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Paleomires of Eocene Lignites of Bhavnagar, Saurashtra Basin (Gujarat), Western India: Petrographic Implications

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ABSTRACT

The Tertiary basins of Gujarat have always been a potential target for their hydrocarbon resources. The lignite resources of the region have also been an important field of research. The present paper presents the results of the petrological study carried out on the lignites of the Saurashtra basin. For this purpose samples were collected from lower and upper lignite seams from the Surkha lignite mine of Bhavnagar, Saurashtra. These samples were subjected to detailed petrographic analysis (both maceral and microlithotype). The study reveals that these lignites are dominantly composed of huminite group macerals while liptinite and inertinite group macerals occur in subordinate amounts. These lignites have attained a thermal maturity up to 0.28-0.30 percent vitrinite reflectance (VRr) which classifies them as 'low rank C' coals. Moreover, Bhavnagar lower lignite seam shows relatively less gelification as compared to the upper seam which suffered relatively more biochemical degradation. These lignites are characterized by high gelification index (GI) and low tissue preservation index (TPI). With the help of petrography based facies models an attempt has been made to reconstruct the environment of the paleomire of these lignites.

INTRODUCTION

Coal petrography is an important tool to understand the heterogeneity of coal. The physico-chemical properties of coal are related to its petrographic composition; the technological behaviour and potential utilization of a coal may also be predicted based on its petrographic framework. In Gujarat the lignite occurrences have been reported from the Cambay basin (Vastan, Tadkeshwar and Rajpardi), Kachchh basin (Panandhro) and Saurashtra basin (Bhavnagar). These lignite deposits are Eocene in age and are significant, in the region, due to their strategic location which is far away from the main coal producing belt of India. Based on the palynotaxa recovered from Bhavnagar lignites, Samant (2000) assigned an early Eocene age to them. Discussing on the regional sub-continental distribution of the Tertiary lignites of Gujarat, Sahni et al. (2006) believed that these lignite deposits were formed on the plate margin of India consequent to the withdrawal of the Neotethys in Pakistan, western India, northern India and north-eastern India. Subsequently, the lignites, along with mud-rich sediments and siderite, were deposited in a mostly low-energy, nearshore/coastal setting (Mc Cann, 2010). He correlated this setting to the northeast coast of S. America where a muddy environment is spread along the coast. A warm period existed during the late Paleocene-middle Eocene period which resulted in an increase in the deep sea water temperature by ~6°C. It began as the Paleocene-Eocene Thermal Maximum (PETM) and ended as an early Eocene Climatic Optimum (EECO) causing faunal and floral changes in many parts of the world (Kennett and Stott, 1991; Koch et al., 1992; Katz et al., 1999; Schmitz et al., 2001). It is further believed that due to movement of the Indian Plate towards the Asian landmass the Neotethys current flow was lowered and there was substantial reduction in the clastic influx (Sahni et al., 2006) which resulted in euxinic condition along the western margin of the Indian plate. This led to a multifold increase in the productivity of organic matter which ultimately converted into lignite/coal deposits in the western margin of India and continued even in Pakistan. Prasad et al. (2013) have reported the development of these lignite-bearing sequences in the western Indian margin as a consequence of a widespread transgressive event.

In the present investigation, Bhavnagar lignites from the Saurashtra basin have been subjected to petrographic and geochemical analyses and their results have been used for the reconstruction of the paleo-depositional environment.

GEOLOGICAL SETTING

The Saurashtra peninsula is bounded by the sea from all sides except north-eastern side and comprises rocks of Juro-Cretaceous to recent age. This peninsular block is considered as a faulted cratonic horst surrounded by rift grabens (Biswas, 1980, 1982, 1987; Merh, 1995) which include the Kachchh rift fault, the western Cambay basin border fault, the Narmada rift extension and west coast fault. The eastern side of the peninsula is flanked by the N-S trending western Cambay basin bounding fault (Merh, 1995). In addition to the major faults, several related small faults occur in the area. Thus, the triangular shape reveals the boundary faults on all the sides (Merh, 1995). The tertiary sediments have also undergone folding and faulting due to movement of the block along the major faults. The important folds include the Bhavnagar nose, the Avania syncline and the Ghogha nose with the Bhumbhali and the Kuda monocline (GMDC, 1989). The major rivers like Machhu, Bhadar, Sukhbhadar, Bhogavo and Shetrunji follow the fracture trends and a number of abrupt terminations of ridges and hills also show the presence of faults (Merh, 1995). Saurashtra peninsula is characterized by cone and crater type physiography with a prominent central highland. Formation of a series of different rock types from a single lava mass due to magmatic differentiation makes it geologically interesting. Nearly two-third of the area of the Saurashtra peninsula is covered by basaltic lava flows and provides the basement for the deposition of Tertiary sediments (Fig. 1). The Deccan traps overlie the upper Mesozoic sediments. The marine Tertiary rocks are spread all along the fringes of the Saurashtra peninsula. There has been a regular break in sedimentation marked by unconformities (Table 1). The Khadsaliya clay is lignite bearing which is greenish-grey clay formation and is of Eocene age. Lignite is not exposed in the area and occurs in two sub-surface horizons, top lignite horizon and bottom lignite horizon (Fig. 2). The lignite seams lie unconformably over the weathered trappean sediments on the lithomargic clay and become deeper towards the eastern and north-eastern part of the basin while diminishing towards the sea (Fig. 3). The former is 0.1-13m and occurs throughout the area while the latter is 0.2-4m in thickness and is not continuous.

The lignite deposits of Cambay basin have been studied by Sahni

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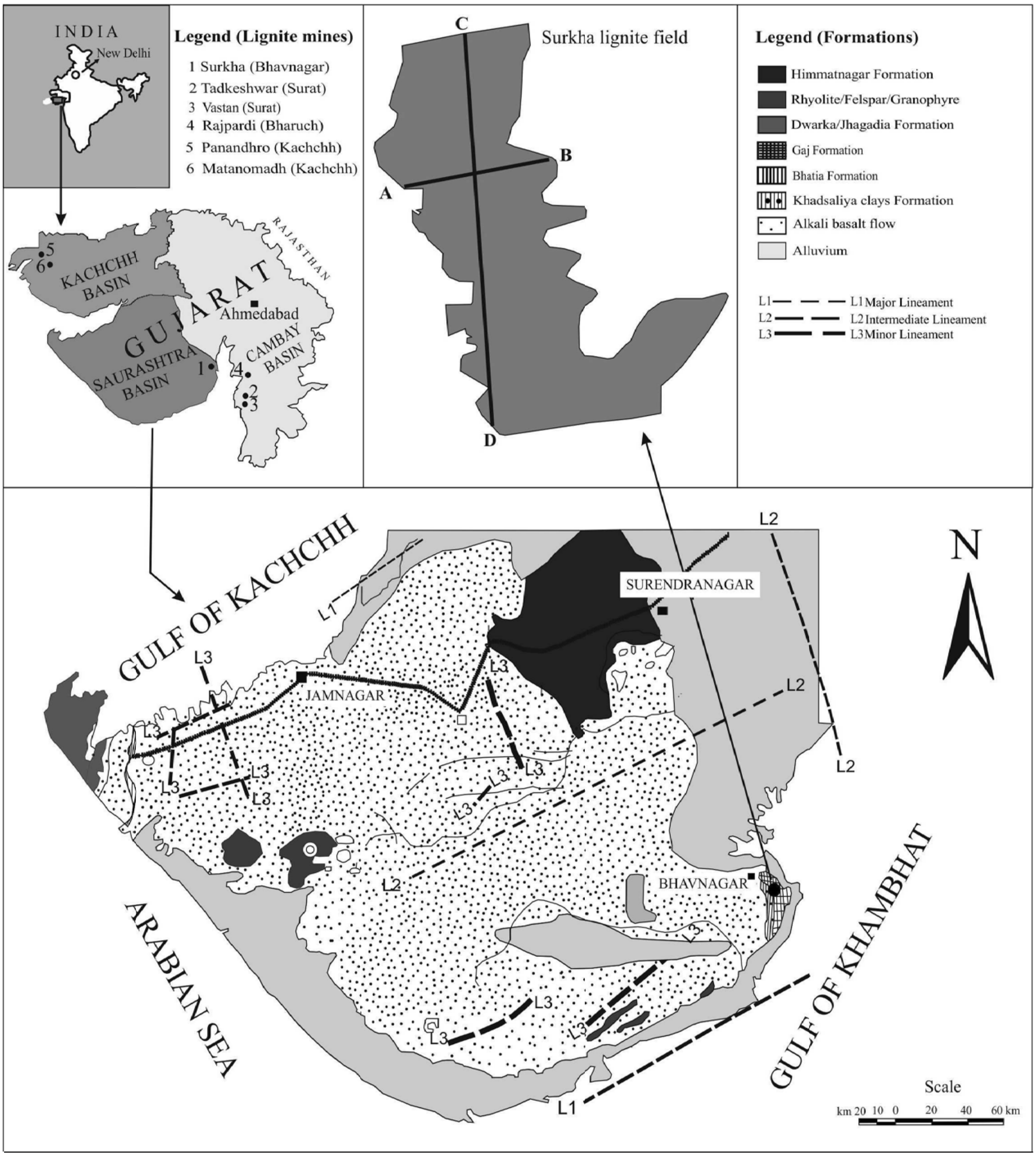


Fig.1. Regional geological map of Saurashtra basin (after GSI, 2012) showing Surkha lignite mine.

et al. (2006), Singh (2012) and Singh et al. (2010a, 2012a, 2016). Preliminary studies have also been made on the lignites of Kachchh basin (Singh and Singh, 2005) and Saurashtra basin (Thakur et al., 2010). The total lignite reserves in this basin as identified by Gujarat Mineral Development Corporation (GMDC, 1989) are nearly 107.5 million tonnes which occurs at a depth of 22-195m.

METHOD OF STUDY

Lignite samples were collected from both the seams (lower and upper) from the Surkha lignite mine of Bhavnagar, Saurashtra Basin, Gujarat (Fig. 1). The samples were collected adopting the pillar sampling method (Schopf, 1960) in such a way that full seam thickness could be reconstructed in the laboratory. Based on similar megascopic characteristics, the lignite samples were clubbed to form composite bands. Each composite band has been treated as one sample and has been given a particular number. The lignite samples were crushed, and through coning and quartering, reduced in quantity and subjected to various analyses. The -18 mesh size samples were used for preparing polished mounts for petrography and -70 mesh size for proximate and other chemical analyses. Maceral analysis was performed under reflected light using a Leitz Orthoplan-Pol Microscope equipped with Wild Photoautomat MPS-45 in the Coal and Organic Petrology Laboratory, Department of Geology, Banaras Hindu University. White light was obtained from a 12 V/ 100 W halogen lamp while for fluorescence system- Ploemopak with filter block I 2/3 having blue excitation filters (BP450-490), dinomatic mirror (RKP510) and suppression filter (LP520) was used. The line-to-line and point-to-point spacing was maintained at 0.4 mm and more than 600 counts were taken on each sample. The methodology described by Taylor et al. (1998) was adopted. Huminite macerals were termed and described as per ICCP-1994 (Sykorova et al., 2005), while ICCP (2001) was followed for inertinite macerals. The vitrinite/huminite reflectance measurement was conducted at National Metallurgical Laboratory, Jamshedpur following ISO 7404-5:2009. A minimum of 200 measurements were taken on each sample.

RESULT AND DISCUSSION

Petrographic Elements

Megascopically, the upper lignite seam consists dominantly of

Table 1. General stratigraphic succession in the Saurashtra basin, Gujarat

Formations	Lithology	Age
Recent Deposits	Soil & Alluvium. Coastal dunes & beach sands.	Recent & Sub- recent
	~~ Unconformity ~~~~~~~~~~~	
Lakhanka Formation (Agate Conglomerate formation)	Agate bearing conglomerates ferrugenous sandstones and loose sand.	Pleistocene to Sub-recent
	~~ Unconformity ~~~~~~~~~~~	
Piram beds	Fossiliferous conglomerates Grits and sandy clays	Late Mio-cene to Pliocene
	~~ Unconformity ~~~~~~~~~~~	
Gaj Formation	Variegated shales with gypsum veinlets, sandstones, marls & conglomerates	Early Miocene
	~~ Unconformity ~~~~~~~~~~~	
Khadsaliya Clays	Grey to greenish grey clays sandstone, lignite with or without siderite nodules	Eocene
	~~ Unconformity ~~~~~~~~~~~	
Supratrapean	Laterite, lithomarge, bentonite	Early Eocene
	~~ Unconformity ~~~~~~~~~~~	
Deccan Trap	Plutonic masses and dykes intrusive in the trap flows	Cretaceous to Eocene
	~~ Unconformity ~~~~~~~~~~~	

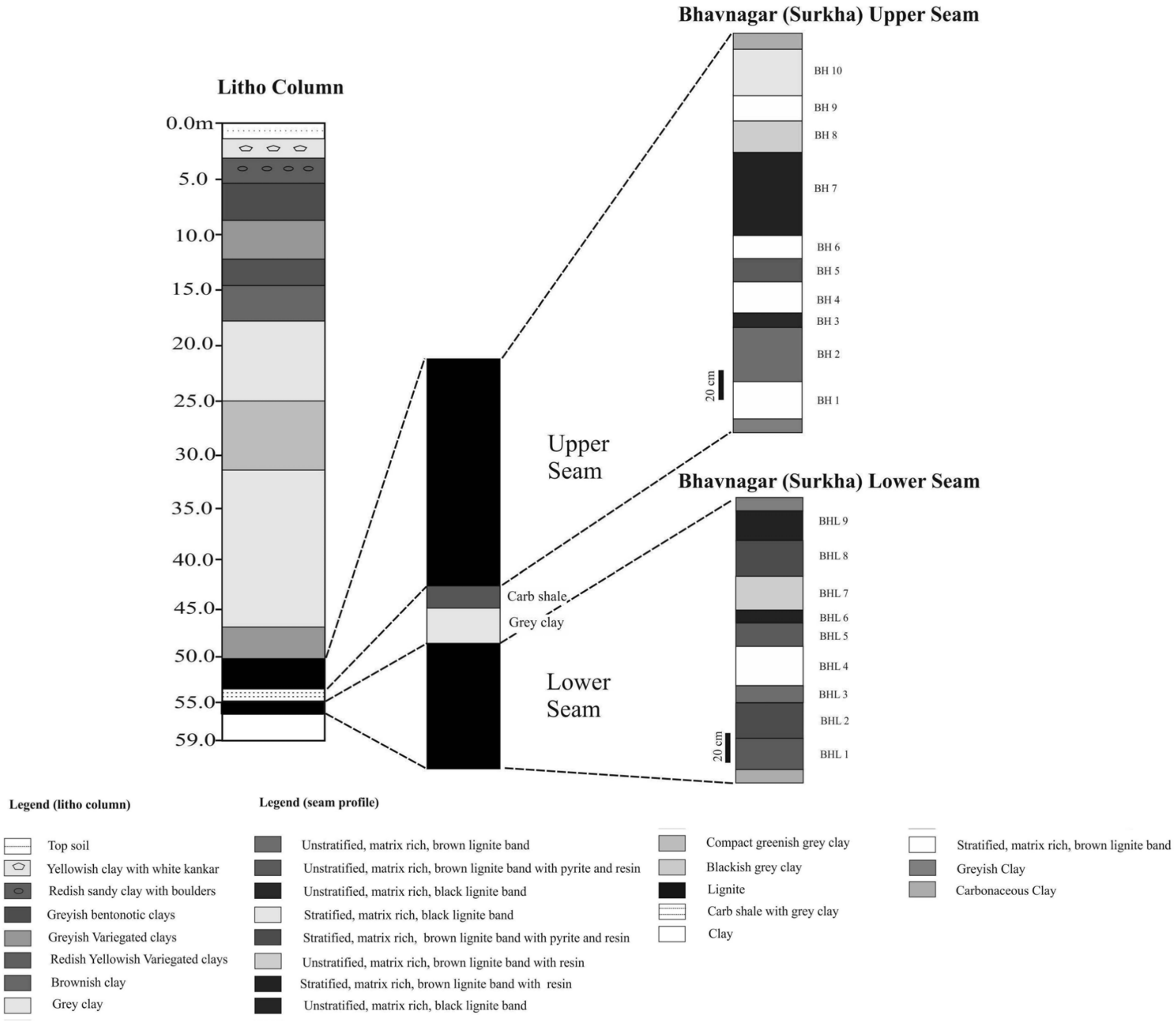


Fig.2. Litho column showing various rock units in Saurashtra basin along with lignite seam profiles at Surkha lignite mine.

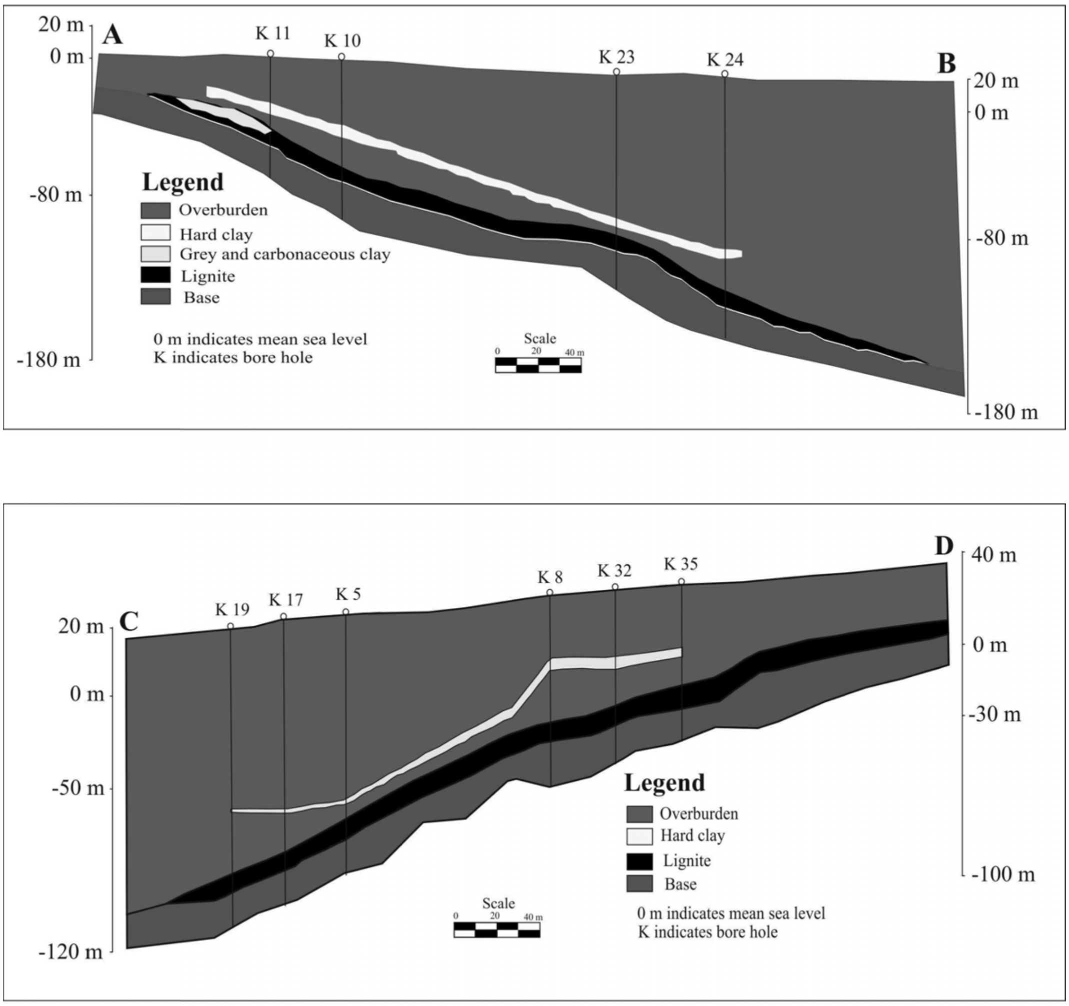


Fig.3. Cross sectional views of coal bearing sequences in Surkha lignitefield (A-B along east-west and C-D along north-south) (redrawn after GMDC, 2013).

unstratified brown bands while the lower seam is characterised by alternately stratified and unstratified brown bands. Most of the bands contain resin which is visible. The lignites of Saurashtra basin are dominantly composed of huminite group macerals while liptinite and inertinite group macerals occur in subordinated amounts (Fig. 4a-l). Textinite (Fig. 4d, g-h) occurs in very low concentration and its cell lumens are mainly filled with argillaceous minerals and sometimes with corpohuminite/gelinite. Cracks and fractures have been observed mainly in ulminite-B (Fig. 4g-i). Oval to rounded corpohuminite (Phlobaphinite) (Fig. 4f), normally in clusters, occurs frequently associated with ulminite. Few oxidized grains of corpohuminite are also seen in these lignites. Few gelinite patches with prominent cracks have been recorded. Among liptinites, the occurrence of resinite (5-50µm) sporinite and cutinite is common (Fig. 4a-b). Few patches of suberinite are seen with well developed cortex cells. Bituminite grains (Fig. 4c) with massive structures have also been identified under UV light. Among inertinites, funginite is common and occurs as single chambered to multichambered bodies of oval to rounded shape up to 100µm in size. Few samples (BH5, BH8, BH10, BHL4 and BHL5) show well preserved fungal bodies (Fig. 4e, j).

Bhavnagar (Surkha) Upper Lignite Seam

Huminite is the dominating maceral group (80.8-90.8 %; av. 85.4 % mmf basis) in this seam which comprises mainly of detrohuminite followed by telohuminite. Detrohuminite comprises of densinite (19.5-54.7%; av. 37.9% mmf basis) and attrinite (8.5-59.1%; av. 21.9% mmf basis) while telohuminite is mainly contributed by ulminite-A (1.2-20.5%; av. 10.7% mmf basis) and ulminite-B (1.8-24.0%; av. 7.8% mmf basis). Gelohuminite is present in small amount. Liptinites (5.9-12.9%; av. 9.3% mmf basis) and inertinites are relatively low in content (3.1-8.6%; av. 5.3% mmf basis). Mineral matter occurs in moderate quantity and varies from 12.2-22.6% (av. 19.7%). The relative abundance of maceral groups and mineral matter along the seam profile in Surkha upper lignite seam are shown in Fig. 5 while their details are furnished in Table 2.

Bhavnagar (Surkha) Lower Lignite Seam

The most abundant maceral group is huminite (57.1-85.6%; av. 76.4% mmf basis) which is largely contributed by detrohuminite. This is represented chiefly by densinite (18.9-29.3%; av. 24.1% mmf basis) and attrinite (8.6-37.3%; av. 20.7% mmf basis). Telohuminite is chiefly represented by ulminite-B (8.7-28.6%; av. 16.9% mmf basis) and ulminite-A (4.5-15.6%; av. 8.7% mmf basis) while textinite contributes only little. Macerals of the liptinite group are second in abundance (8.8-18.1%; av. 13.7% mmf basis), while inertinite is still low (5.5-25.0%; av. 9.9% mmf basis).The mineral matter content is moderate and varies from 10.0-25.1% (av. 19.7%). The relative abundance of maceral groups and mineral matter along the seam profile in Surkha lower seam are shown in Fig. 5 while their details are furnished in Table 2.

Vitrinite Reflectance

Bhavnagar Eocene lignites of Saurashtra basin have attained a thermal maturity up to 0.28-0.30 % vitrinite reflectance

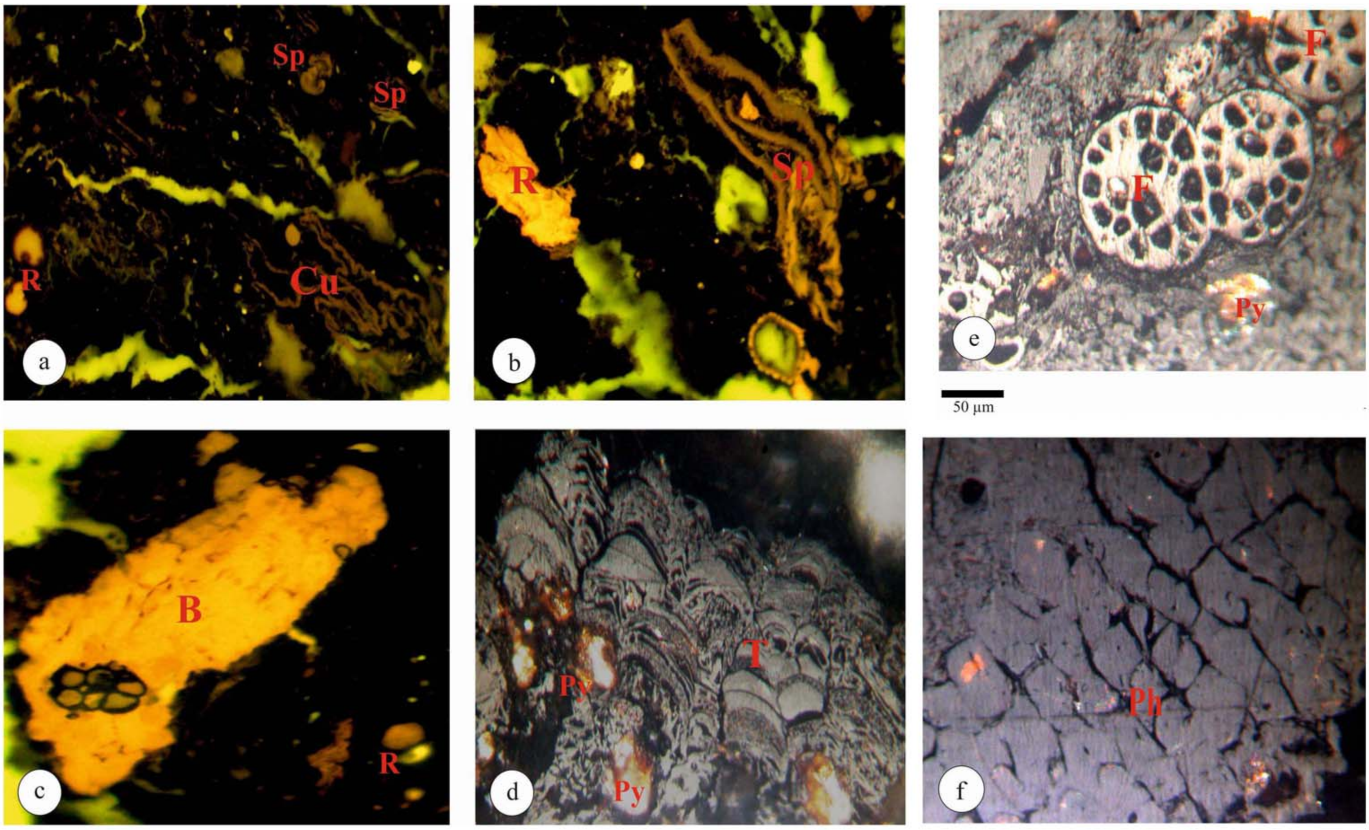


Fig.4. Characteristic photomicrographs in the lignites of Saurashtra basin: a-cutinite (Cu), sporinite (Sp) and resinite (R); b- sporinite (Sp) and resinite (R); c-bituminite (B); d- textinite (T) and pyrite (Py); e- funginite (F); f- phlobaphinite (Ph)

(VRr) which classifies them as 'low rank C' coals as per ISO- 11760 (2005). The Ro_{min} measured values range from 0.08 to 0.22% while Ro_{max} measured values range from 0.41 to 0.45%. Their variance is from nil to 0.0033 while the standard deviation is from 0.043 to 0.07. This shows a normal variation in the values for this rank of lignites.

Chemical Constituents

Chemical composition of Bhavnagar lignite is provided in Table 3. Bhavnager upper lignite seam is characterized by >21% moisture, >10% ash yield and > 57% volatile matter (daf) while Bhavnagar lower lignite seam has > 29% moisture, 8% ash yield and high volatile matter (> 66% on daf basis). The ultimate analysis reveals that both the lignite seams have >70% carbon and their sulphur content is over 2%. Total Organic Carbon (TOC) is over 41% in the upper seam and around 38% in the lower seam (Table 3). The vertical variation of these constituents along the lignite seam profile is shown in Fig. 6.

Depositional Environment

Bhavnagar lower lignite seam is relatively less gelified as compared to the upper seam. This is indicated by variation in the proportion of huminite and inertinite macerals in the two seams. The upper seam appears to have suffered relatively severe biochemical degradation. Since macerals are directly related to plants and environment, they bear the true signatures of the paleomire environment. Teichmüller (1989) correlated the presence or absence of certain macerals with the paleo-depositional environment. Teichmüller et al. (1998ab) and Lin and Tian (2011) have discussed that the peat forming plant communities, nutrient supply, bacterial activity, types of deposition, temperature, pH and redox potential are responsible for properties and composition of a coal. Inundation increases the supply of clastic mineral matter in the basin. Petrography based models have been used to reconstruct the environment of paleomire of Bhavnagar lignite basin. Cohen and Spackman (1972), Styan and Bustin (1983), Cohen et al. (1987), Calder et al. (1991), Grady et al. (1993), Hawke et al. (1996), Singh and Singh (1996), Shearer and Clarkson (1998), Sun et al. (1998), Jasper et al. (2010), Singh et al. (2010a,b), Deng and Sun (2011), Singh et al. (2012ab) are some examples who have successfully reconstructed the paleoecological environment with the help of petrological studies.

Gelification index (GI) and tissue preservation index (TPI) were introduced by Diessel (1986) to characterize the paleomire of Australian Permian coals. Less humified structured and strongly humified unstructured tissue derived macerals are indicative of vegetation type and degree of humification (Diessel, 1992). High subsidence rates of a basin are indicated by high TPI and predominance of wood derived tissues, while a low TPI is indicative of a low rate of subsidence with enhanced humification due to the predominance of herbaceous vegetation in the mire. The GI shows the degree of gelification of huminite macerals and differentiates between gelified and ungelified macerals. A continuous presence of water is necessary for gelification to take place and fluctuation in water table would affect the GI because inertinites, due to increasing oxidation, would form during dry spell periods.

Nevertheless, care must be taken while using these indices. Palynological and paleobotanical data would provide higher precision in the determination of paleoenvironment (Calder, 1993; Collinson and Scott, 1987). A number of researchers have made serious remarks for using such indices for tertiary or low rank coals (Lambersen et al., 1991; Crosdale, 1993; Dehmer, 1995; Wust et al., 2001; Scott, 2002; Moore and Shearer, 2003; Amijaya and Littke, 2005). Few researchers have tried a combination of petrographic, organic geochemical and/or isotope data for reconstructing the environment of paleomire (Bechtel et al., 2002, 2003; Singh et al., 2013). These indices have been modified by few workers so as to use them for low rank coals (Kalkreuth et al.,

Table 2. Maceral composition (in vol%) of upper and lower lignite seams of Bhavnagar (Surkha) mine, Saurashtra basin.

	Bhavnagar (Surkha) upper lignite seam										Bhavnagar (Surkha) lower lignite seam								
S.No.	BH1	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH10	BHL1	BHL2	BHL3	BHL4	BHL5	BHL6	BHL7	BHL8	BHL9
Liptinite (mmf basis)																			
Textinite-A	1.2	0.5	2.8	0	0	1	0.5	0.7	0.7	0.7	0.3	2.1	0	2.9	2.8	1.2	2.1	1.5	1
Textinite-B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ulminite-A	9.8	5.3	17.8	5.1	1.2	20.5	10.3	8.6	10.7	17.6	6.7	4.5	15.6	7.1	5.6	10.1	5.6	11.7	11
Ulminite-B	14.5	8.7	24	2.3	2.4	9.5	9.8	2	1.8	2.7	12.8	28.6	24.8	16.4	16.1	8.7	21.1	9.3	14.6
Attrinite	14	33.6	8.5	26.1	59.1	15.9	19.1	13.5	12.5	17.2	37.3	19.6	8.6	25.4	22.4	14.6	19.2	18.3	20.5
Densinite	37.6	30.5	25.8	46	19.5	36.4	43.8	49.5	54.7	35.5	19.5	23.6	25.1	27	27.6	18.9	23.5	29.3	22.4
Phlobaphinite	2.2	4.1	5.9	10	1.5	3.3	0	6.9	6.4	8.8	4	0	2.8	6.6	1.3	3.5	4	4.6	7.8
Pseudo-Phlobaphinite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Levi-Gelinite	1.2	1	2.6	1.3	0.2	0.3	0	0	0	0.2	0	0	0.8	0	0	0	0	0	0.2
Pori-Gelinite	0.2	0.5	2.3	0	0	0.3	0	0.7	0.7	1	0	0.5	0.8	0.2	1	0	0	0	2.4
Total	**80.8**	**84.2**	**89.9**	**90.8**	**83.9**	**87.2**	**83.5**	**81.9**	**87.5**	**83.8**	**80.5**	**79**	**78.6**	**85.6**	**76.8**	**57.1**	**75.5**	**74.8**	**80**
Liptinite (mmf basis)																			
Sporinite	3.9	2.8	2.1	2	2.9	2.6	2.1	3.2	0.7	2	3.2	3.5	2.2	3.8	3.3	4	2.1	3.2	4.1
Cutinite	0.5	0	0.5	0.5	0.7	0.8	0.8	0.5	0	0.7	0	0	1.4	0	1.3	1.7	0.5	0	0.7
Resinite	3.9	3.3	2.3	2.3	1.9	4.6	4.4	4.2	1.2	4.6	5.1	3.5	4.1	1.8	0.8	5.9	3.5	5.4	4.9
Liptodetrinite	2.5	2	0.5	0.8	1.2	1.3	3.9	1.7	3.9	2.5	2.7	3.1	1.9	2.2	2.6	3.5	4.5	5.6	1.7
Suberinite	0	0	0	0	0.7	0	0	0	0	0	0	0	2.8	0	0	0	0	0	0
Bituminite	1.7	0.8	0	0	1.7	0	1.8	0	1.8	0.5	2.1	1.9	1.9	0.7	2	2.8	2.7	3.2	2.4
Fluorinite	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0.4	0.5	0	0	0.7	0.5
Alginite	0.2	0.3	0	0	0.2	0	0	0	0	0.2	0.3	0	0.3	0	0	0	0.3	0	0
Total	**12.8**	**9.2**	**5.9**	**6.1**	**9.5**	**9.2**	**12.9**	**9.6**	**7.5**	**10.5**	**13.3**	**12.1**	**14.8**	**8.8**	**10.5**	**17.9**	**13.6**	**18.1**	**14.4**
Inertinite (mmf basis)																			
Pyrosemifuginite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0
Degradosemifuginite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyrofusinite	1	2.3	2.1	1	2.4	0	0	3.7	2.1	2.7	1.1	1.4	0.8	3.1	3.1	2.1	1.6	1.2	1
Degradofusinite	0	0.3	0	0	0	0	0	0	0	0.5	0	0.5	0	0	1.3	0	0.3	0	0.3
Funginite	3.4	3.6	2.1	2	3.4	1.5	1.5	3.2	2.7	0.7	3.5	4.5	4.7	2.2	4.6	21	7.2	5.1	4.1
Secritinite	0	0.3	0	0	0	1.5	1.5	0.2	0	0.2	0.5	2.1	0	0	1	0.2	0.3	0	0.5
Inertodetrinite	2	0.3	0	0	0.7	0.5	0.5	0.7	0	0.7	1.1	0.5	1.1	0.2	2.6	1.7	1.6	0.7	0
Micrinite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macrinite	0	0	0	0	0	0	0	0.7	0	0.7	0	0	0	0	0	0	0	0	0
Total	**6.4**	**6.6**	**4.1**	**3.1**	**6.6**	**3.6**	**3.6**	**8.6**	**5**	**5.6**	**6.1**	**9**	**6.7**	**5.5**	**12.8**	**25**	**10.9**	**7.1**	**5.6**
Total Maceral (mmf)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Mineral Matter																			
Argillaceous	10	10.8	14.1	11.4	12.6	10.6	11	8.8	10.2	9	18.6	11.4	25.2	8	11.2	7.4	18.6	7.8	11.8
Sulphide	4.4	4.8	8.8	9.8	1.4	10.6	10.6	9.2	2	9.2	6.6	3.6	2.2	2	9.6	7.4	5.6	10.2	6
Carbonaceous	4.4	6	0	0.6	3.8	1	1	0.6	0	0.6	0	0.2	0.8	0	0.8	0.2	0.6	0.2	0.4
Siliceous	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0.2	0.2	0	0
Total	**18.8**	**21.6**	**22.9**	**21.8**	**17.8**	**22.2**	**22.6**	**18.6**	**12.2**	**18.7**	**25.1**	**15.4**	**28.2**	**10**	**21.6**	**15.2**	**25**	**18.2**	**18.2**

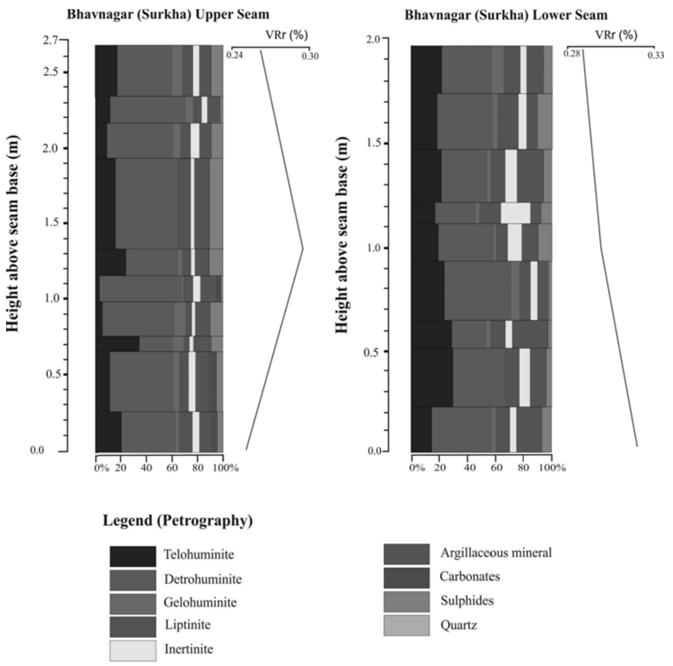


Fig.5. Vertical variation of petrographic constituents in the lignites of Surkha lignite seams of Saurashtra basin.

1991; Petersen, 1993; Flores, 2002). In the present study, the indices were taken from Flores (2002) which is a modified version of Kalkreuth et al. (1991), for brown coals and the calculations are as per the following formulae:

GI = (huminite+macrinite)/(fusinite + semifusinite + inertodetrinite)

TPI = (telohuminite + fusinite + semifusinite)/(gelinite + macrinite + inertodetrinite + detrohuminite)

Bhavnagar lignites are characterized by high gelification and low tissue preservation indices which are indicative of continuous wet conditions prevailing in the basin and a slow subsidence rate during the decay of organic matter. Surkha lower seam, however, suffered few shorter spells of relatively drier periods which are evidenced by the formation of inertinite macerals in relatively high concentration in few sections represented by the samples (BHL-5, BHL-6 and BHL-7) as compared to the Surkha upper seam. While working on SE Asian coals, Hoekel (1989) discussed that intensive gelification of plant tissues is a function of acid ground water which is due to marine influence and this could also be the case with Bhavnagar lignites. Further, detrital vitrinite is related to the decay of plant material under limno-telmatic and open marsh environment. GI values over 10 indicate deposition in a topogenous mire facies in the Saurashtra basin, where a permanently flooded marsh-reed environment prevailed (Fig. 7). The formation of Bhavnagar lower seam began under a limnic environment and then there was a shifting towards limno-telmatic environment for a shorter period as indicated by an increase in TPI values and again there was a shifting to a limnic environment for the remaining period of seam formation. Similarly, the formation of Bhavnagar upper seam began under limnic environment; it shifted to telmatic environment for a shorter spell and then returned to limnic condition. Thus, a limnic to limno-telmatic swamp existed with a low rate of subsidence and a very slow fall in ground water table. This is further characterized by development of treeless open marsh and limnic plant communities. Most of the samples show TPI values less than one which indicates that trees were rare in the basin. This is also in agreement with the study of Iordanidis and Georgakopoulos (2003) and Jasper et al. (2010).

Calder et al. (1991) emphasised the influence of ground water for characterizing the environment of a paleomire and used the ground water index (GWI) and vegatation index (VI) for paleoenvironmental reconstruction. It is understood that mires are formed in successive variations between rheotrophic and ombrotrophic hydrological conditions. Ombrotrophic to mesotrophic paleoenvironments are characterized by low GWI values (< 1) while more than 1 is indicative of rheotrophic hydrological condition. GWI values exceeding 5 indicate drowning of peat. In the present study the following formulae have been used for calculation.

Table 3. Geochemical constituents of Bhavnagar lignites, Saurashtra basin

Sample No.	Air dried basis (wt%)		Dry ash free (wt %)							TOC (%)
	Moisture*	Ash	Volatile Matter (daf)	Fixed Carbon (daf)	C	H	N	O	S	
BH10	15.47	10.07	59.19	40.81	62.44	5.15	0.78	29.48	2.15	44.47
BH9	12.82	10.33	62.36	37.64	na	na	na	na	na	42.78
BH8	16.72	10.15	60.59	39.41	na	na	na	na	na	38.12
BH7	18.64	10.57	59.57	40.43	na	na	na	na	na	45.25
BH6	24.32	9.79	53.97	46.03	na	na	na	na	na	na
BH5	23.30	9.52	60.69	39.31	82.99	5.49	0.97	8.77	1.79	47.28
BH4	24.78	8.43	48.94	51.06	na	na	na	na	na	40.56
BH3	34.91	10.05	49.63	50.40	na	na	na	na	na	38.05
BH2	21.38	10.08	59.26	40.74	na	na	na	na	na	na
BH1	25.74	14.59	58.12	41.78	73.34	3.41	1.06	19.51	2.69	38.78
Mean	21.81	10.36	57.23	42.76	72.92	4.68	0.93	19.25	2.21	41.91
BHL9	25.15	10.34	68.19	31.81	68.14	4.87	1.07	23.28	2.64	36.03
BHL8	35.32	6.63	74.25	25.75	na	na	na	na	na	na
BHL7	33.71	7.86	65.81	34.19	na	na	na	na	na	na
BHL6	26.05	8.51	64.06	35.94	na	na	na	na	na	na
BHL5	28.13	7.79	64.14	35.86	na	na	na	na	na	37.20
BHL4	28.72	8.40	59.75	40.25	na	na	na	na	na	na
BHL3	35.16	5.86	62.17	37.83	na	na	na	na	na	na
BHL2	30.40	10.37	73.43	26.57	na	na	na	na	na	na
BHL1	22.97	8.02	70.19	29.81	72.69	6.05	1.07	18.38	1.80	42.00
Mean	29.51	8.20	66.89	33.11	70.41	5.46	1.08	20.83	2.22	38.41

* Analysis was carried out four months after the sample collection; na-not analyzed

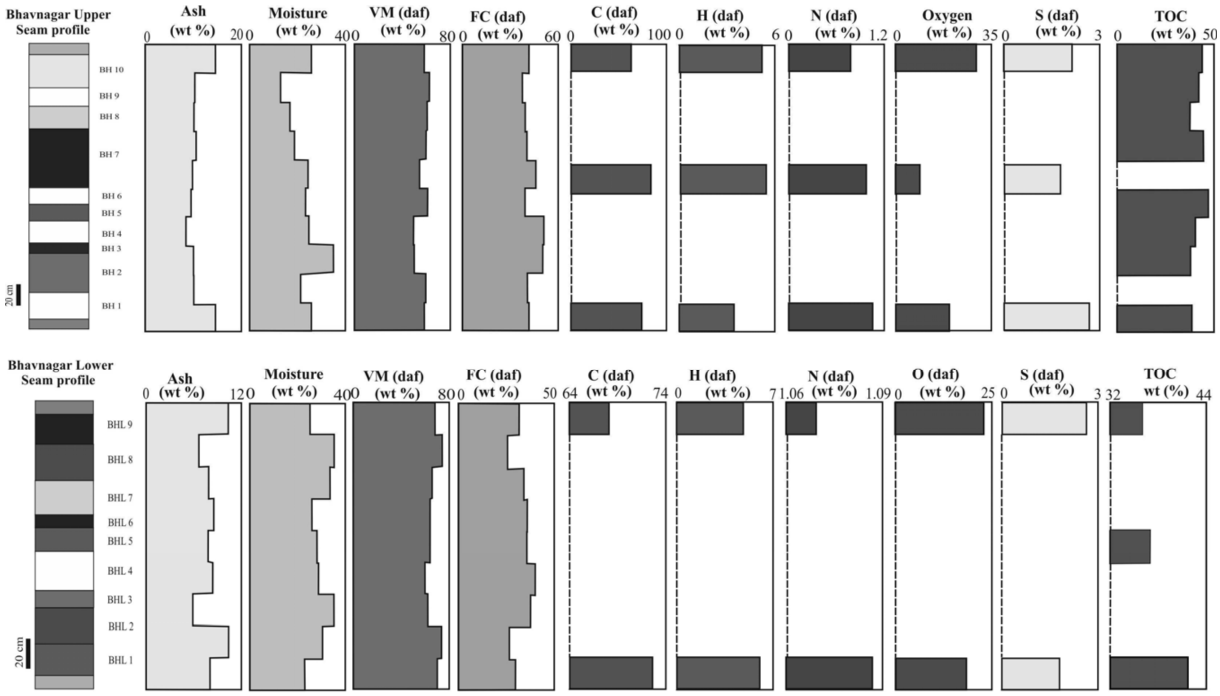


Fig.6. Vertical variation of chemical constituents in the lignites of Surkha lignite seams of Saurashtra basin

GWI = (gelinite + corpohuminite + mineral) / (textinite + ulminite + densinite)

VI = (textinite + ulminite + fusinite + semifusinite + suberinite + resinite)/(densinite + inertodetrinite + alginite + liptodetrinite + sporinite + cutinite)

The GWI and VI values of investigated lignites suggest rheotrophic paleoenvironment (Fig. 8) where inundated marsh to marsh condition prevailed. During the formation of the upper seam shorter spells of periodic drowning of peat existed. Variation of GI, TPI, GWI and VI values from base to top of the lignite seams of Bhavnagar is shown in Fig. 9. A maceral based model which is modified from Mukhopadhyay

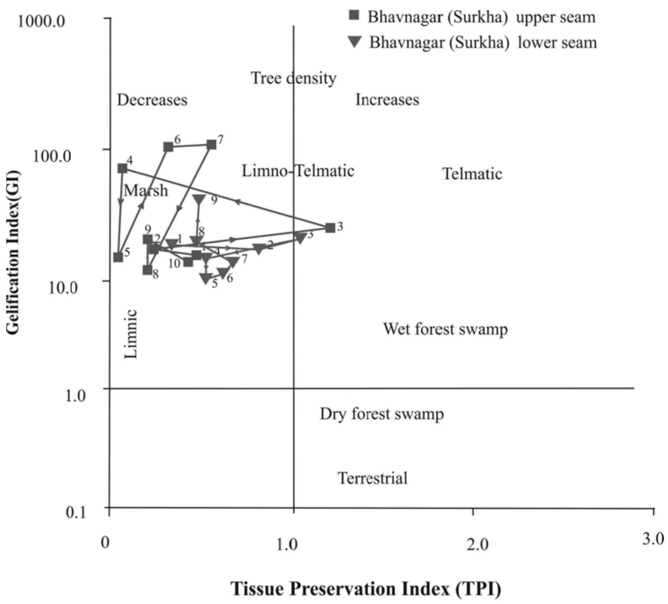


Fig.7. Coal facies determined from Gelification Index (GI) and the Tissue Preservation Index (TPI) in relation to depositional setting and type of mire for the lignites of Saurashtra basin (taken from Flores, 2002 which is a modified version of Kalkreuth et al., 1991 for lignites).

(1986) has been used to understand the environment of deposition of Bhavnagar lignites. The plots do not fall exactly within the field of either forest swamp or reed marsh. However, tissue preservation is relatively higher in the lower seam, while gelification is more pronounced in the upper seam (Fig. 10). Di Michele et al. (1987) and Shearer and Moore (1994) have suggested that under such condition these models may be taken as indicators and may be used complementary to paleobotany and palynology for determining the coal forming environment. Singh et al. (2012a) proposed a ternary model for Rajpardi Eocene lignite deposit of adjacent Cambay basin which was based on macerals and clastic minerals. The plots of Bhavnagar lignites on this model indicate a paleoenvironment of wet moor where high flooding occurred and the tissue preservation was low to moderate (Fig. 11). This model corroborates the discussions made using GI, TPI, GWI and VI indices. Teichmüller et al., (1998a) have discussed that the coals rich in calcium suffer severe structural decomposition through bacterial activity which leads to humic gel formation. Eventually the bacterial degradation of the plant remains will follow bacterial reduction of sulphates and higher amounts of ulminite would form. Further, presence of considerable amount of

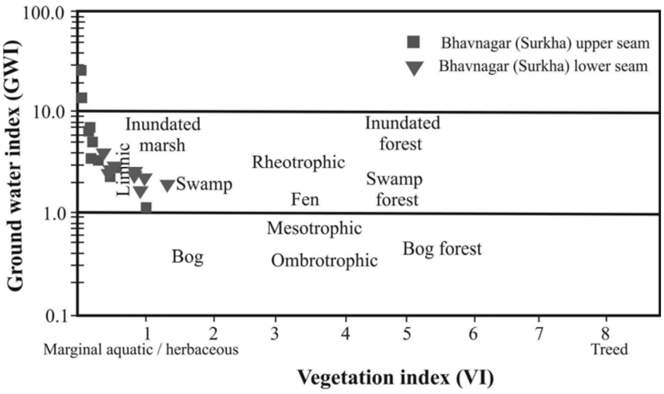


Fig.8. Plots of ground water influence index (GWI) versus vegetation index (VI) for the lignites of Saurashtra basin, Gujarat (after Calder et al., 1991).

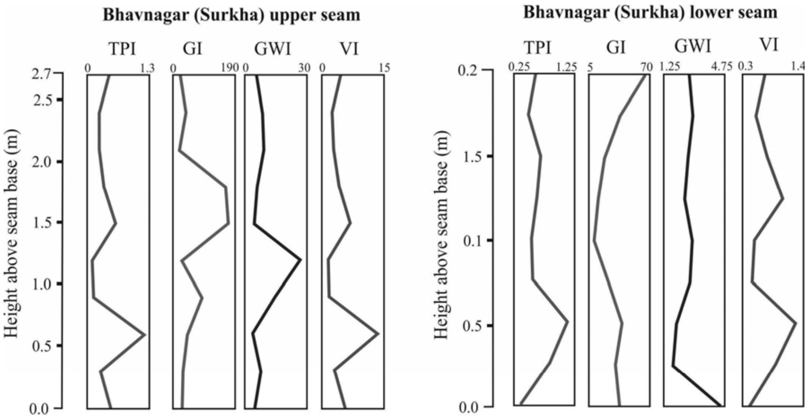


Fig.9. Variation of GI, TPI, GWI and VI from base to top of the lignite seams of Saurashtra basin.

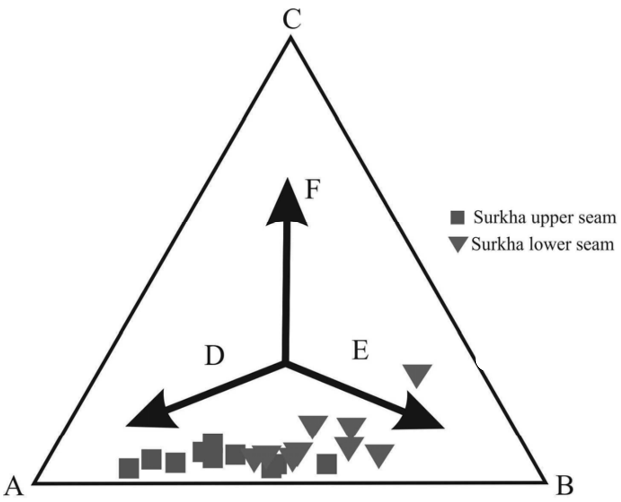
deltaic environment (Samant, 2000) and marine incursion (Samant and Phadtare, 1997). The dicots and the palms flourished and the climate was conducive for the growth of woody taxa and swamp dwellers (Samant, 2000). Samant and Phadtare (1997) believe, that dinocysts along with mangrove pollen taxa is a definite evidence of the deltaic environment with marine incursion. The clay sequence, lying in between the two lignite seams, is devoid of microfossils and indicates a change in the environment from reducing to oxidizing as a result of overflooding or sea transgression. Early Paleogene eustatic sea level rise of 70-140m higher than the present day sea level has been suggested by Haq et al. (1987) which is supported by the records preserved in the late Paleocene-early Eocene sedimentary sequences formed as a result of global transgressions during 58.5-52.8 Ma (Sluijs et al., 2008). Haq et al. (1987) and Hardenbol et al. (1998) further believe that during 55-52Ma the eustatic sea-level curve was high, though small scale fluctuations were also recorded.

detrohuminite supports formation under aerobic condition (Teichmüller et al., 1998a). Kuder et al. (1998) have discussed that at plate margins of peat beds the physical breakdown is prominent. The presence of framboidal pyrite is indicative of an increase in the activity of sulphate-reducing bacteria present in the carbonate and sulphate rich waters of the basin at the time of peat formation (Kuder et al., 1998; Teichmüller et al., 1998a). This indicates marine influence in the Saurashtra basin where the pyrite framboids formed through bacterial activity. This study also gets support from the work of Samant (2000). She has reported high frequency of fungal hyphae and pteridophytic spores with some angioscperms in these lignite seams. The dominance of fern spores of *Polypodiaceae* and *Schizaeaceae* and other microfossils indicates the presence of marsh. Moreover, the presence of mangrove element Nypa, megafossils like shells of lamellibranchs and foraminifera and Palaeocirrenalia (a characteristic fungus of marine or brackish condition) from Bhavnagar lignites are indicative of a deltaic to near

CONCLUSIONS

The investigated Saurashtra basin has two lignites seams (Surkha upper and lower seams). Based on their detailed petrological study, following conclusions are drawn:

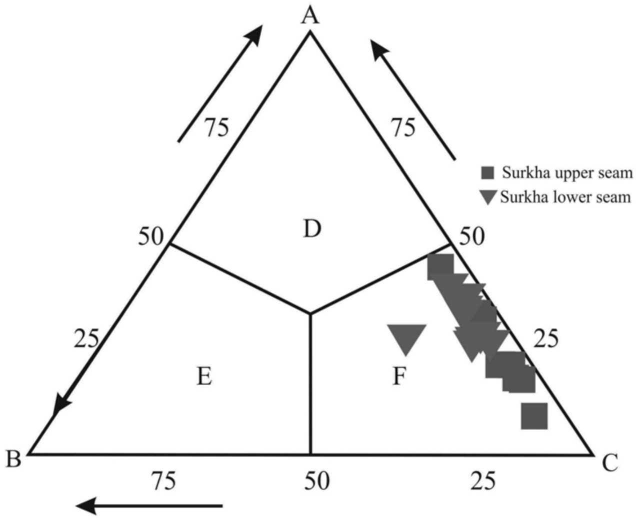
1. The lignites of Saurashtra basin are dominantly rich in huminite group macerals (av. 85.4% in upper seam and 76.4%in lower seam, on mmf basis).



A - Textinite+ulminite+terrestrial liptinite
B - Attrinite+densinite+corpohuminite+liptodetrinite+ gelinite
C - Intermediates

D - Forest swamp, milky oxic to anoxic with good tissue preservation
E - Reed marsh, increasing maceration and bacterial activity, increasing anoxic
F - Dry oxic condition

Fig.10. Ternary diagram illustrating facies- critical maceral associations in lignites of Saurashtra basin, Gujarat and suggested peat forming environments. (modified from Mukhopadhyay, 1986).



A - Telohuminite+gelohumite+sporinite+cutinite+resinite+ suberinite
B - Fusinite+semi-fusinitee+macrinites as groundmass+ secretinite+fuginite
gelinite
C - Clastic mineral matter+detrohumite+inertodetrinite+ liptodetrinite+discrete macrinite+alginite

D - Wet moor having moderate flooding with moderate to good tissue preservation
E - Oxic (dry) moor with increased tissue preservation
F - Wet moor with high flooding and low to moderate tissue preservation

Fig.11. Peat forming environment of lignites of Saurashtra basin, Gujarat, based on macerals and mineral mattere (after Singh et al., 2012).

2. A continuous wet condition prevailed in the basin as revealed by high gelification and low tissue preservation indices. This indicates a low subsidence rate during decay of organic matter. Bhavnagar upper seam is relatively more gelified and has suffered more biochemical degradation as compared to the lower seam. Shorter spells of drier period prevailed especially during the formation of lower seam.
3. The formation of lower and upper seams began under limnic environment but there was a shifting towards telmatic condition for a shorter spell and again a limnic environment prevailed for rest of the period of seam formation.
4. The ground-water and vegetation indices indicate rheotrophic hydrological condition where inundated marsh to marsh prevailed. During the formation of upper seam, periodic drowning of peat existed.
5. Maceral based ternary plots also support the prevalence of a wet moor environment having moderate flooding with bacterial activity. There was marine influence in the Saurashtra basin where pyrite framboids formed through bacterial activity.

Petrographically these lignites have close resemblance to the lignite deposits of the Cambay basin which have excellent hydrocarbon potential. Therefore, the Saurashtra lignites may also be further evaluated for their hydrocarbon content taking recourse to petrography, chemical analyses and rock-eval pyrolysis.

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