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Petrographic Characterization of Khadsaliya Lignites, Bhavnagar District, Gujarat

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Abstract: The petrological studies on Khadsaliya lignites from Bhavnagar district have been carried out for their microconstituent's characterization. Quantitative estimation of macerals reveal, due to high amount of macerals of huminite group, that this lignite deposits has formed from forest dominated vegetation in a fast subsiding basin, experiencing almost uniform environmental conditions, with slight intermittent fluctuations. The rank based on $R_{o\,max}$% values indicates that lignites are less mature and have not reached the sub-bituminous stage of coalification as those of the lignites from Panandhro (Gujarat) and Neyveli (Tamil Nadu) fields. High pyrite content in the Khadsaliya lignite makes it not much suitable for combustion purpose.

Keywords: Maceral, Maturation, Palaeodeposition, Khadsaliya lignite, Cenozoic, Gujarat.

INTRODUCTION

The earliest known lignite deposits in Gujarat were found in Kutch district. The occurrence of lignite around Khadsaliya village of Bhavnagar district first came into light in 1980. With the further investigations and exploration taken up by the Gujarat State Government, extensive drilling programme from 1987 revealed the exploitable reserves of lignite in Lakhanka-Khadsaliya Block, about 20-30 km from SSE of Bhavnagar city (Fig. 1). The lignite in the area is presently being mined by Gujarat Mineral Development Corporation (GMDC) and Gujarat Heavy Chemicals Limited (GHCL).

Lignites are evaluated for various purposes utilizing different parameters. Petrographic characterization of lignites has importance in academic and technological pursuits. Extensive and intensive palaeofloral (Saxena, 1979; Lakhanpal and Guleria, 1983; Kar, 1985; Guleria, 1991) and organic petrological (Misra, 1992; Misra and Navale, 1992, Singh and Singh, 2003, 2005) investigations on lignites from various mines of Gujarat have helped to understand the then existed vegetation and environmental/climatic conditions prevailed at the time of lignite formation. The petrological results helped to interpret the utilization potential of these lignites, besides many other rank/maturation related properties (Misra and Navale, 1992; Singh, 2002; Singh and Singh, 2003). The present paper provides detailed information on organic petrographic characterization (nature, maceral composition and maturation) of Khadsaliya lignites and an interpretation for the palaeodepositional conditions and utilization prospects.

GENERAL GEOLOGY AND LIGNITE DEPOSITS

Geology of the area is part of the Saurashtra peninsula, bounded by sea except on NE where it is flanked by alluvial plains. The peninsula is bound by N–S trending Cambay Basin fault in the east, the extension of Narmada geofracture (a fault system) in the south, E–W rtending gulf of Kutch fault in the north, and the major WNW–ESE fault (an extension of the West Coast fault system in the Arabian Sea) in the west. As per Biswas (1980, 1987) and Merh (1995), the Aravalli trend in the SW portion of the region splays out into three components. The main NE–SW trend continues across the Cambay Graben into Saurashtra as a southwesterly plunging arch. Biswas and Deshpande (1983) consider the Saurashtra region as a horst surrounded by rift graben and demonstrate that central, southern and northern Saurashtra exhibit distinct volcano-tectonic characteristics. On the eastern side of Saurashtra, a sharp contact of alluvium with basalt is observed in the N–S direction, extending from the west of Nal Sarovar to Bhavnagar.

Saurashtra peninsula is about 65% covered by basaltic lava flows (Deccan Trap), overlying the Mesozoic sediments in north and underlying the Tertiary-Quaternary sediments at coastal fringe. The Deccan Trap provides the basement for the deposition of Tertiary sediments that are exposed at

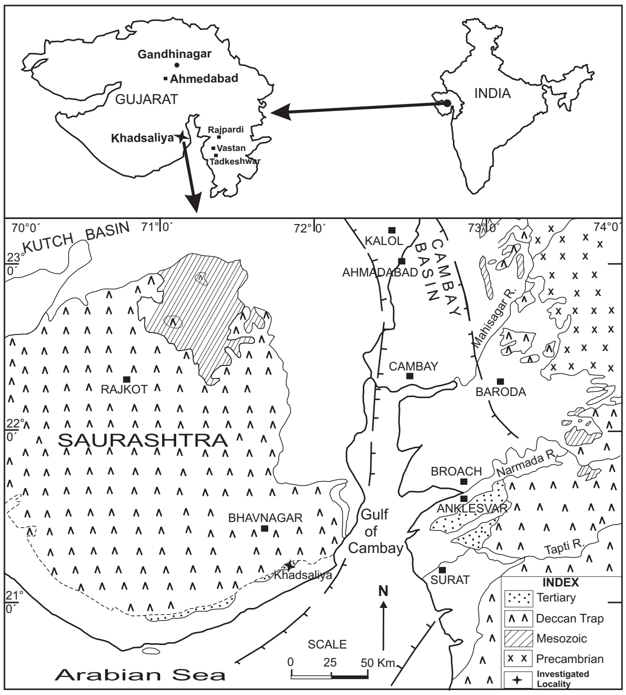

Fig.1. Location and geological map of the Khadsaliya area (source: GMDC, 2008).

some places (Fig. 1). Geological succession of the area is shown in Table 1.

Lignite in the region occurs in Khadsaliya Clays Formation (? Eocene), which is never exposed on the surface.

Table 1. Geological succession around Khadsaliya lignite mine, Gujarat (Srivastava, 1963; GHCL, 2008)

Formation	Lithology	Age
Recent	Alluvial, coastal dunes and Beach sands, mud flats, soil, etc	Recent to Sub-recent
	-Unconformity-	
Lakhanka Formation (Agate Conglomerate Formation)	Agate, conglomerate and associated ferruginous sandstone with intercalation of clays	Pleistocene to Sub-recent
	-Unconformity-	
Gaj Formation	Variegated sandstone, marl, conglomerate, and impure Limestone and Gypsum clays	Lower Miocene
	-Unconformity-	
Khadsaliya Clays	Grey to greenish-grey clays with carbonaceous clay and lignite with siderite nodules	Eocene
	-Unconformity-	
Supratrapean	Laterite, lithomerge, bentonite	Lower Eocene
	-Unconformity-	
Deccan Trap	Basaltic lawa flows with intrusive dykes	Cretaceous to Eocene

This green to greenish-grey clay formation, overlying the Supratrappean (Lower Eocene) and Deccan Traps (Cretaceous-Eocene) holds the lignite deposits together with carbonaceous clay. The basin extending in a length of about 12 km opens up towards north with a general slope towards sea. It extends from Lakhanka to Rampur-Navades-Ratanpur and beyond in NS direction up to Bhumbhali and Thordi, the width is about 1-3 km in EW. Lignite seams unconformably lie on the weathered trap on lithomargic clay. They become deeper towards east to northeast and diminish towards sea. The seams show an average gradient of 5-10° dip towards center of the basin. In Khadsaliya-Lakhanka Block, lignite is found at a depth of 11.99 m to 195.81 m with the thickness of two seams varying between 0.20 to 11.05 m (source GHCL report). The lignites are brownish black, fine grained and amorphous and tend to develop cracks when exposed to air. The lignite seams contain specks of resin, pyrite and iron nodules in abundance that can be picked by hands.

MATERIAL AND METHOD

Total 10 lignite samples representing top and bottom seams, collected vertically in ascending order– 2 from top portion of seam II (bottom seam, about 1.0 m exposed for mining), and 8 from seam I (the main/top seam- about 4 m thick at collection site), are utilized for the petrographic studies (Fig. 2). The two seams exposed in Khadsaliya mine are separated by about one meter thick carbonaceous clay parting.

The particulate lignite pellets were prepared by embedding ±1-2 mm size grain particles in a mixture of epoxy resin and hardener in a ratio of 5:1. The hardened pellets were ground and polished successively on finer grades of silicon cloth and with polishing alumina respectively and used for the study as per the specifications of ICCP (1971, 1975). The reflectance were measured on huminite constituents (preferably ulminite) in monochromatic light on Leica DM4500P microscope using Sapphire (0.594) as a reflectance standard (along with the standards: Yttrium-Aluminium-Garnet (0.904) and Gadolinium-Gallium-Garnet (1.725)), immersion oil (refractive index 1.518) and 50x objective lens along with a pair of 10x oculars. Microscopephotometery System (PMT III) and Software MSP 200 is used for the reflectance measurements, calculations and data collection. The desired measurements were equally distributed on entire pellet. The maceral analyses under incident light in reflected and fluorescent (blue light excitation) modes were carried out on the same microscope. Software tool- Leica applications

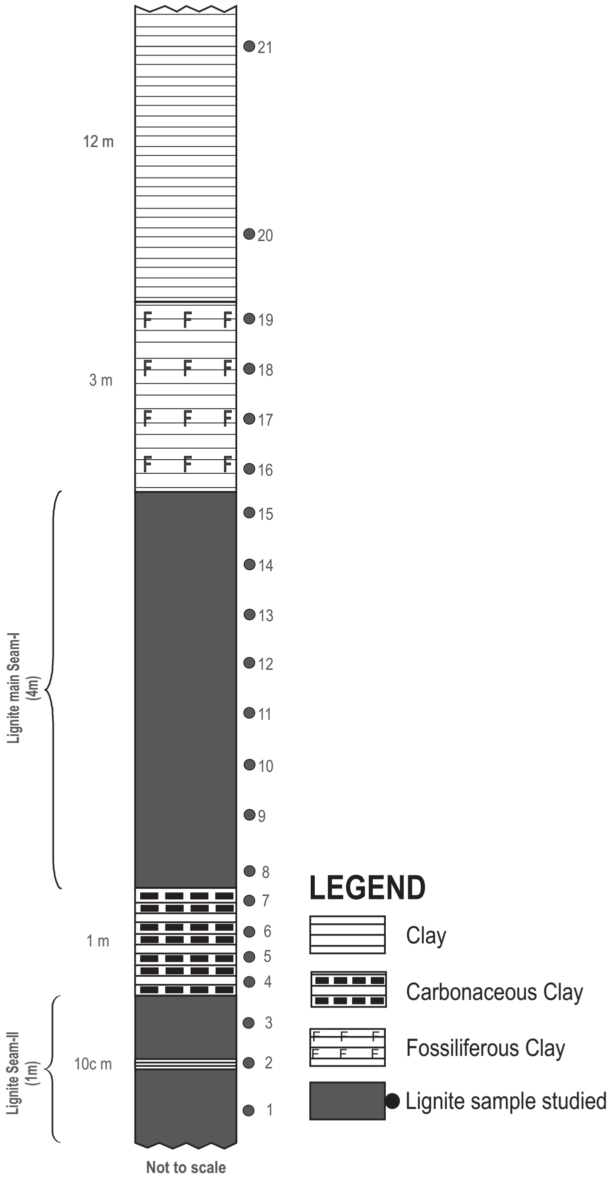

Fig.2. Litholog of Khadsaliya mine showing distribution of lignite seams and samples studied.

suit (LAS) has been used for maceral images. Quantitative estimation of macerals has been made on 500 counts per sample counted on automatic computerized point counter using 2.35 version of Petroglite software.

MACERAL CHARACTERISTICS AND COMPOSITION

Under Normal Reflectance Mode

Huminite Group: In the studied lignites, grey to medium grey huminite macerals range between 70.0 and 85.2 vol. % (average 77.7 vol. %) in seam I (top), and between 34.5 and 42.9 vol. % (av. 38.7 vol. %) in seam II (bottom). The huminite is represented by almost all the macerals incorporated in this group. Structured telohuminite (textinite + ulminite) is dominant in the bottom seam (17.5-27.2 vol. %, av. 22.3 vol. %) as compared to the top seam (6.8-32.0 vol. %, av. 18.7 vol. %), followed by detrohuminite (av. 13.8 vol. %) and gelohuminite (av. 2.5 vol. %). Detrohuminite consisting detrital macerals (attrinite + densinite) predominates in the top seam (24.3-69.3 vol. %, av. 56.4 vol. %), followed by telohuminite (av. 18.7 vol. %) and gelohuminite (2.7 vol. %). Ulminite normally dominates over textinite in both the seams.

Liptinite Group: The group is mainly represented by sporinite (spores-pollen), cutinite (cuticles) and resinite (resins/waxes/oil, etc.). The macerals are recorded in higher concentration in the bottom seam (10.8-14.0 vol. %, av. 12.4 vol. %) as compared to the top seam (2.4-5.8 vol. %, av. 3.6 vol. %).

Inertinite Group: Semifusinite, fusinite, inertodetrinite and funginite represent the group, though not recorded in all the samples individually. The group is fairly represented in top seam (0.2-11.6 vol. %, av. 4.0 vol. %), however its concentration is very less in the bottom seam (0.5-0.6 vol. %, av. 0.5 vol. %). Amongst all the inertinite macerals, funginite is the most common maceral (0.3-3.6 vol. %) in both the seams, followed by pyrofusinite (also as fusinite needles, i.e. inertodetrinite).

Mineral Inclusions

The minerals associated with the Khadsaliya lignites are mainly represented by clay, quartz, sulphide and carbonate. The most common among these are pyrite and clay minerals. The minerals are introduced during the early stage of lignite formation, i.e. are of early diagenetic or syngenetic type. Clay minerals are intimately associated with the macerals, while pyrite is recorded as fine crystalline or concretionary form, as individual euhedral crystals, as massive and in framboidal form as well (Plate 1: 1-2). Carbonate mineral (siderite) is rare and recorded in concretionary form.

The bottom seam contains higher frequency of associated mineral matter (45.7-51.0 vol. %, av. 48.3 vol. %) as compared to the top seam (3.6-26.2 vol. %, av. 14.7 vol. %). On the contrary, pyrite is present in both the seams in fairly well amount (bottom seam II: av. 1.6 vol. %, top seam I: av. 4.5 vol. %), however higher (>5-12 vol. %) in some samples.

Under Fluorescence Mode

As observed under blue light excitation, the H_2-rich liptinite group is represented by sporinite, resinite, cutinite, suberinite (suberin), and liptodetrinite (detritus). Liptodetrinite (13.2-23.6 vol. %; avgs. 29.6 vol. % in seam

Table 2. Maceral composition (vol. %) and rank ($R_{o\,max}$ %) of Khadsaliya lignites as assessed under normal incident light and under blue light excitation

	Seam II (bottom)			Seam I (top)								
Sample Nos. Macerals	1	3	Avg.	8	9	10	11	12	13	14	15	Avg.
Maceral composition (vol. %) and rank ($R_{o\,max}$ %) of Khadsaliya lignites as assessed under normal incident light												
Huminite	42.9	34.5	38.7	77.4	77.2	75.8	85.1	70.0	75.6	85.2	75.6	77.7
	(79.0)	(70.4)	(74.7)	(95.3)	(92.1)	(95.2)	(93.8)	(94.8)	(88.3)	(88.4)	(82.5)	(91.3)
Textinite	0.3	0.5		0.6	0.6	1.2	1.3	1.6	-	1.6	1.2	
Ulminite	26.9	17.0		10.8	20.8	30.8	11.3	39.9	6.8	13.6	7.2	
Humotelinite	27.2	17.5	22.3	11.4	21.4	32.0	12.6	41.5	6.8	15.2	8.4	18.7
Attrinite	4.6	11.0		11.0	14.0	16.4	53.3	11.5	40.0	42.4	46.0	
Densinite	8.0	4.0		53.6	39.2	25.6	16.0	12.8	26.8	25.2	17.2	
Humodetrinite	12.6	15.0	13.8	64.6	53.2	42.0	69.3	24.3	66.8	67.6	63.2	56.4
Corpohuminite	1.2	2.0		0.8	2.2	1.6	3.2	1.6	2.0	2.4	4.0	
Gelinite	1.9	-		0.6	0.4	0.2	-	2.6	-	-	-	
Humocollinite	3.1	2.0	2.55	1.4	2.6	1.8	3.2	4.2	2.0	2.4	4.0	2.7
Liptinite	10.8	14.0	12.4	3.2	5.8	3.6	2.5	3.8	2.4	3.2	4.4	3.6
	(19.9)	(28.6)	(24.2)	(3.9)	(6.9)	(4.5)	(2.8)	(5.2)	(2.8)	(3.3)	(4.8)	(4.3)
Sporinite+Cutinite	10.2	12.5		3.2	5.8	3.6	2.0	3.5	1.2	-	1.2	
Resinite	0.6	1.5		-	-	-	0.5	0.3	1.2	3.2	3.2	
Inertinite	0.6	0.5	0.5	0.6	0.8	0.2	3.1	-	7.6	8.0	11.6	4.0
	(1.1)	(1.0)	(1.0)	(0.7)	(1.0)	(0.2)	(3.4)		(8.9)	(8.3)	(12.7)	(4.4)
Semifusinite	0.3	-		-	-	-	0.8	-	2.0	3.6	5.2	
Fusinite	-	-		-	-	0.2	-	-	-	-	-	
Funginite	0.3	0.5		0.6	0.8	-	1.0	-	1.2	2.8	3.6	
Inertodetrinite	-	-		-	-	-	1.3	-	4.4	1.6	2.8	
Mineral matter	45.7	51.0	48.3	18.8	16.2	20.4	9.3	26.2	14.4	3.6	8.4	14.7
Pyrite	2.2	1.0		3.2	3.6	8.4	4.5	12.1	2.4	0.4	1.6	
$R_{o\,max}$ %	0.31	0.29	0.30	0.29	0.27	0.31	0.29	0.28	0.28	0.26	0.28	0.28
Maceral composition (mmf. %) of Khadsaliya lignites as assessed under blue light excitation												
Huminite fluorescing	(6.5)	(9.3)	(7.9)	(48.4)	(36.0)	(39.2)	(26.0)	(19.2)	(24.8)	(49.2)	(23.6)	(33.3)
Sporinite	(6.0)	(9.3)		(4.4)	(7.2)	(3.6)	(3.6)	(2.4)	-	(2.8)	(4.8)	
Cutinite	(2.0)	(0.7)		(1.6)	(3.2)	(0.8)	(2.8)	(2.8)	(3.6)	-	(1.2)	
Suberinite	-	-		-	-	(1.6)	(1.2)	-	(1.2)	(1.2)	(3.2)	
Resinite	(3.0)	(2.0)		(5.2)	(3.6)	(4.8)	(8.8)	(4.8)	(2.4)	(8.0)	(5.6)	
Liptodetrinite	(14.0)	(14.7)		(16.0)	(23.2)	(14.8)	(16.8)	(13.2)	(23.6)	(13.2)	(16.4)	
Liptinite (total)	(25.0)	(26.7)	(25.8)	(27.2)	(37.2)	(25.6)	(33.2)	(23.2)	(30.8)	(25.2)	(31.2)	(29.2)
Total fluorescing (huminite+liptinite)	(31.5)	(36.0)	(33.7)	(75.6)	(73.2)	(64.8)	(59.2)	(42.4)	(55.6)	(74.4)	(54.8)	(62.5)
Non-fluorescing (huminite+inertinite)	(68.5)	(64.0)	(66.3)	(24.4)	(26.8)	(35.2)	(40.8)	(57.6)	(44.4)	(25.6)	(45.2)	(37.5)

Figures in parenthesis are on mineral matter-free basis.

I, 14.3 vol. % in seam II), followed by resinite (2.0-8.8 vol. %; avgs. 4.0 vol. % in seam I, 2.5 vol. % in seam II) are the chief macerals in almost all the samples studied. Resinite is observed as globular/ rounded isolated bodies and as cell-fillings. The discrete bodies vary in colour from yellow, yellowish-green to brown to reddish-brown (Plate 1: 5-6). Sporinite (Plate 1: 3) and cutinite are also well represented in both the lignite seams, however the former is in higher proportion in seam II (6.0-9.0 vol. %, av. 7.6 vol. %) as compared to seam I (2.4-7.2 vol. %, av. 3.6 vol. %). The frequency of the cutinite ranges between 0.7 and 3.6 vol. %, without much difference in individual sample. These are mostly of tenuicutinite type, i.e. thin walled (Plate 1: 4).

Total liptinite macerals under blue light excitation ranges between 25.0 and 26.7 vol. % (av. 25.8 vol. %) in bottom (II) seam and between 23.2 and 37.2 vol. % (av. 29.2 vol. %) in top seam (I). In addition, brown to dark brown fluorescing or perhydrous huminite is recorded in high percentage in the top seam (19.2-49.2 vol. %, av. 33.3 vol. %) and in relatively lower frequency in the bottom seam (6.5-9.3 vol. %, av. 7.9 vol. %). The amount of total fluorescing macerals (liptinite + perhydrous huminite) in

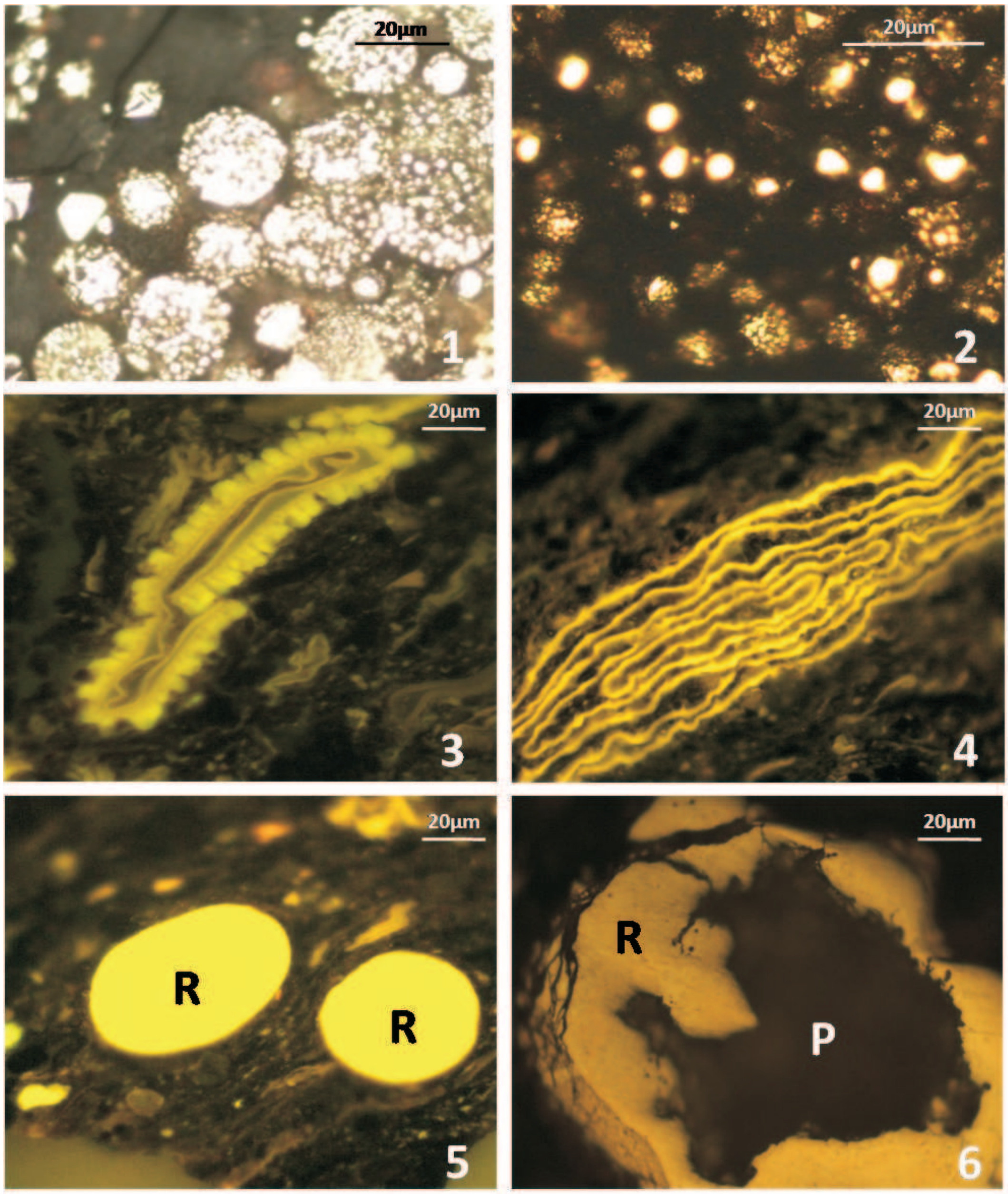

Plate 1. 1-2 - Framboidal pyrite associated with huminite (under nomal incident light). **3** - Sporinite (sculptured pollen). **4** - Cutinite. **5** - Resinite bodies (R-Resinite). **6** - Pyritic degradation of resinite (P - Pyrite) (3-6: blue light excitation using oil immersion).

seam I (42.4-75.6 vol. %, av. 62.5 vol. %) are almost double the amount in seam II (31.5-36.0 vol. %, av. 33.7 vol. %).

RANK OF LIGNITES

The reflectance measurements data on both the lignite seams are listed in Table 2. The calculated mean maximum huminite reflectance values ($R_{o\ max}$ % values) for seam I (top) range between 0.26 to 0.31% with the average $R_{o\ max}$ value of 0.28%. The values do not reveal any specific increasing or decreasing trend with depth of the seam. The seam II (bottom) shows an average $R_{o\ max}$ value 0.30%, with the individual readings of two samples as 0.31% and 0.29%. The rank (maturity) values indicate that the studied lignites as per the German Standard (DIN) and American Standard for Testing Materials (ASTM) classification (in Stach et al. 1982) are in brown coal and lignitic stage, respectively.

DISCUSSION AND CONCLUSIONS

The accumulated vegetal matter undergoes physical and chemical changes under the influence of temperature and pressure induced biological and geological processes, in order to convert into lignite/coal (Stach et al. 1982; Taylor et al. 1998). The organic microconstituents or macerals, thus formed are the basic units of lignite/coal that provide all the information about their origin (basin conditions, swamp water conditions, environment of deposition, climate, type of vegetation etc). Depending on the morphological and chemical properties these macerals are grouped into three main groups, viz. oxygen-rich huminite/vitrinite derived from woody tissue, hydrogen-rich liptinite originated from lipid rich organic matter and carbon-rich inertinite originated from oxygenated matter, each formed in different environmental conditions (reducing/oxidizing, alkaline/ acidic water etc). Their frequency thus reflects variation or fluctuation in depositional/ environmental conditions.

Overall predominance of huminite in both the studied lignite seams (Table 2, 70.4-95.3 vol.% mineral matter-free) indicates the existence of woody forest contributing as the source vegetation and reducing conditions of swamp during the formation of Khadsaliya lignites. The dominance of telohuminite in bottom seam (although in ± equal proportion of top seam) and detrohuminite in top seam, however suggest fluctuating pH conditions of swamp water, favouring the formation of telohuminite in relatively more alkaline, reducing and high groundwater table conditions during the formation of bottom (II) seam. Detrohuminite further suggests the contribution of soft tissues from angiosperms woods and herbaceous/ bushy plants as a source material, which tend to decompose easily giving rise to detrohuminite (attrinite and densinite). The presence of concretionary siderite (and also Fe nodules in the seams) that forms in anaerobic conditions suggests that formation of huminite proceeded under anaerobic conditions from quite an early stage. Low proportion of inertinite, in particular the structured fusinite/ semifusinite, indicates short exposure time for the peat surface vis-a-vis rapid basin subsidence. Funginite, the major constituent of inertinite, suggests warm and moist climatic conditions favourable for the growth of fungi, the chief degrading agents and also for the luxuriant vegetation.

Highly anaerobic and elevated pH (>6-7) conditions caused severs degradation of organic matter releasing several *in situ* minerals to be incorporated in the lignites during the course of transformation (Taylor et al. 1998). Pyrite in the seam appears to be formed mainly by the precipitation of syngenetic pyrite. Large amount of pyrite causes decomposition of organic matter (i.e. pyritic degradation, Singh and Singh, 1994) and consequently the formation of detrohuminite and liptodetrinite.

Under blue light excitation the seams show almost similar proportions of liptinite in contrast to the variable frequencies as observed under normal incident mode. The difference may be due to certain obscure/ unidentifiable macerals (resinite, suberinite, liptodetrinite etc) under normal light. Fluorescence mode reveals the dominance of liptodetrinite in both the studied lignite seams (in much higher frequency in top seam). Bottom seam has almost half the frequency of total fluorescing macerals (liptinite + perhydrous huminite) in that of the top seam. The difference may be assigned to higher proportion of perhydrous huminite in the top seam. Alginite is easily decomposed and gets incorporated with other macerals. After degradation it forms liptodetrinite and some times perfuses in vitrinite forming perhydrous vitrinite. And hence the reason for alginite in non-recordable proportion may be related to its major contribution in the formation of liptodetrinite and perhydrous huminite (Hutton and Cook, 1980).

The maturation determination or rank ($R_{o\ max}$ 0.26 %-0.31 %) indicates that the lignites have reached up to brown coal (German Standard) or lignite stage (ASTM). The normal increase in rank (though slightly increased in the bottom seam) with depth following the Hilts' Law has been observed. When compared with the lignites of Panandhro field (Kutch Basin; Singh, 2002), Gujarat and Neyveli field (Cauvery Basin; Singh and Singh, 1994), Tamil Nadu, the studied lignites from Saurashtra area have not reached the sub-bituminous stage and are relatively of lower rank or are less mature. The reason may be assigned to faster rate of basin subsidence (experiencing short coking time) or lower geothermal gradient, because greater the influence of time, higher is the temperature (Welte, 1972; Hood et al. 1975).

Both the lignite seams of Khadsaliya appear to have been originated from wood-dominated forest vegetation in more or less similar conditions of swamp with only minor fluctuations in swamp water/ environmental conditions. The basin initially experienced relatively higher reducing conditions and faster rate of subsidence. Abundance of iron nodules (pyrite/siderite) that form in highly reducing environmental conditions also strengthens the conclusions drawn from the petrographic studies. A detailed study on Fe nodules may further add to the information on their mode of formation. Large pyritic content (massive and nodules as well) makes the lignites unsuitable for the combustion, however clean lignites (at least free from Fe nodules) can be used when combined with good quality (low mineral/ high rank) coals.

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