

Petrological and Geochemical Considerations to Predict Oil Potential of Rajpardi and Vastan Lignite Deposits of Gujarat, Western India

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Abstract: This paper entails the results of the investigations undertaken to assess the oil potential of two lignite deposits, Rajpardi and Vastan, from Gujarat, western India. They are 'Low rank B' type lignite. Petrographically, they are enriched in huminite and are low in liptinite and inertinite. Their elevated hydrogen content, in relation to carbon, has probably made them perhydrous in nature and oil prone. The reactivity of these coals during liquefaction has also been discussed in the light of petrofactor. Good correlation has been noticed between oil yield and conversion ($r^2 = 0.999$) in both the lignite deposits. The VRr (0.24 – 0.35% in both lignites), H/C atomic ratio (0.11 – 1.39 in Rajpardi and 1.09 – 1.88 in Vastan), reactive maceral content (91.6 – 99.8 vol % mmf in Rajpardi lignite and 75.5 – 99.7 vol % in Vastan lignite) and VM_{daf} (64.8 – 67.9 wt % in Rajpardi lignite and 42.1 – 80.0 wt % in Vastan lignite) of these lignites have a favourable range required for a coal to generate oil. Huminite is seen to play a vital role in conversion and maintains a good correlation with it. The calculations show that these lignites have a high conversion (> 95%) and oil yield (> 65%).

Keywords: Macerals, Liquefaction, Petrofactor, Lignite deposits, Rajpardi-Vastan, Gujarat.

INTRODUCTION

Oil and natural gas are derived from the decomposition of organic matter, and coal being composed of over 50% organic matter, is a significant source rock for hydrocarbon. Though a number of oil basins are reported to have coal-bearing sequence as source rocks, less than one percent of known reserves of the world comes from them (Powell and Boreham, 1994). Useful contributions, on hydrocarbon bearing basins, have been made by various workers (Hacquebard and Donaldson, 1970; Bartenstein and Teichmuller, 1974; Alpern, 1975; Teichmuller and Ottenjann, 1977; Shibaoka et al. 1978; Teichmuller et al. 1979a; Bustin et al. 1985). Kutei basin of Indonesia and the Gippsland basin of Australia are examples of such basins (Macgregor, 1994). Almost 80 % of oil reserves of Australia and 10-30% of south-east Asia are derived from coal-bearing sequences (Macgregor, 1994). The oil-prone detritus deposited in coastal environment under wet tropical conditions led to the formation of oil containing coal bearing sequence (Fleet and Scott, 1994). The generation of oil from coal source rock is fundamentally related to the availability of hydrogen (Hunt, 1996; Petersen and Nytoft, 2006). The expulsion of liquid hydrocarbon also depends on the length of the aliphatic chains present in them (Isaksen et al., 1998). To appreciate the ability of coal to expel hydrocarbon, it is

imperative to comprehend the properties of exuded hydrocarbons. Such indications have been recorded in the Permian Gondwana coal in the Rajmahal basin of India (Singh, 1992; Singh and Singh, 1994ab) and Tertiary coals of North Eastern India (Singh and Singh, 2003). Huc et al. (1986) have reported that hydrocarbon yield in the Mahakam delta of Indonesia is more from coals than from shales. The ability of Kerogen Type-III (humic coal) source rocks to expel hydrocarbon, has opened new insights (Petersen, 2006), inviting more researches on petroleum generating potentials of such source rocks. The main objective of the present investigation is to envisage the oil potential of the Rajpardi and Vastan lignite deposits of Gujarat on the basis of their petrographic and geochemical attributes.

GEOLOGICAL SETTING

Rajpardi Lignite Deposit

Deccan traps and Tertiary sediments are the two major formations in Rajpardi area (Table 1). Here the lignite deposit is being mined in the Amod Lignite block of Bharuch district. The major litho units in this area include Babaguru Formation underlain by Tadkeshwar Formation, which, in turn, is underlain by Nummulitic Formation (Table 1a). The Tadkeshwar Formation begins with grey clay-bed and is

Table 1a. Regional stratigraphic sequence with lithounits in and around investigated area (based on the work of Oil & Natural Gas Corporation)

Age	Formation	Lithounits	Thickness (m)
Pleistocene to Recent	Alluvium	Varied coloured sands, soil and Kankar	-
Middle Miocene to Pliocene	Jhagadia Formation	Light coloured sandstones, marls, limestone and conglomerate	300
Early Miocene	Kand Formation	Limestone, marls, clays with sandstone bands and agate bearing conglomerate	450
Early most Miocene	Babaguru Formation	Agate Conglomerates Ferruginous sandstone Sandy	150
Oligocene to Late Eocene	Tadkeshwar Formation	Grey Clay Carbonaceous Clay Lignite Carbonaceous Clay Lenses of sandstone Carbonaceous Clay, lignite Grey Clay	150
Late Eocene to Early Eocene	Numulitic Formation	Numulitic limestone, clays with sandstone lenses	120
Early Eocene	Vagadkhol Formation	Bentonitic clays, friable sandstone and conglomerates	120
	~~~~~Unconformity~~~~~		
Cretaceous	Deccan Traps	Basalts with basic intrusives	-

continuous in nature with varying thickness. It is overlain by the carbonaceous clay-bed. The grey clay embraces few lenses of sand, sandstone, carbonaceous clay and lignite. The thickness and lateral extent of lignite lenses vary. The carbonaceous clay-bed is conformably overlain by a five-meter-thick lignite seam, which, is a marker bed. The lignite seam is brown in colour, soft and friable in nature and also contains yellow resin and pockets of clay. The upper carbonaceous clay lies conformably over the lignite seam and is further overlain by the grey, plastic, bentonitic clay. The proportion of sand increases towards the upper portion of the bentonite clay and gradually converts into sandy clay.

Two persistent lignite seams, top (4.2 to 8.8 m thick)

**Table 1b.** A general succession of the Vastan region (after Sahni et al. 2006)

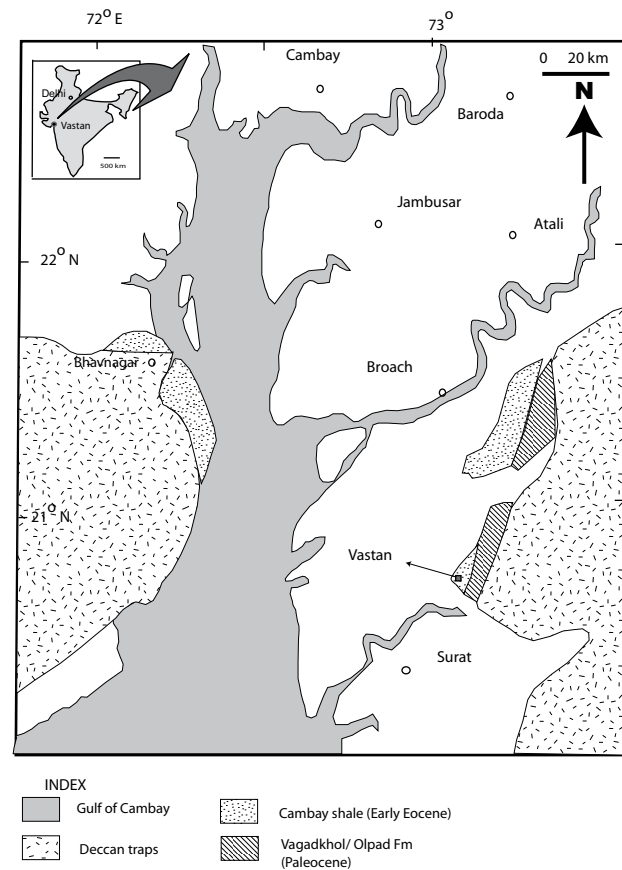
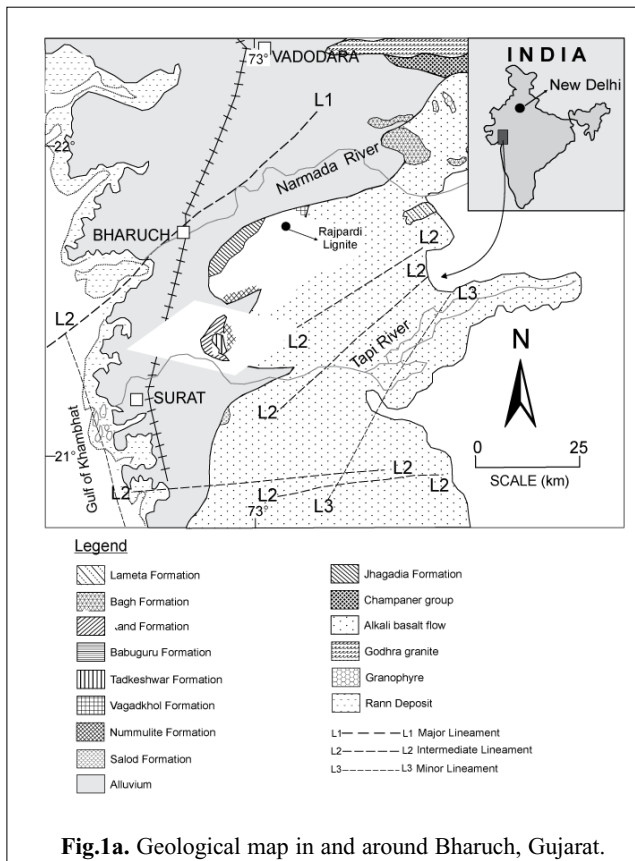
Lithology	Age	Thickness (m)
Alluvium & Black shale	Recent	75-150 (total Cambay Formation)
Calc Bentonitic clay	Late Eocene	
Lignite with clay	Early Eocene	20-145 (in Vastan area)
Lithomargic clay	Paleocene	
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Deccan Trap	Late Cretaceous	-

and bottom (1.0 to 3.4 m thick), occur in the area. Few local seams also occur in this block but they are non-mineable and uneconomic. The lignite seams have a gentle dip of 6-7 degrees towards west. The major formations in the Rajpardi area are shown in a simplified geological map (Fig 1a). Lithology of the lignite bearing strata is summarised in Table 1a and the megascopic seam profile (after Singh et al. 2012) is shown in Fig 2a.

Vastan Lignite Deposit

The Vastan lignite mine is in Surat district located nearly 60 km NE from the main town. It is one of the important lignite deposit of Gujarat and is of Eocene age. The lignite bearing sequence is a part of Cambay Formation (or Cambay shale) trending in a NNW-SSE intra-cratonic graben called Cambay basin. Extending all along the Sanchor-Mehsana-ahmedabad-Tarapur-Broach-Surat areas of Gujarat and continuing northwards (Fig.1b) into the Barmer region of Rajasthan, Cambay basin forms a significant tertiary hydrocarbon belt (Mathur et al. 1968; Raju, 1968; Biswas, 1987).

Cambay Formation comprises 75-150 m thick beds of greenish and whitish grey and black clay/shales with lignite



seams. The Vagadkhol Formation and its equivalent Olpad Formation underlie the Cambay Formation. The cambay shale is further subdivided into a lower (older Cambay) and upper (younger Cambay) shale and has a marked unconformity between the two units.

A muddy succession (200 m) is exposed at the Vastan mine directly over the Deccan traps, which, is differentiated into three successions namely A, B and C. Succession A (45 m) encloses the lignite beds and consists of lignites, greenish grey shales, carbonaceous shales and shell carbonates (Garg et al. 2008). The succession B is composed of greenish grey shales and succession C comprises mainly of reddish brown shales.

The Cambay shale, in Vastan area, attains 20-145m thick sequence of lignite beds alternating with dark grey to black and greenish grey shales and clay marls (Sahni et al. 2006). Two lignite seams, upper lignite seam and lower lignite seam, occur with cyclic repetition of shell carbonate, carbonaceous shale, green shale, and lignite succession between the two seams (Garg et al. 2008). A number of thin lignite bands also occur as split seams and the beds have a low dip of 3° - 4° towards NW. The geological map of Vastan has been provided in Fig.1b and megascopic seam profile is shown in Fig 2b.

Fig.1b. Geological map around Vastan area (after Rana et al. 2004).

MATERIALS AND METHODS

The lignite samples from Amod lignite mine (Rajpardi) and lower and upper seams of Vastan were collected from the open cast lignite mines following pillar sampling method given by Schopf (1960). For microscopic study, the samples were crushed to -18 mesh size, mounted in cold medium araldite and hardener and subsequently ground and polished. They were crushed and, by quartering and coning, reduced in quantity to prepare composite samples and were then subjected to detailed petrographic and chemical analyses. The maceral analysis was carried out on polished pellets under reflected light using Leitz Orthoplan- Pol Microscope equipped with Wild Photoautomat MPS 45. 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 under oil immersion. The methodology given by Taylor et al (1998) has been followed; for huminite macerals, the terminology of ICCP-1994 (Sy'korova' et al. 2005), and for inertinite macerals, ICCP (2001) were followed. The proximate analysis was carried out as per BIS, 2003. The elemental analysis (C, H, N, and S) was performed at C.D.R.I. Lucknow using Vario EL-III Analyzer. The vitrinite

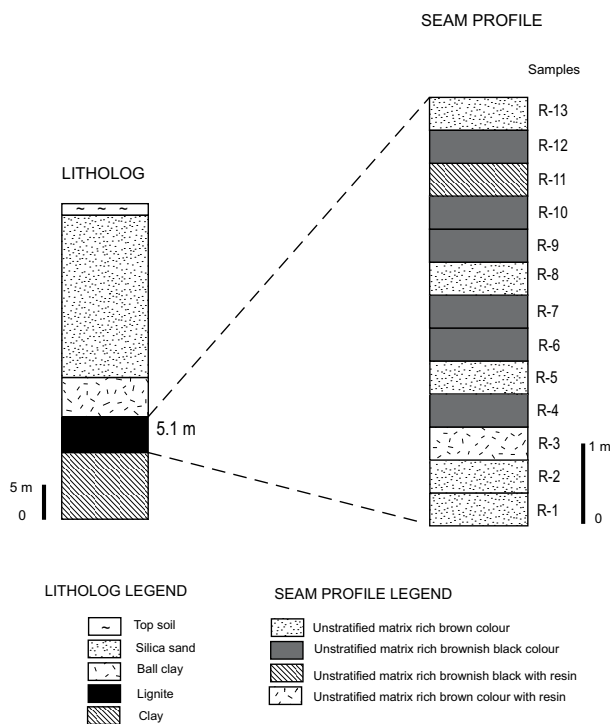


Fig.2a. Megascopic seam profile of Rajpardilignite.

reflectometry was carried out in the Research and Development centre of Tata Steels P Ltd., Jamshedpur using J &M MSP 200 software developed by J&M Analytische Mess- und Regeltechnik GmbH, Robert-Bosch-Strasse 83, D-73431 Aalen, Germany. A minimum of 100 counts were made on each sample.

RESULTS

Chemical Constituents

Vastan lignite has elevated moisture (Singh et al., 2010) content (mean 18.5 % in bottom seam; mean 11.1 % in Top seam) and maintains a negative correlation with volatile matter ($r^2 = -0.635$). Rajpardilignite, on the other hand, has moderate to low moisture (Singh et al. 2011) content (mean 7.03 %) maintaining a positive correlation with its volatile matter ($r^2 = 0.759$). Both the lignite deposits have elevated volatile matter (mean 53.3 % and 66.4 % for bottom and top Vastan seams; 66.1 % for Rajpardilignite seam). The elemental composition as determined by the ultimate analysis reveals that carbon content of the Rajpardilignite is 67.7 % (mean value), while, that of Vastan has 63.9 % for bottom and 64.5 % for top seam. The hydrogen content is reasonably high (with mean 5.8 % in Rajpardilignite seam; 7.3 % in bottom Vastan and 6.9 % in top Vastan seam). There is a low but positive correlation between H_{daf} and C_{daf} ($r^2 = 0.249$ for Rajpardilignite and $r^2 = 0.299$ for Vastan lignite). The

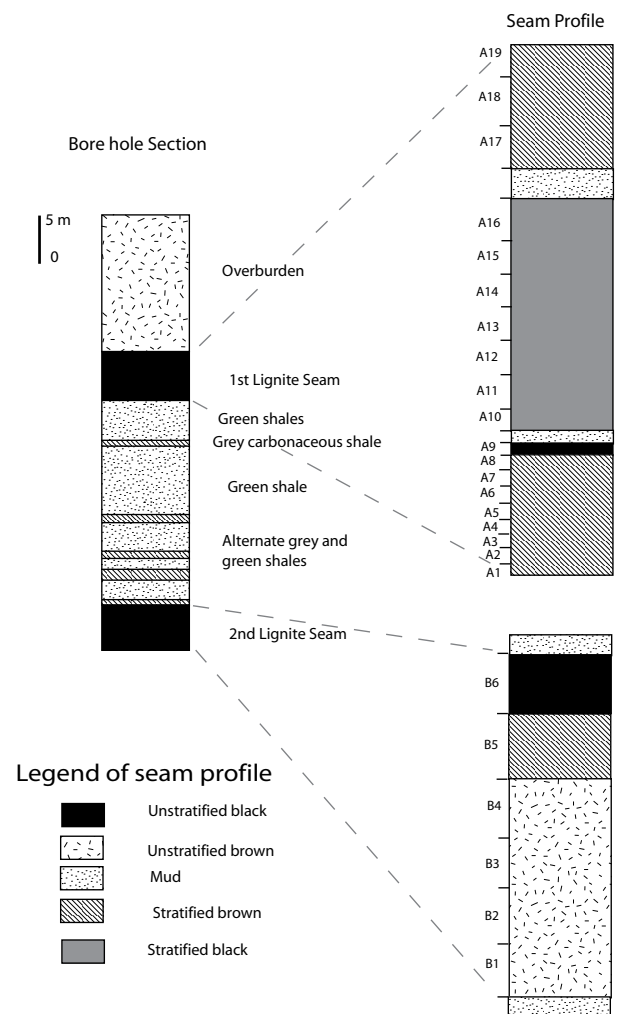


Fig.2b. Megascopic profiles of the two Vastan lignite showing various bands (borehole section is taken from Bajpai and Kapur, 2004).

H/C ratio in Rajpardilignite is 1.03 (mean value), whereas, it is 1.37 % and 1.28 % respectively in the bottom and top Vastan lignite seams. The O/C ratio in Rajpardilignite is 0.29 whereas, it is 0.31 in Bottom and 0.33 in the top Vastan seams. The total sulfur content of Vastan is higher (mean 2.24 %) in the bottom Vastan seam, whereas, it is relatively low in the top Vastan seam (mean 0.59) and Rajpardilignite seam (mean 0.43 %). However, few samples have shown high sulfur values indicating enrichment of sulfur in those horizons and may be attributed to marine influence (Bustin and Lowe, 1987; Casagrande, 1987). High sulfur content in coal requires its removal (Baruah et al. 2006) owing to its environmental implications.

The ash content has a positive correlation with total sulphur in Vastan lignite ($r^2 = 0.878$ in Vastan bottom seam). This supports the view that there was an increase in pH of the paleomire due to infilling water, diluting the humic acids.

Further rise in pH was through the carbonate-rich surface waters, which, led to the elevated sulphur content. However, there is negative correlation with Rajpardi lignite ($r^2 = -0.322$). This could be attributed to relatively varied depositional environments of the two lignite deposits (Singh et al., 2010; Singh et al. 2012). The proximate and ultimate constituents of Rajpardi and Vastan lignite samples are given in Table 2.

Petrographic Composition

The Rajpardi and Vastan lignite deposits have low liptinite and inertinite contents and the latter may be attributed to a lack of forest fire. The liptinite content (mean value) of Rajpardi lignite is 2.3 % (2.5 % mmf), whereas, it is 1.0 % (1.1 % mmf) in Vastan bottom lignite seam and 3.1 % (3.5 % mmf) in Vastan top lignite seam. These lignite

Table 2. Chemical constituents of Rajpardi and Vastan lignite (in wt %), Gujarat

S. No	Proximate Analysis				Ultimate Analysis				Atomic Ratio		
	Air Dried basis		daf basis		daf basis				S _{total}	H/C	O/C
	M	A	VM	FC	C	H	N	O			
J-13	7.4	6.2	67.4	32.6	67.5	0.6	0.5	31.5	0.21	0.11	0.35
J-12	7.6	5.4	66.6	33.4	62.8	7.3	1.4	28.5	0.78	1.39	0.34
J-11	8.7	5.7	67.9	32.1	67.3	6.0	0.5	26.2	0.55	1.08	0.29
J-10	6.4	6.2	66.2	33.8	64.4	4.8	0.4	30.4	0.32	0.9	0.35
J-9	6.9	5.5	66.6	33.4	67.8	6.3	0.5	25.5	0.46	1.11	0.28
J-8	7	6.1	66.5	33.5	66.7	6.5	0.6	26.2	0.39	1.17	0.29
J-7	6.3	5.2	65.2	34.8	64.3	5.1	0.5	30.1	0.38	0.94	0.35
J-6	6.6	4.9	64.2	35.8	64.3	5.8	0.7	29.2	0.47	1.09	0.34
J-5	6.9	6.1	65.2	34.8	73.3	7.8	0.2	18.7	0.38	1.28	0.19
J-4	7.2	5.9	66.7	33.3	69.7	6.9	0.5	22.9	0.52	1.19	0.25
J-3	6.8	5.1	65.8	34.2	71.1	7.1	0.3	21.5	0.36	1.19	0.23
J-2	6.6	6.8	64.8	35.2	71.5	6.2	0.3	22.1	0.43	1.03	0.23
J-1	7	7.3	66.5	33.5	69.0	5.1	0.5	25.5	0.37	0.88	0.28
mean	7.0	5.9	66.1	33.9	67.7	5.8	0.5	26.0	0.43	1.03	0.29
A-1	11.9	4.2	57.9	42.1	69.1	6.3	1.1	23.5	0.10	1.09	0.26
A-2	10.4	3.6	58.1	41.9	65.4	6.0	1.1	27.4	0.10	1.09	0.32
A-3	11.9	3.6	66.7	33.3	61.6	6.6	0.9	30.7	0.22	1.28	0.37
A-4	11.6	4.2	57.4	42.6	62.2	6.2	0.6	31.0	0.00	1.20	0.37
A-5	14.2	3.2	64.1	35.9	68.9	6.3	1.2	23.1	0.50	1.10	0.25
A-6	11.4	3.2	63.3	36.7	63.6	6.1	1.0	29.3	0.02	1.14	0.35
A-7	13.9	3.6	71.3	28.7	67.5	6.3	1.1	24.5	0.59	1.12	0.27
A-8	7.2	4.4	62.4	37.6	60.8	5.7	1.1	31.5	0.88	1.13	0.39
A-9	13.5	5.2	64.2	35.8	69.9	7.0	1.1	21.4	0.50	1.20	0.23
A-10	5.8	27.2	78.7	21.3	55.6	6.8	1.2	35.7	0.78	1.47	0.48
A-11	9.2	28.4	74.9	28.0	77.3	7.8	1.5	12.4	0.93	1.21	0.12
A-12	10.3	25.3	62.2	37.8	72.9	7.9	1.2	17.2	0.82	1.31	0.18
A-13	8.3	26.2	79.8	20.2	56.4	6.3	1.1	35.6	0.64	1.35	0.47
A-14	7.6	28.0	73.6	26.4	57.7	6.9	0.8	34.0	0.51	1.45	0.44
A-15	6.3	40.4	80.0	20.0	47.6	7.5	0.7	43.9	0.34	1.88	0.69
A-16	11.9	47.2	69.7	30.3	64.6	8.9	1.2	23.1	2.13	1.65	0.27
A-17	20.3	8.9	57.2	42.8	68.3	7.3	1.5	22.5	0.47	1.28	0.25
A-18	17.4	15.5	61.4	38.6	70.3	7.9	1.2	19.5	1.10	1.34	0.21
A-19	7.9	15.1	59.1	40.9	64.7	6.5	0.8	27.4	0.55	1.21	0.32
mean	11.1	15.7	66.4	33.7	64.5	6.9	1.1	27.0	0.59	1.28	0.33
B-1	15.1	17.5	69.8	30.2	66.8	7.8	1.3	20.5	3.67	1.40	0.23
B-2	22.3	10.9	65.1	34.9	68.6	7.8	1.4	20.2	2.10	1.36	0.22
B-3	23.7	6.8	44.2	55.8	66.7	8.1	1.3	22.9	1.05	1.46	0.26
B-4	17.3	6.6	42.1	57.9	64.7	7.2	1.1	24.7	2.33	1.34	0.29
B-5	17.7	5.8	44.3	55.7	57.6	6.3	0.5	34.1	1.41	1.31	0.44
B-6	14.9	11.9	54.6	45.4	59.3	6.6	0.7	30.7	2.87	1.33	0.39
mean	18.5	9.9	53.3	46.7	63.9	7.3	1.0	25.5	2.24	1.37	0.31

J1-J13- Rajpardi lignite samples; B1-B6- Vastan bottom lignite samples; A1-A19- Vastan top lignite samples; M-moisture; A-ash; VM-volatile matter; FC-fixed carbon

deposits have high huminite content which is 85.1 % (94.7 % mmf basis) in Rajpardi and 86.2 % (95.4 % mmf) in Vastan bottom, whereas, 74.8 % (93.4 % mmf) in Vastan top seam.

These lignite deposits have variable mineral matter. Among them, the argillaceous mineral matter dominates, followed by carbonates and sulfides. The results of petrographic analyses are summarized in Table 3.

Reflectance

To know the level of maturation the samples were subjected to huminite reflectance measurements. The measurements were performed on the selected grains of ulminite (huminite), which, were homogeneous and free from scratch, pits and inclusion. The huminite reflectance values of Rajpardi lignite is 0.30, whereas, it is 0.28 in both the seams of Vastan (Table 3). Based on the reflectance values, both the lignites may be classified as 'Low-rank B' (as per ISO-11760, 2005).

DISCUSSION

Properties of Coal for Liquefaction

Oil-prone coals are relatively richer in hydrogen content (Thomas, 2002). Powell and Boreham (1994) have shown that a source rock should possess 10-20 % of organic matter equating to Kerogen Type-I or 20-30 % equating to Kerogen Type-II in order to have reasonable potential of hydrocarbon and the bulk H/C ratio should be in the range of 0.8 to 0.9. Coal liquefaction is highly influenced by its rank and composition (Fisher et al. 1942; Chen and Ma, 2002). Coals with rank below medium volatile bituminous can be successfully converted to distillable products (Given et al. 1980ab) and low rank coals with elevated hydrogen content give an increased oil yield. Kalkreuth et al. (1986) have observed that under a constant coal rank condition, the oil yield and the nature of solid residue depend on maceral composition and mineral matter content. Consequently, high H/C atomic ratio is closely related to rank and petrographic composition. It has been established that coals and terrestrial kerogen having H/C atomic ratio more than 0.9 and liptinite content exceeding 15 % may be considered to generate oil (Taylor et al. 1998). Hunt (1991) has shown that more than 15-20 % of liptinite content in coal makes it plausible to be considered as oil-prone. Coals keep hydrogen and have the capability to retain the potential of hydrocarbon generation especially below 1 % VRr (Boudou et al. 1984; Littke et al. 1990). However, the thermal, maturation, which is necessary for a humic coal source rock, to start oil generation, does not correspond to the degree of maturation required for the

Table 3. Petrographic constituents (in vol %) of Rajpardi (Singh et al. 2012) and Vastan (Singh et al. 2010) lignite, Gujarat

SN	Huminite	Liptinite	Inertinite	Mineral Matter	VRr
J-1	68.9 (98.1)	1.0 (1.4)	0.4 (0.6)	29.8	0.35
J-2	87.3 (98.2)	1.4 (1.6)	0.2 (0.2)	11.1	0.27
J-3	86.2 (95.5)	2.1 (2.4)	1.9 (2.1)	9.8	0.33
J-4	86.2 (97.1)	1.2 (1.3)	1.4 (1.6)	11.2	0.25
J-5	91.0 (96.6)	1.5 (1.6)	1.7 (1.8)	5.8	0.3
J-6	89.7 (95.4)	2.8 (2.9)	1.6 (1.7)	5.9	0.32
J-7	92.6 (97.7)	1.4 (1.5)	0.8 (0.8)	5.3	0.3
J-8	80.8 (88.9)	6.5 (7.1)	3.5 (3.9)	9.2	0.26
J-9	89.2 (95.8)	1.6 (1.8)	2.3 (2.5)	6.9	0.31
J-10	92.1 (96.4)	1.7 (1.8)	1.7 (1.8)	4.5	0.29
J-11	70.8 (90.4)	0.9 (1.2)	6.6 (8.4)	21.7	0.33
J-12	84.7 (87.3)	5.3 (5.5)	7.0 (7.2)	3.0	0.3
J-13	87.0 (93.7)	2.8 (2.9)	3.1 (3.4)	7.1	0.24
mean	85.1 (94.7)	2.3 (2.5)	1.9 (2.8)	10.1	0.30
A-1	91.2 (92.3)	0.7 (0.7)	7.0 (7.1)	1.1	0.28
A-2	93.2 (94.3)	1.6 (1.6)	4.1 (4.1)	1.1	0.28
A-3	89.8 (91.0)	0.7 (.7)	8.2 (8.3)	1.3	0.27
A-4	92.8 (93.7)	0.9 (1.0)	5.3 (5.3)	1.0	0.29
A-5	91.9 (94.8)	0.9 (1.0)	4.1 (4.2)	3.1	0.27
A-6	90.2 (91.4)	1.8 (1.9)	6.7 (6.8)	1.3	0.26
A-7	72.2 (74.8)	0.7 (0.7)	23.7 (24.5)	3.5	0.26
A-8	90.2 (92.8)	0.8 (0.9)	6.1 (6.3)	2.8	0.28
A-9	79.6 (84.5)	0.9 (1.0)	13.6 (14.5)	5.8	0.30
A-10	57.2 (95.6)	1.3 (2.2)	1.3 (2.2)	40.2	0.27
A-11	57.2 (97.8)	1.1 (2.0)	0.2 (0.3)	41.5	0.31
A-12	73.3 (98.4)	0.7 (0.9)	0.5 (0.7)	25.5	0.27
A-13	73.0 (96.4)	1.6 (2.1)	1.1 (1.5)	24.2	0.26
A-14	63.7 (93.5)	3.1 (4.6)	1.3 (1.9)	31.9	0.28
A-15	28.8 (94.9)	1.0 (3.4)	0.5 (1.7)	69.7	0.35
A-16	15.0 (94.8)	0.5 (3.1)	0.3 (2.1)	84.2	0.32
A-17	96.2 (98.9)	0 (0)	1.0 (1.0)	2.8	0.31
A-18	73.0 (96.5)	1.5 (1.9)	1.2 (1.5)	24.3	0.24
A-19	92.4 (98.1)	0 (0)	1.8 (1.)	5.9	0.28
mean	74.8 (93.4)	1.1 (1.6)	4.6 (5.0)	19.5	0.28
B-1	71.2 (93.1)	0.6 (0.8)	4.6 (6.1)	23.5	0.27
B-2	92.9 (97.7)	1.1 (1.2)	0.9 (1.0)	4.9	0.3
B-3	86.0 (92.4)	1.5 (1.6)	5.6 (5.9)	6.9	0.25
B-4	91.3 (95.1)	1.8 (1.9)	2.9 (3.1)	3.9	0.28
B-5	92.3 (97.0)	0.5 (0.5)	2.3 (2.4)	4.9	0.3
B-6	83.6 (96.8)	0.5 (0.6)	2.3 (2.7)	13.6	0.29
mean	86.2 (95.4)	1.0 (1.1)	3.1 (3.5)	9.6	0.28

values in parenthesis are on mmf basis; J1-J13- Rajpardi lignite samples; B1-B6- Vastan Bottom lignite samples; A1-A19- Vastan Top lignite samples

oil expulsion to begin (Sykes and Snowdon, 2002). Bright coals, having less than 89 % carbon, have shown better liquefaction (Fisher et al. 1942; Gorin, 1981). The best liquefaction was noticed in high volatile coals with > 70% reactive macerals (vitrinite/huminite and liptinite) content (Davis et al. 1976). The reactive maceral content of a coal has good relationship with conversion and relative ease of its liquefaction. Vitrinite possess thermoplastic properties at bituminous rank; a strong correlation exists between

conversion and thermoplastic properties (Senftle, 1981; Senftle et al. 1984). In coals having low liptinite content, the oil-generating component is hydrogen-enriched vitrinite (Bertrand, 1989; Newman et al. 1997; Petersen et al. 2000; Singh et al. 2011; Sykes, 2001). Such coals are sulphur rich and have marine influence (Diessel, 1992; Sykes, 2001) and the source of perhydrous vitrinite is the increased aliphatic compounds in vitrinite (Masterlez et al. 1993). Perhydrous vitrinites containing more than 5.5% hydrogen are considered to be the progenitor for liquid hydrocarbons (Bertrand, 1984; Smith and Cook, 1984). It has been worked out that liptinite macerals exhibit high reactivity during liquefaction (Fisher et al. 1942; Given et al. 1975; Davis et al. 1976). They yield more oil owing to their elevated aliphatic content. Teichmuller (1974) and Spackman et al. (1976b) could identify several secondary liptinite macerals and other materials with the help of fluorescence microscopy, which, are significantly important for liquefaction. The inertinites have been mostly inert during the process of liquefaction (Fisher et al. 1942; Given et al. 1975b; Davis

et al. 1976). However, macrinite and semifusinite show partial reactivity.

Oil Potential of Gujarat Lignite Deposits

Huminite reflectance is observed to make weak correlation with carbon contents ($r^2 = 0.362$ in Rajpardhi lignite and $r^2 = -0.247$ in Vastan lignite), whereas, it holds a strong correlation with volatile matter ($r^2 = 0.759$ in Rajpardhi lignite and $r^2 = -0.635$ in Vastan lignite). This variation could be attributed to variation in the environment of deposition in the paleomire. The behavior of H/C and O/C atomic ratios has been observed with maturity by plotting these parameters against reflectance. Though the correlation is low, the H/C and O/C values have been observed to increase with maturation in Vastan lignite indicating that gain of hydrogen and oxygen is characteristics for the coalification of these lignite deposits (Fig.3). However, in Rajpardhi lignite it is seen that loss of hydrogen and oxygen is characteristic for the coalification (Fig.4).

When the carbon and hydrogen values of Gujarat lignite

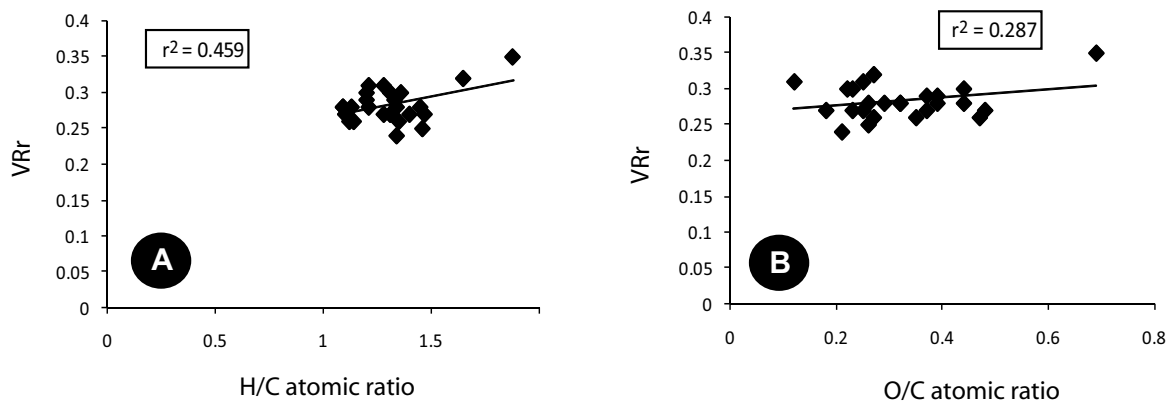


Fig.3. Relationship of vitrinite reflectance (VRr) with H/C atomic ratio (A) and with O/C atomic ratio (B) in Vastan lignite.

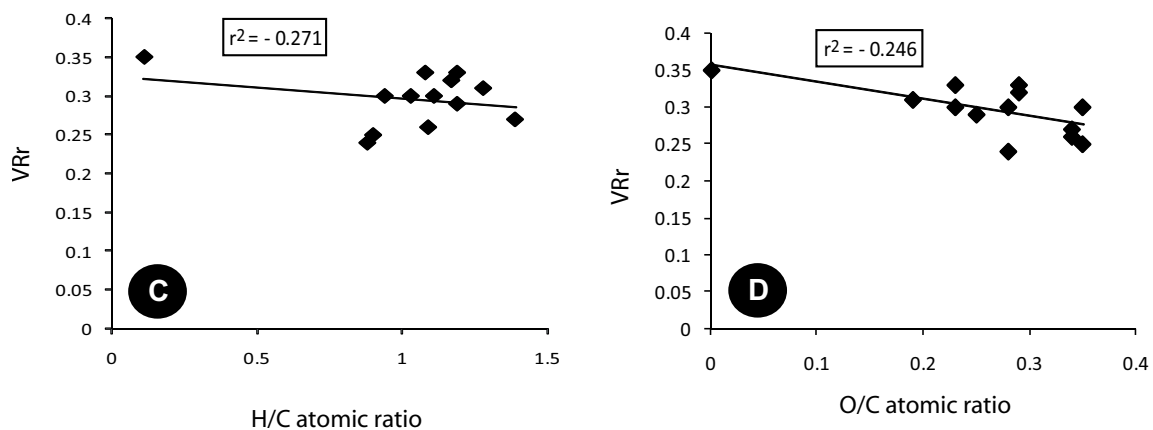


Fig.4. Relationship of vitrinite reflectance (VRr) with H/C atomic ratio (C) and with O/C atomic ratio (D) in Rajpardhi lignite.

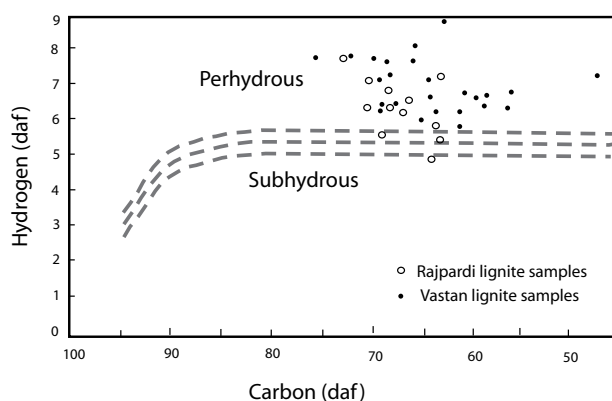


Fig.5. Plots of carbon (daf) and hydrogen (daf) of Gujarat lignites on Seyler's chart showing their perhydrous nature.

samples are plotted on the simplified Seyler's diagram (Seyler, 1931), their perhydrous nature is reflected (Fig.5). This nature could be attributed to their marine water influence. It is substantiated by the contention given by Diessel (1992), who, showed that the coals formed under marine influence fall in the zone above the bright coal band in Seyler chart. This situation appears to have caused enrichment of sulfur in the Vastan bottom seam (av 2.24 wt%) and also in some of horizons of Vastan top seam and Rajparddi lignite seam. While working on petroleum generation potential of humic coal, Petersen (2006) observed that marine influenced coals cause enrichment of hydrogen in vitrinite than the normal vitrinite. Sometimes such marine influenced coals are affected by vitrinite reflectance suppression (up to 0.25 %; George et al. 1994).

Cudmore (1977) has demonstrated that coals that are favourable for liquefaction or hydrogenation should possess reflectance (VRr) less than 0.8 %, H/C atomic ratio more than 0.75, reactive macerals (Vitrinite or huminite + liptinite) more than 60 % and volatile matter (daf) more than 35%. The lignite deposits of Gujarat possess these properties, which, are furnished in Table 4. While working on the influence of coal characteristics on the conversion and oil yield, Guyot (1978) and Jim and Shi (1997) have designed empirical formula, which, have been used for calculating the 'conversion' and 'oil yield' of Gujarat lignite deposits.

Table 4. Coal characteristics required for hydrogenation

Sl No	Properties of coal required for hydrogenation (after Cudmore, 1977)		Characteristics of Rajparddi Vastan lignite	
			Rajparddi lignite	Vastan lignite
1	Vitrinite Reflectance (VRr)	< 0.8	0.30	0.28
2	H/C atomic ratio	>0.75 %	1.03	1.36
3	Vitrinite + Liptinite content	> 60 %	96.45	95.31
4	Volatile Matter (daf)	>35 %	66.12	63.29
5	Concentration of heteroatoms	Relatively low	Low	Low

Table 5. Values of conversion, oil yield and petrofactor calculated for Rajparddi and Vastan lignites of Gujarat using empirical formula

S No	Conversion %		Oil yield % = [oil yield % = 0.2 RM+76.6] ¹	Petrofactor [RF = 1000R _{max} /RM]
	[conversion % = 99-0.84 RF] ¹	[conversion % = 0.22 RM+44.8] ²		
j1	96.48	96.04	66.67	3.52
j2	96.55	96.73	66.75	2.71
j3	96.17	96.17	66.33	3.37
j4	96.28	96.87	66.45	2.54
j5	96.23	96.43	66.40	3.06
j6	96.26	96.27	66.43	3.25
j7	96.43	96.46	66.62	3.03
j8	95.82	96.73	65.94	2.71
j9	96.11	96.33	66.26	3.18
j10	96.24	96.52	66.41	2.95
j11	94.91	95.97	64.94	3.60
j12	95.15	96.28	65.21	3.23
j13	95.92	96.91	66.05	2.48
Mean	96.04	96.44	66.19	3.05
A1	95.18	96.47	65.24	3.01
A2	95.78	96.55	65.90	2.92
A3	94.94	96.53	64.97	2.95
A4	95.54	96.43	65.63	3.06
A5	95.77	96.63	65.88	2.82
A6	95.25	96.66	65.32	2.79
A7	91.70	96.11	61.41	3.44
A8	95.33	96.49	65.41	2.99
A9	93.71	96.05	63.62	3.51
A10	96.16	96.68	66.32	2.76
A11	96.54	96.39	66.74	3.11
A12	96.46	96.72	66.65	2.72
A13	96.30	96.78	66.47	2.64
A14	96.21	96.60	66.38	2.86
A15	96.26	96.01	66.42	3.56
A16	96.19	96.26	66.34	3.27
A17	96.40	96.37	66.58	3.13
A18	96.29	96.95	66.46	2.44
A19	96.22	96.60	66.38	2.85
Mean	95.59	96.49	65.69	2.99
B1	95.39	96.59	65.46	2.87
B2	96.39	96.45	66.56	3.03
B3	95.40	96.77	65.48	2.66
B4	95.98	96.57	66.12	2.89
B5	96.11	96.42	66.26	3.08
B6	96.07	96.50	66.21	2.98
Mean	95.89	96.55	66.02	2.92

RM= reactive macerals (vitrinite + liptinite), RF = petrofactor

J1-J13- Rajparddi lignite samples; B1-B6- Vastan bottom lignite samples; A1-A19- Vastan top lignite samples. ¹Jin and Shi (1997); ²Guyot (1978)

To predict the coal reactivity during liquefaction of these lignites the role of petrofactor (RF) has also been evaluated. Guyot (1978) gave the concept of petrofactor and formulated the interrelationship between coal rank and coal type. He defined the petrofactor (RF) as:

$$RF = 1000 R_{\max} / RM$$

Where R_{\max} refers to the maximum reflectance of vitrinite/huminite; RM is the total reactive macerals that includes vitrinite (huminite) % and liptinite %.

He also observed that increasing order of petrofactor is related to:

- i) Decrease in volatile matter (VM) and H/C atomic ratio of feed coal

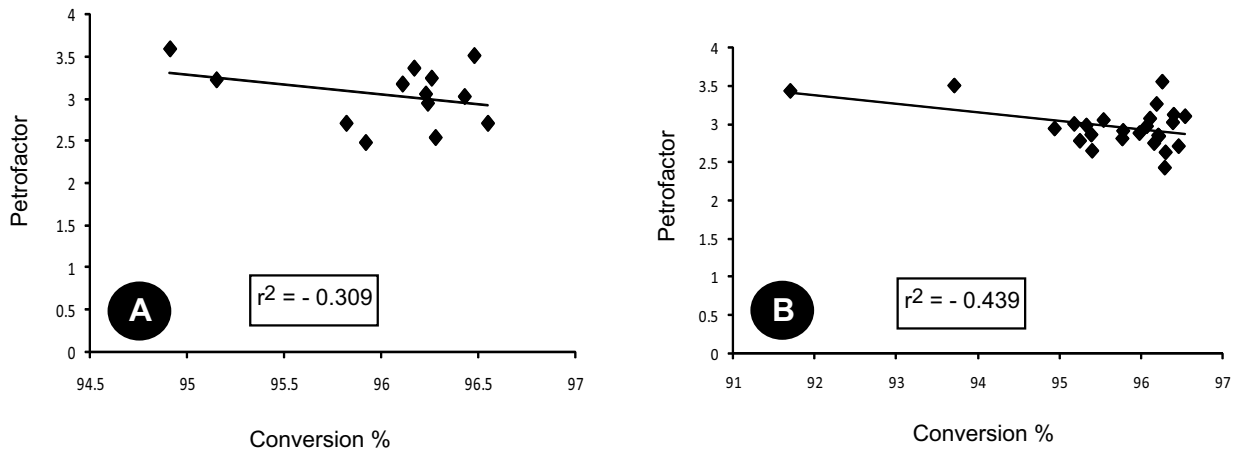


Fig.6. Relationship between petrofactor and oil conversion in Rajpardi lignite (A) and Vastan lignite (B).

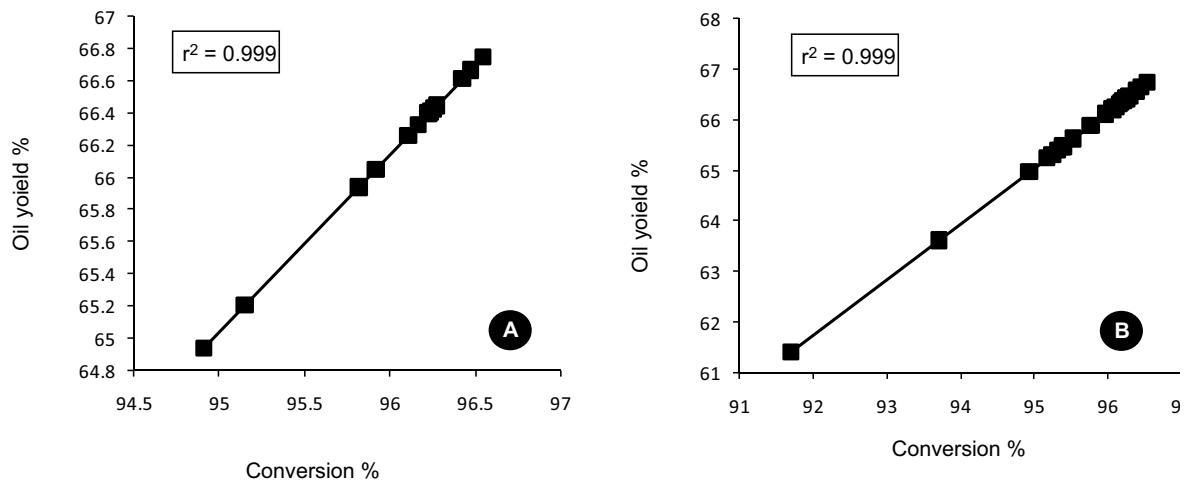


Fig.7. Relationship between conversion and oil yield in (A) Rajpardi and (B) Vastan lignite deposits.

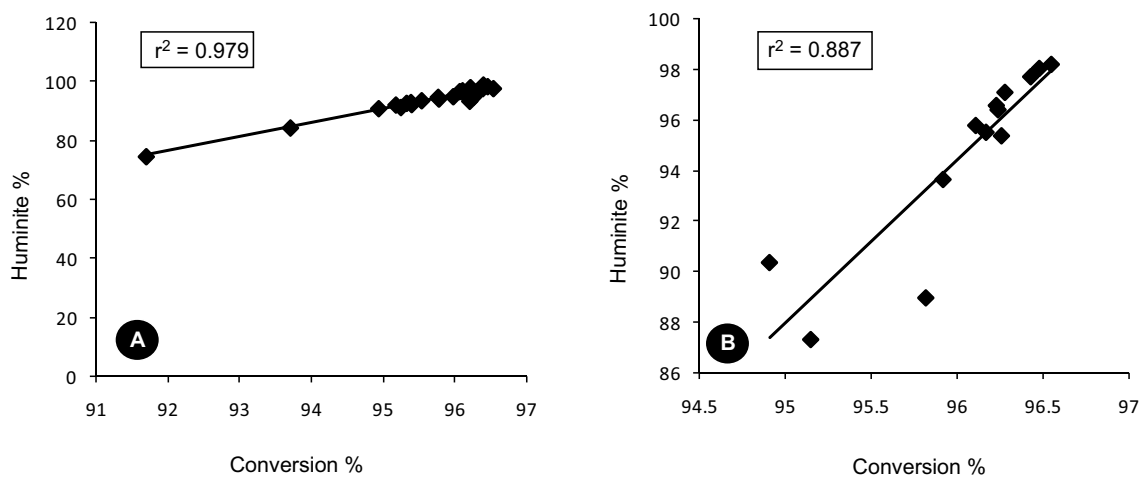


Fig.8. Relationship between conversion and huminite maceral in (A) Vastan and (B) Rajpardi lignite deposits.

- ii) Decrease in coal conversion and oil yield
- iii) Increase in density, specific energy and carbon content of coal derived oil
- iv) Increase in semi-coke in char residue.

Based on the empirical formula, the detailed values of conversion, oil yield and petrofactor have been calculated, which, are furnished in Table 5. Moderate correlation is seen to exist between petrofactor and conversion (Fig.6), whereas, a good correlation exists between conversion and the oil yield (Fig.7). There exists a good correlation between huminite macerals and conversion ($r^2 = 0.887$ in Rajpardi lignite and $r^2 = 0.979$ in Vastan lignite deposit) (Fig.8). This indicates that huminite plays a vital role in the oil conversion of these lignite deposits. The study reveals that favourable characteristics of Gujarat lignite deposits (Rajpardi and Vastan lignites) prevail for their high conversion (> 95%) and oil yield (>65%).

CONCLUSIONS

The oil potential of Rajpardi and Vastan lignite from Gujarat has been investigated in this study. The results reveal that:

1. These lignites may be classified as 'Low-rank B' on the basis of their reflectance values and are exceptionally rich in huminite macerals (94.7% Rajpardi; 93.4 %

Vastan top; 95.4 % Vastan bottom) and low in liptinite and inertinite.

2. Due to elevated hydrogen content, these lignites are perhydrous in nature.
3. The H/C and O/C ratios decrease with increase in rank in Rajpardi lignite, whereas, it is vice-versa in Vastan lignite. The sulphur content is elevated in few horizons due to marine influence.
4. Huminite plays a vital role in conversion in these lignites. The conversion (> 95 %) and oil yield (> 65%), as calculated using empirical formula, favour them for liquefaction.

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