite and carbonaceous shale (Table 2).

Liptinite Group

Sporinites fluoresce with pale yellow to yellow colour. However, some of them show yellowish brown to dull orangish-brown colour. Cutinite and suberinite emit yellowish orange to orangish-brown and yellowish-brown to brown colours respectively. Alginite (*Botryococcus* and *Pleurocapsa*) has highest fluorescence intensity among the liptinite macerals and shows bright yellow colour. Fluorinite with bright greenish yellow to yellow colour occurs sporadically in many samples associated with cell-

Table 2—Maceral composition (under incident blue light excitation-m.m.f.) of lignite seams (1-4) from Panandhro Lignitefield, Kutch

Lithology of samples	Seam 1 (1-5)	Seam 2 (9-11)	Seam 3 (13-20)	Seam 4 (30-37, 39)	Shaly lignite (8,28,29, 38,40)	Carbonaceous (6,7,27, 49)	Lignitic shale (12,43-45,48)	Lignitic clay (41,46, 47)	Grey shale (21-26, 50-52)	Clay (42)
Maceral Composition (volume % m.m.f.) under blue light excitation										
Huminite + Inertinite (non-fluorescing)	32.7-72.5 (61.0)	54.4-75.1 (67.1)	47.0-69.5 (59.8)	46.4-58.8 (51.8)	40.9-83.5 (53.4)	32.4-75.5 (62.1)	47.5-80.9 (61.2)	53.5-93.0 (72.7)	54.8-96.0 (86.7)	78.4
Huminite (Fluorescing)	0.9-6.5 (2.9)	0.7-2.6 (1.4)	1.9-17.0 (9.0)	—	0.2.4 (0.7)	0-2.0 (0.5)	—	—	—	—
Sporinite	0.4-1.7 (1.1)	0.6-1.7 (1.2)	0.7-2.1 (1.4)	0.3-1.3 (0.7)	0.5-2.0 (1.0)	0.7-2.4 (1.2)	0.9-2.5 (1.6)	0-1.0 (0.6)	0-1.5 (0.8)	1.0
Cutinite	0.8-2.5 (1.7)	2.5-4.8 (3.9)	0.5-5.2 (3.0)	0-3.2 (1.3)	0.4-3.3 (1.5)	0.4-4.8 (3.1)	3.1-7.7 (4.6)	0-2.8 (1.8)	0-3.3 (1.05)	2.8
Suberinite + Exsudatinite + Fluorinite + Alginite	0-1.5 (0.6)	0-1.2 (0.4)	0-2.0 (0.6)	0-1.6 (0.7)	0-1.6 (0.8)	0-0.8 (0.4)	0-2.4 (1.0)	0-1.7 (0.9)	0-0.6 (0.5)	0.4
Alginite* (recorded & observed)	— Less common	— Less common	0.4-0.6 Frequent	0.4-0.8 Frequent	0.4-0.8 Frequent	— Less common	0.4-1.0 Frequent	— Less common	0.6 Sporadic	0.4 common
Resinite	6.9-15.3 (11.6)	4.9-16.1 (10.1)	6.1-16.5 (9.2)	7.6-23.8 (16.1)	4.4-26.8 (17.3)	5.2-13.2 (8.3)	6.7-12.0 (9.5)	3.0-26.0 (10.6)	3.0-10.8 (5.6)	11.2
Liptodetrinite	11.9-43.9 (21.1)	10.0-24.6 (15.9)	12.4-27.7 (17.0)	16.2-43.6 (29.4)	10.4-39.9 (25.9)	13.2-50.8 (24.4)	18.4-38.0 (22.1)	4.0-21.0 (13.4)	0-37.6 (7.8)	6.2
Liptinite (total)	26.0-64.0 (36.1)	24.1-44.9 (31.5)	26.8-46.0 (31.2)	41.2-54.4 (48.2)	15.7-58.3 (46.5)	24.5-67.6 (37.4)	19.1-52.2 (34.8)	7.0-46.3 (27.3)	4.0-45.2 (15.3)	21.6

Data in parenthesis are average. *Recorded and observed frequencies of alginite are given additionally.

filling resinites and leaf sections. Exsudatinite is rare and fluoresces with yellowish orange to brownish orange colour. The resinite fluoresces with widest range of colour and intensity—bright yellowish green to dull brown. Fluorescence properties of liptinite macerals have already been dealt in detail by Misra (1991).

In general (Table 2), Seam no. 4 has the highest average content of liptinite (48.2%) followed by shaly lignite (46.5%), carbonaceous shale (37.4%), Seam no. 1 (36.1%), lignitic shale (34.8%), Seam no. 2 (31.5%) and Seam no. 3 (31.2%). Seam no. 4 and shaly lignite have the highest proportions of liptodetrinite (average 29.4% and 25.9%) and resinite macerals (7.6-23.8% and 4.4-26.8%). Cutinite is especially common in lignitic shale, Seam nos. 2 and 3 and carbonaceous shale. Suberinite is sporadic (up to 1.7%) in occurrence. Though the alginite has been recorded only in 11 samples (0.4-1.0%), it is present in almost all of them.

Rank (Reflectance Measurement)

Reflectance measurements on lignite and non-lignite samples suffered from insufficient amount of suitable huminite macerals with the result densinite and phlobaphinite macerals were also used to complete 100 measurements. Meagre content of densinite and phlobaphinite in grey shale, lignitic clay and clay samples restricted the number of measurements to only 25-50.

The calculated mean maximum reflectance values were averaged for various lithologies to assess their rank (Table 1). Seam no. 1 has higher R_o max (0.44%) than rest of the three seams (0.43%). The rank attained by the lignite seams is equivalent to Matt-brown coal stage or sub-bituminous C/B stage (ref. table 4 and fig. 25 of Stach *et al.*, 1982). The variation in R_o max values of lignite and non-lignite samples are apparently caused by the measurements made on densinite and phlobaphinite macerals. It is also possible that certain amount of recycled or partially oxidized huminite macerals, especially in shale and clay samples, contributed to higher than the normal R_o max values.

DEPOSITIONAL ENVIRONMENT AND GENESIS OF THE LIGNITE

The coastal basins of western India are largely tectonic in origin formed by marginal fracturing of Indian land mass during Early Permian (Saraswati & Banerjee, 1984a). Black shale facies developed locally, as in Panandhro, comprising black pyriteous shale, predominance of argillite and lignite beds are suggestive of low energy lagoonal to marine shelf environments (Biswas & Raju, 1973; Hardas & Biswas, 1973). On the other hand, Saraswati and Banerjee (1984a) relate the formation of lignite and carbonaceous shale beds from flood drifted vegetal matter under lacustrine condition.

The lignite seams and associated sediments of Panandhro Formation have yielded a variety of pollen and spores, algae and phytoplanktons (Kar, 1985). Fungal elements are especially frequent (60.0-80.0%) in Seam no. 1 and 2. Phytoplanktons are occasionally dominant in Seam no. 1 (up to 78.0%) whereas, algae (*Botryococcus*) is persistently present (5.0-40.0%) with occasional dominance above Seam no. 4.

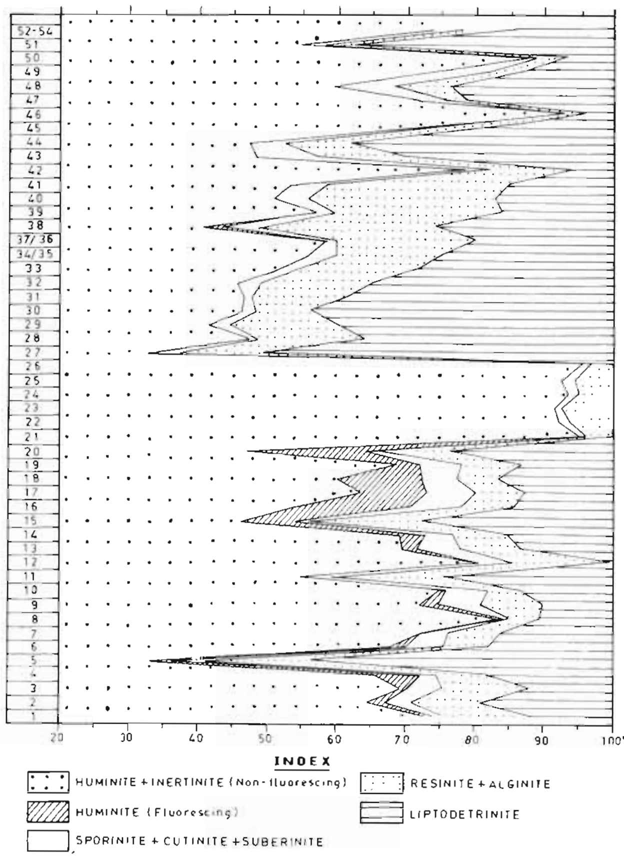
Pteridophytic spores in the assemblage are referable to families Lycopodiaceae (*Lycopodiumsporites*), Schizaeaceae (*Lygodiumsporites*) and Matoniaceae (*Dandotiaspora*). Recovered significant angiospermous pollen belong to families—Alangiaceae, Apiaceae, Arecaceae (*Proxapertites, Arengapollenites, Spinomonosulcites, Spinozonocolpites*, etc.), Bombacaceae (*Lakiapollis*), Asteraceae, Clusiaceae, Combretaceae, Lecythidaceae (*Barringtonia*), Liliaceae, Meliaceae, Poaceae, Polygalaceae, Proteaceae, Rhizophoraceae and Thymeliaceae.

Very little megafossil information is available from the area (Lakhanpal & Guleria, 1983). The taxa recorded include *Terminalia* (Combretaceae), *Cinnamomum* (Lauraceae), *Lagerstroemia* (Lythraceae), *Ficus* (Moraceae), *Syzygium* (Myrtaceae) and *Pandanus* (Pandanaceae).

Palynological and megafloral evidences (Lakhanpal & Guleria, 1983; Kar, 1985) reflect a coastal, beach and littoral swampy including mangrove plant communities of evergreen forest dominated by angiospermous plants (mostly tree) flourishing under humid tropical climate in the Panandhro and nearby areas during Early Eocene Epoch in contrast to the present day shrubby vegetation under sub-xeric conditions.

The dominance of huminite macerals (Table 1; Text-fig. 4) in the lignite seams suggest their origin chiefly from woody vegetation. High proportion of resinite (Table 2; Text-fig. 5), in the absence of gymnospermous plants, suggests common presence of resin or latex producing and gum or essential oil secreting angiospermous plants. Presence of thick-walled cutinite in the Panandhro samples is possibly related with the existence of mangrove vegetation supporting palynological evidences.

Relatively high inertinite contents in the basal parts of the lignite seams and its recurrence in the upper part of Seam no. 3 (Text-fig. 4) has been

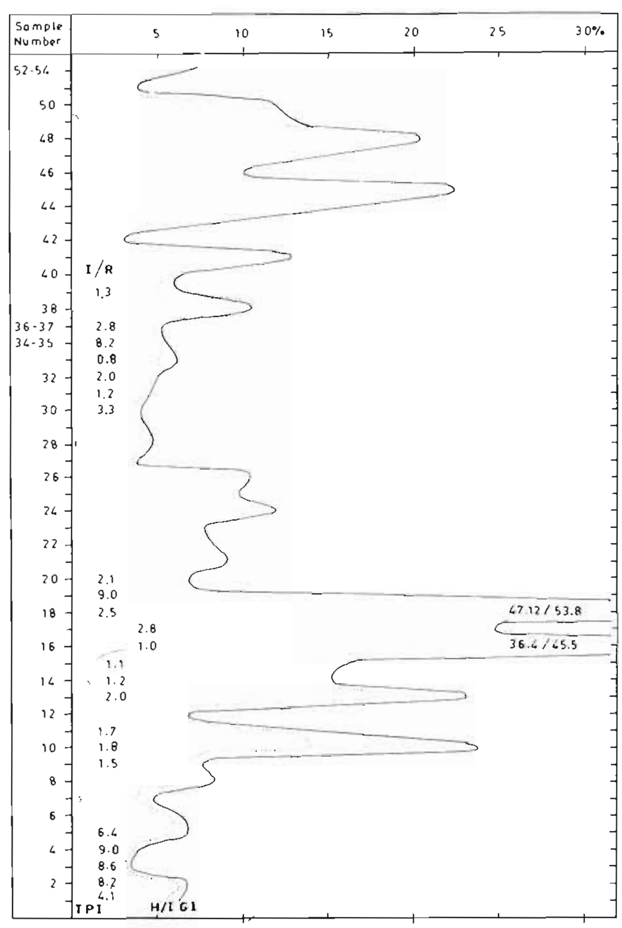


Text-figure 5—A cumulative frequency diagram of fluorescing and non-fluorescing macerals (m.m.f) in the lignite and non-lignite samples from Panandhro lignitefield (from analysis under blue light excitation).

found to be related with the increase in the population of undergrowths, especially pteridophytes (Smyth, 1980; Misra, 1991a). Sporadic occurrence of fusinite in very low amount preclude the possibility of forest fire. However, occasional wet cindering or aerial exposure of ancient peat locally due to receding water table might have favoured such sporadic inertinite formation. Presence of chiefly rank- and degrado-semifusinites in the Panandhro samples suggests their formation from biodegradation and oxidation of ungelified (mostly cellulosic fraction) and gelified humic material during diagenesis (Teichmüller, 1989).

Huminite/Inertinite ratio (H/I in Text-fig. 6) of Seam no. 2 (> 6·14) and Seam no. 3 (> 12 –> 47) indicates their formation near palaeochannels with high tree density. Whereas, Seam nos. 1 and 4, with relatively low H/I ratios were formed some distance away (Harvey & Dillion, 1985). This conclusion is not in conformity with the liptinite and clastic mineral contents of the lignite seams (Tables 1, 2, Text-fig. 6). Harvey and Dillion (1985) found higher liptinite contents in coals formed near palaeochannels than those formed away from them.

Petrographic composition (Tables 1, 2; Text-figs 4, 5) shows that the vegetal matter in the ancient peat and associated sediments were subjected to high degree of microbial degradation. In order to assess the degree of degradation some selected maceral and mineral contents (average %) for lignite seams, shaly lignite, carbonaceous shale and lignitic shale beds, arranged according to humodetrinite contents (on 100% huminite basis), are given in Table 3. The data shows that the vegetal degradation, i.e., the percentage of humodetrinite increases with increasing pyrite content. However, the degree of degradation is not directly proportional to their contents. A somewhat similar relation, with one exception (Seam no. 1), exists between humodetrinite and clastic contents. The behaviour of liptodetrinite with humodetrinite and pyrite is incompatible with the observed relation between the latter two. Seam no. 3 showing highest vegetal preservation (and lowest humodetrinite content) in



Text-figure 6—A biaxial diagram showing trends of Tissue Preservation Index (TPI), Gelification Index (GI), Huminite/Inertinite Ratio (H/I) and I/R Ratio (in numerals) of lignite and non-lignite samples from Panandhro Lignitefield.

Table 3—Some selected maceral and mineral matter data (average %) of the lignite seams, shaly lignite, lignitic shale and carbonaceous shale samples compiled to show their inter-relationships

Lithology	Average % of Maceral and Mineral Matter						
	Humode-trinite$_1$	Liptode-trinite$_4$	Pyrite$_3$	Pyrite$_2$	Calcite$_2$	Clastic mineral$_2$	Mineral matter$_3$ (total)
Lignitic shale	83.0	22.1	28.4	39.5	16.8	43.7	71.9
Shaly lignite	80.2	25.9	18.6	37.4	20.7	41.9	49.7
Carbonaceous shale	73.8	24.4	17.3	30.7	16.3	53.0	56.4
Seam No. 4	64.4	29.4	11.8	28.8	31.5	39.7	41.0
Seam No. 2	62.8	15.9	4.5	23.1	30.2	46.7	19.5
Seam No. 1	58.5	21.1	3.4	12.8	13.2	74.0	26.5
Seam No. 3	41.5	17.4	6.6	32.8	41.8	25.4	20.1

1-3. Data from analysis under normal reflected light, 4. under blue light excitation (m.m.f.), 1 on 100% huminite basis, 2. on 100% mineral matter (total) basis.

contrast to relatively high pyrite content (Table 3) is an exception. Its very low clastic content and high degree of vegetal preservation relates its pyrite contribution from a secondary source, i.e., by leaching from the overlying thick and highly pyriteous (average 37.8% for sample nos. 21-26) grey shale band. It has also been presumed (refer Table 3) that pyrite contents between 3 to 5 per cent (or 12-30 per cent on total m.m. basis) are sufficient to cause a reasonably high degree of degradation (> 50 -> 60%). Further degradation beyond this level, probably under elevated pH conditions, is rather slow presumably retarded by some chemical factor not understood presently.

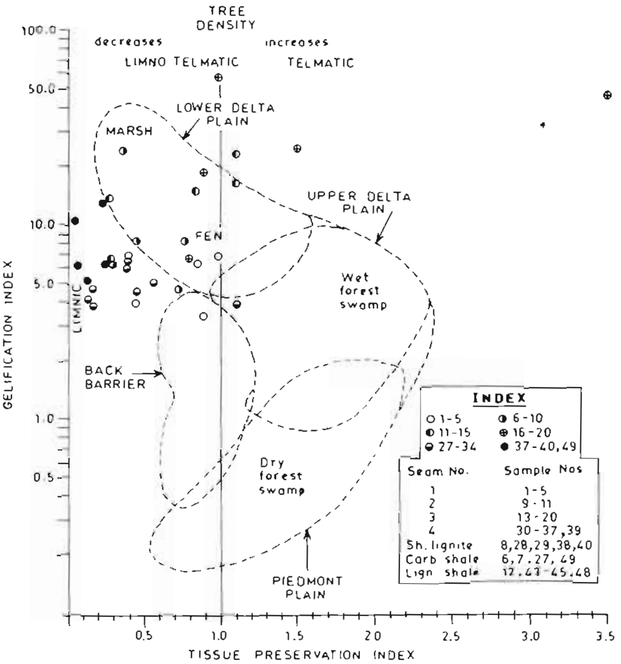
The discrepancy in the relations between liptodetrinite and humodetrinite and pyrite and disproportionate relation between the latter two can be simply explained as to have been caused by certain degree of aerobic fungal and bacterial degradation: aerial aerobic (when plants were still living or out of water) and subaqueous aerobic (when plants died and incorporated in the swamp). In fact, in present day wet-forests of India trees (also soil and surface litter) have prolific fungal and lichen growth for 6 to 8 months during the year.

High proportions of syngenetic pyrite and calcite in lignite seams and associated lithologies in the Panandhro section (Text-figs 3, 4) indicate a relatively quiet or stagnant water depositional conditions without any turbulence (Krumbein & Garrels, 1952; Cecil *et al.*, 1981). Such a condition preclude any detrital influx by the feeding channels in the ancient peat swamp as well as suggests that the vegetal accumulation took place in rheotrophic swamp because of its alkaline nature. Therefore, high clastic contents in the lignite seams (Table 1; Text-fig. 4) can be explained mainly as a result of *in situ* release of amorphous minerals bound in the plant tissues degrading under alkaline (pH > 6) swamp water (Renton *et al.*, 1979; Cecil *et al.*, 1979). Additional amount of mineral matter is generated through fixation by reactions between inorganic ionic fractions of organic matter and that of the swamp water (Renton & Bird, 1991).

According to chemical model proposed by Cecil *et al.* (1979) and Renton *et al.* (1979), the high frequencies of pyrite and calcite in the Panandhro section (Text-figs 3, 4) suggest that the lignite Seam nos. 1, 2 and 4 were formed from peats that were subjected to high degree of microbial degradation as a result of elevated pH (> 6) of the swamp water, which in turn also facilitated increased release of plant-derived inorganic matter. Minor shaly lignite (sample nos. 8, 28, 29, 38, 40), carbonaceous shale (sample nos. 6, 7, 27) and lignitic shale (sample no. 12) bands above, below and within the lignite seams reflect a depositional condition favouring high rate of degradation of organic material and pyrite and calcite precipitation. With the result prevailing rate of vegetal supply fell short for normal peat growth to form non-lignite beds. As has been mentioned earlier that the lignite seams show splitting and merging tendencies in the field, the three lower seams (1-3) evidently represent splits of a single seam caused by the formation of minor authigenic partings from severe vegetal degradation (Renton & Hamilton, 1988). During the formation of Seam no. 3 chemical conditions in the swamp became conducive for the preservation of accumulated plant material under relatively low pH conditions of the swamp water which presumably retarded degradation and thus, inhibited release of plant-derived minerals (Tables 1, 2; Text-fig. 4).

The TPI pattern (Text-fig. 6) clearly shows that the rise in its ratio corresponds with the initiation of lignite seam formation whereas, a progressive decrease marks the demise. Evidently, the termination of peat accumulation for lignite Seam nos. 1 and 2 are related with apparent rather than actual vegetal short supply induced by severe microbial degradation. Similar was the case for the end of Seam no. 4. However, termination of lignite Seam no. 3, overlain abruptly by highly pyriteous grey shale band, was caused by inundation of the ancient peat by abrupt and relatively faster rate of basin subsidence unaccompanied by coarse clastic matter. Absence of coarse clastic material subsequent to seam demise reflects an almost peneplained provenance which is evident from the complete absence of arenaceous sediments in entire lithologic sequence of the area. The end of lignite formation phase in the area is apparently related with the onset of slow encroachment of the sea due to continued basin subsidence thereby causing extermination of existing vegetation by inundation, thus swamp formation was inhibited in the area. The provenance could not supply enough detritus with the result calcareous sediments were deposited in the later phases (Biswas & Raju, 1973; Saraswati & Banerjee, 1984a; Pareek, 1984). It has also been presumed that in the wake of a general high degradation rate the requirement of vegetal supply for the formation of lignite seams was appreciably high, therefore, the vegetation must have been prolific and profuse as has been visualized by Lakhanpal and Guleria (1983) on the basis of palaeobotanical evidences.

Tissue preservation indices (TPI) and gelification indices (GI) of the Panandhro samples (calculated by substituting brown coal macerals for those of hard coals) on the facies diagram of Diessel (1986) suggest that the lignite seams formed under wet to very wet (telmatic, limno-telmatic to limnic) conditions (Text-fig. 7). Seam no. 3 with high TPI and GI values originated from a peat formed by vegetation with high tree density than the rest of the seams. Seam nos. 1 and 4 have higher TPI and lower GI than Seam no. 2. A general high GI and low TPI of lignite seams, shaly lignite, carbonaceous shale and lignitic shale beds, high amount of humodetrinite and common to frequent association of *Botryococcus* with ubiquitous pyrite (Tables 1, 2; Text-figs 4, 7) suggest their deposition in a lagoon (Teichmüller, 1989; Neavel, 1981; Misra, 1991a) rather than in a lake as evinced by Saraswati and Banerjee (1984a) and also apparent from the facies diagram (for > 50% samples). The lagoonal model of deposition is also supported by the geological evidences (Biswas & Raju, 1973; Hardas & Biswas, 1973). It appears that the facies diagram of Diessel (1986) is reasonably good for broad generalization but, it does not conform very well with the presently deduced depositional model based on geological, palaeobotanical and biopetrological evidences.



Text-figure 7—Facies diagram of lignite seams and associated sediments from Panandhro Lignitefield in terms of Gelification and Tissue Preservation indices in relation to palaeodepositional environments (after Diessel, 1986).

Geological, megafloral, palynological and biopetrological information concerning specifically the Panandhro lignite deposit are glaringly meagre, therefore, only generalized statements have been made so far about its origin. Pareek (1984) on the basis of highly degraded nature of vegetal matter in the lignite seams considered them to be of allochthonous origin. Similar opinion has been expressed by Saraswati and Banerjee (1984a). However, palaeobotanical evidences with well-preserved megafloral remains (Lakhanpal & Guleria, 1983; Kar, 1985), high amount of *in situ* pyrite and calcite, fluctuating but high I/R ratio (Text-fig. 6; I/R ratio = sf + f/inertodet. + det. + macri. + micri. of Kalkreuth & Lackie, 1989), mostly clean nature of huminite and inertinite macerals and an overall low-energy to almost stagnant depositional regime preclude the possibility of large scale transportation of the vegetal matter. Instead, on the basis of presently deduced depositional conditions, chiefly autochthonous and a fraction of hypoautochthonous vegetal source seems to be responsible for the formation of Panandhro lignite deposit.

UTILIZATION PROSPECTS OF THE PANANDHRO LIGNITE

Report on the industrial application of Panandhro lignite, after pilot plant test, indicates its amenability for use in thermal power generation, briquetting and carbonization besides production of ammonia and methanol (Nadhamuni, 1976). The present study, however, indicates that all the lignite seams, in general, and Seam nos. 1 and 4, in particular, are well-suited for the manufacture of organic chemicals, resins and waxes. In addition, the carbonaceous shale, shaly lignite and lignitic shale beds underlying and overlying the Seam no. 4 may also be utilized for the above purposes provided they are suitably cleaned by washing. The lignite Seam nos. 1 and 3 may also be used for thermal power generation. As the entire section studied presently is rich in pyrite, a sulphuric acid plant can easily be installed there.

CONCLUSIONS

The Panandhro lignite seams are rich in huminite macerals with subordinate amount of liptinite and inertinite macerals when analyzed under normal light. They have low to moderately high proportion of mineral matter consisting of syngenetic pyrite and calcite and quartz and clay. Under blue light excitation, the seams alongwith associated sediments, viz., shaly lignite, lignitic shale and carbonaceous shale beds, have been found to be quite rich in liptinite macerals especially, the liptodetrinite and resinite. The entire section studied is characterized by common occurrence of alginite (*Botryococcus*). The present rank of the lignite seams have been presumed to be due to low geothermal gradient as is also evident by the thin sequence of entire Tertiary sediments (total ± 140 m) in the area.

From the available geological, mega- and micro-floral information and the present biopetrological analysis, it has been visualized that the lignite seams originated mainly from autochthonous mangrove-mixed angiospermous forest vegetation growing profusely under humid tropical climate. Non-perennial herbs and shrubs, especially pteridophytes, growing as undergrowths contributed mostly in the *in situ* formation of inertinite macerals during dry periods and/or periodic lowering of water table. The lignite Seam nos. 1, 2 and 4 were formed under highly anaerobic and elevated pH (> 6) conditions of swamp water. With the result microbial degradation of organic matter was accelerated and a fair amount of plant-derived mineral matter were released *in situ* to be incorporated in the lignite seams along with precipitation of syngenetic pyrite and calcite. On the other hand, Seam no. 3 was formed from a peat which accumulated under conditions conducive for organic matter preservation with relatively low pH of the swamp water. Its high pyrite content is the result of downward leaching from the overlying highly pyriteous grey shale bed. Minor partings of shaly lignite, carbonaceous shale and lignitic shale were presumably formed *in situ* from severe degradation of organic matter splitting the single basal seam into three seams. Thus, basal three seams may be considered as one composite seam in the present section. The termination of Seam nos. 1, 2 and 4 was the result of accelerated rate of organic matter degradation when prevailing rate of vegetal supply fell short for the lignite formation. The termination of Seam no. 3 was induced by abrupt faster rate of basin subsidence and inundation of the existing peat swamp. The lignite seams were formed in a lagoon from rheotrophic peat swamp near the then existing shore-line. The brackish water influence appears to have been significant as is evident by the highly pyriteous nature of the different lithologies in the present section.

The overall petrographic composition suggests that the lignite seams, especially Seam nos. 1 and 4, are better suited for the manufacture of organic chemicals. Similar is the potential of shaly lignite, lignitic shale and carbonaceous shale bands. High amount of pyrite in the lignite seams and associated sediments can be utilized for the production of sulphuric acid or even fertilizers.

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