



Depositional palaeoenvironment and economic potential of Khadsaliya lignite deposits (Saurashtra Basin), western India: Based on petrographic, palynofacies and geochemical characteristics

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ABSTRACT

The lignite and associated shale of the Khadsaliya Clays Formation (Eocene) of Saurashtra Basin, India have been studied. Organic petrographic, palynofacies and organic geochemical analyses have been carried out to deduce the depositional palaeoenvironment, including the assessment of the hydrocarbon potential of this sequence. Petrographically, the lignites constitute huminite macerals in dominance (av. 60%). The organic facies, as derived from maceral composition and biomarker data, suggests that the peat biomass was formed from woody forest vegetation consists of angiosperms and pteridophytes. Microbial activity was also prominent over the peat biomass. The peat biomass was deposited in tropical-subtropical humid climatic conditions under deltaic control and brackish water influence. Further, there are signatures of intermittent floods in the mire, and is evident from the shift from mesotrophic to rheotrophic conditions. The organic matter has been categorized into two palynofacies and is derived from degraded terrestrial biomass. The extrapolation of Tyson's APP diagram and Pr/n-C₁₇ vs. Ph/n-C₁₈ plot suggest that deposition took place in dysoxic to sub-oxic conditions. The huminite reflectance values (0.30–0.38%, av. 0.34% R_r) suggest that lignites are less mature and have reached up to lignitic stage (low rank B) of coalification. The geochemical (proximate + ultimate) analyses reveal that the lignites are characterized by high moisture content (av. 18%) and relatively low ash yield (av. 27%). The volatile matter yields and carbon contents are moderately high, whereas fixed carbon, sulphur and oxygen contents are average and hydrogen and nitrogen contents are relatively low. Rock-Eval pyrolysis data indicate that the hydrogen index values of the samples vary between 23 and 477 mg HC/g TOC (av. 188 mg HC/g TOC). The T_{max} values of the lignites range between 377 and 433 °C (av. 418 °C), along with the presence of ββ hopanes suggesting the immature nature of the deposits. HI vs. T_{max}, S₂ vs. TOC, HI vs. OI and H/C vs. O/C plots of the studied samples indicate that the organic matters are a mix of type II/III kerogens. The types of kerogen along with high TOC contents (av. 33 wt.%) indicate the ability of lignite-bearing sequence of Khadsaliya to generate mix of oil/gaseous hydrocarbons upon maturation.

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1. Introduction

The past decades of studies demonstrate, despite certain contradictory views and discussions (Moore and Shearer, 2003; Scott, 2002; Wüst et al., 2001; Crosdale, 1993; Dehmer, 1993), that organic petrography is one of the most efficient tools for the reconstruction of depositional environments and deducing the palaeogeothermal conditions of coal-/lignite-bearing basins (Stock et al., 2016; Suárez-Ruiz et al.,

2012; Zdravkov et al., 2011; Dai et al., 2007; Bechtel et al., 2005; and many more). The quantitative maceral analysis of coal/lignite reflects on the peat-forming conditions, and vitrinite/huminite reflectance pattern points to the geothermal evolution of peat.

Palynofacies has also been widely used for interpretation of palaeovegetation and climate during the development of peat swamps (Mendonça Filho et al., 2011, 2012; Tyson, 1995). Besides, the biomarker data have convincingly been utilized for inferring the vegetation source of peat biomass (Peters et al., 2005; Otto and Simoneit, 2001; Otto and Wilde, 2001). The parameters drawn from these studies supported by Rock-Eval pyrolysis data help in the evaluation of

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hydrocarbon source (kerogen types) potential of the organic deposits (Hakimi et al., 2013; Sia and Abdullah, 2012; Hunt, 1996; Mukhopadhyay et al., 1985; Tissot and Welte, 1984), as the oil/gas generation potential depends on the amount, type and maturity of the inherent organic matter.

Gujarat, a state in the western part of India is well-known for the huge deposits of lignites holding valuable signatures of Eocene palaeovegetation and palaeoenvironments (Singh et al., 2013 on Mangrol; Singh et al., 2012 on Tadkeshwar; Sahni et al., 2006 and Singh et al., 2010 on Vastan lignite deposits of the Cambay Basin; Dutta et al., 2011 on Matanomadh, and Singh and Singh, 2005 on Panandhro fields of the Kachchh Basin) (Fig. 1A). Further, these workers have also attempted to figure out the thermal maturity and source rock potential (in some cases) of the lignite deposits of the region.

In Saurashtra Basin of Gujarat, the lignite deposits are associated with the Khadsaliya Clays Formation (Eocene), and are presently being excavated at the Surkha and Khadsaliya areas of Bhavnagar district (Fig. 1A). The basin, as per the Directorate General of Hydrocarbon, Ministry of Mines (Govt. of India), comes under category III–prospective basin, and lies north of commercially proven Mumbai Offshore and south of highly prospective Kachchh Basin. The Saurashtra Basin is surrounded by the sea in western side, whereas its eastern flanks are bordered with the commercially proven Cambay Basin. The petrographic information on the Khadsaliya lignites is provided by Thakur et al. (2010) from old mine section. In the present study, petrographical and palynofacies data from the Khadsaliya new mine section are combined with the organic geochemical studies for interpretation on palaeodepositional conditions of the lignite-bearing sequence, besides to evaluate the hydrocarbon source potential of the deposits.

2. Geological setting

The peninsula of Saurashtra forms a horst bounded between the structural trends of Delhi (NE–SW), Dharwar (NNW–SSE) and Narmada (ENE–WSW) (Fig. 1B). It forms a high level dissected lava plateau and flat top hills of sandstones in the north-east, a low level dissected plateau intervenes the high level plateau, and the flat-broad coastal erosion plains (Merh, 1995). In an aerial view, the Saurashtra peninsula forms a triangular shape, an outcome of various bounding faults. Its northern limit is marked by the E–W orienting Gulf of Kachchh Fault, the south-western coastline parallels a NW–SE fault which is an extension of the West Coast Fault System, whereas the southern coast runs parallel to the extension of the Narmada Geo-fracture. To the east, the peninsula is flanked by the N–S orienting Western Cambay Basin Bounding. Apart from the bounding faults, numerous fault systems and fractures have been identified within the Saurashtra horst.

The Saurashtra peninsula forms a rocky tableland fringed by coastal plains, a major portion of which is occupied by the Deccan lava flows. The central part is made up of an undulating plain broken by hills and considerably dissected by various rivers that flow out in all directions. The highlands provide a zigzag outline and a rugged topography, vaguely forming three almost parallel elevated areas striking ENE–WSW connected by a NNE–SSW ridge. The eastern fringe of Saurashtra is a low-lying ground marking the site of former sea connection between the Gulfs of Kachchh (Kutch) and Khambhat (Cambay). Today, it is a saline wasteland interspersed with marshes and lakes. To the north, the Saurashtra peninsula is flanked by the Gulf of Kachchh and to its west and south is the Arabian Sea (Fig. 1C).

Biswas and Deshpande (1983) consider the Saurashtra region as a horst surrounded by rift graben and demonstrate that central, southern

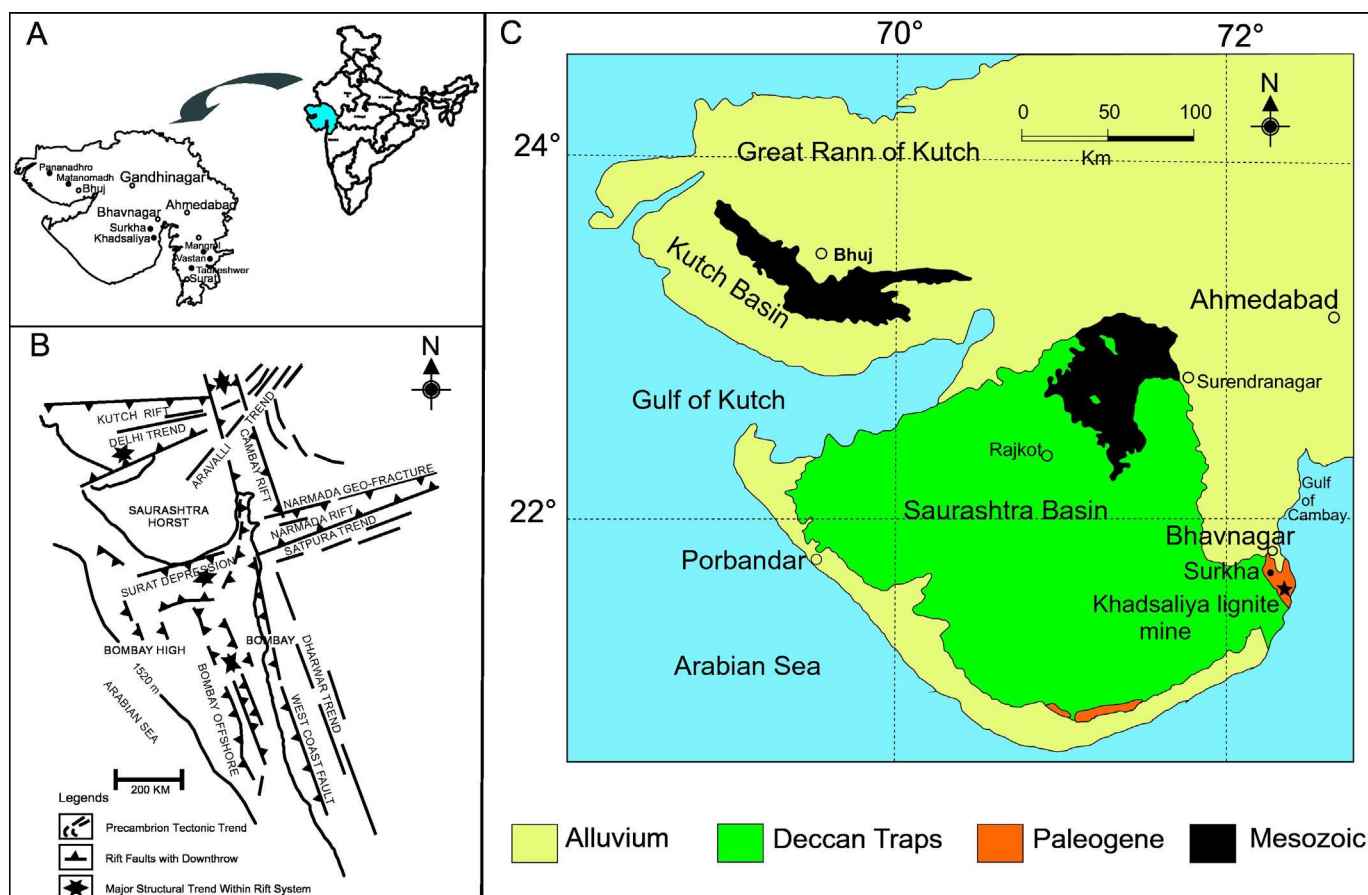


Fig. 1. (A) Location map of Khadsaliya lignite mine in Gujarat state of western India, (B) regional tectonic map of western India showing prominent rift basins and Precambrian orogenic trends (after Biswas and Deshpande, 1983), and (C) geological map of Saurashtra Basin (after Merh, 1995).

and northern Saurashtra exhibit distinct volcano-tectonic characteristics. The Saurashtra peninsula is about 65% covered by basaltic lava flows (Deccan Trap) overlying the Mesozoic sediments in north, and underlying the Palaeogene-Quaternary sediments at the coastal fringe (Fig. 1C). The Deccan Trap provides the basement for the deposition of Palaeogene sediments that are exposed at some places.

The geological succession of the lignite-bearing Saurashtra region is shown in Fig. 2. Lignite in the region occurs in Khadsaliya Clays Formation (Eocene) which is never exposed on the surface (Thakur et al., 2010). This green to greenish-grey clay formation, overlying the Supratrappean (Lower Eocene) and Deccan Traps (Cretaceous-Eocene), encompasses lignite deposits together with carbonaceous shale and shale. The basin extending in a length of about 12 km opens up towards north with a general slope towards sea. The lignite seams unconformably lie on the weathered trap on lithomargic clay. They become deeper towards east to north-east and diminish towards sea.

3. Sample collection and methodology

The Khadsaliya lignite mine (lat. 21° 34' 091" N & long. 72° 14' 289" E) is located at about 30 km south-east to the city of Bhavnagar, Gujarat. The representative lignite samples (15) were collected vertically (from bottom to top) in ascending order from three seams– Bottom seam (approx. 1.5 m thick), Middle seam (approx. 2.0 m), and Top seam (approx. 3.0 m thick; Fig. 3), and were subjected to petrography, geochemistry and Rock-Eval pyrolysis studies. A total of 46 samples from

the lignite-bearing sequence were also utilized for the palynofacies analysis.

3.1. Petrography

Preparation of samples, maceral analysis and reflectance measurements were carried out following the ISO 7404-2 (2009), ISO 7404-3 (2009), ISO 7404-5 (2009) norms, and the ICCP nomenclature. The Leica DM4500P microscope was used for maceral analysis and reflectance measurements. The random reflectance was measured on huminite (ulminite) particles with the help of PMT III and MSP 200 softwares. The quantitative estimation of macerals was made on automatic point counter using the Petroglite 2.35 software. The maceral composition was analysed simultaneously in reflected white and blue lights by using the Single-Scan method (X-axis: 0.6 mm; Y-axis: 0.7 mm). The maceral descriptions and terminologies as provided by the International Committee for Coal and Organic Petrology for huminite (Sýkorová et al., 2005), for liptinite (Pickel et al., 2017; Taylor et al., 1998) and for inertinite (ICCP, 2001) were followed. Leica application suite (LAS) was used for the photomicrography.

3.2. Palynofacies

The lignite and associated shale/clay samples were treated with hydrochloric (HCl) and hydrofluoric (HF) acids to dissolve carbonate and silica contents, respectively. The slides for microscopic observation were prepared by the procedure suggested by Batten (1996a) and

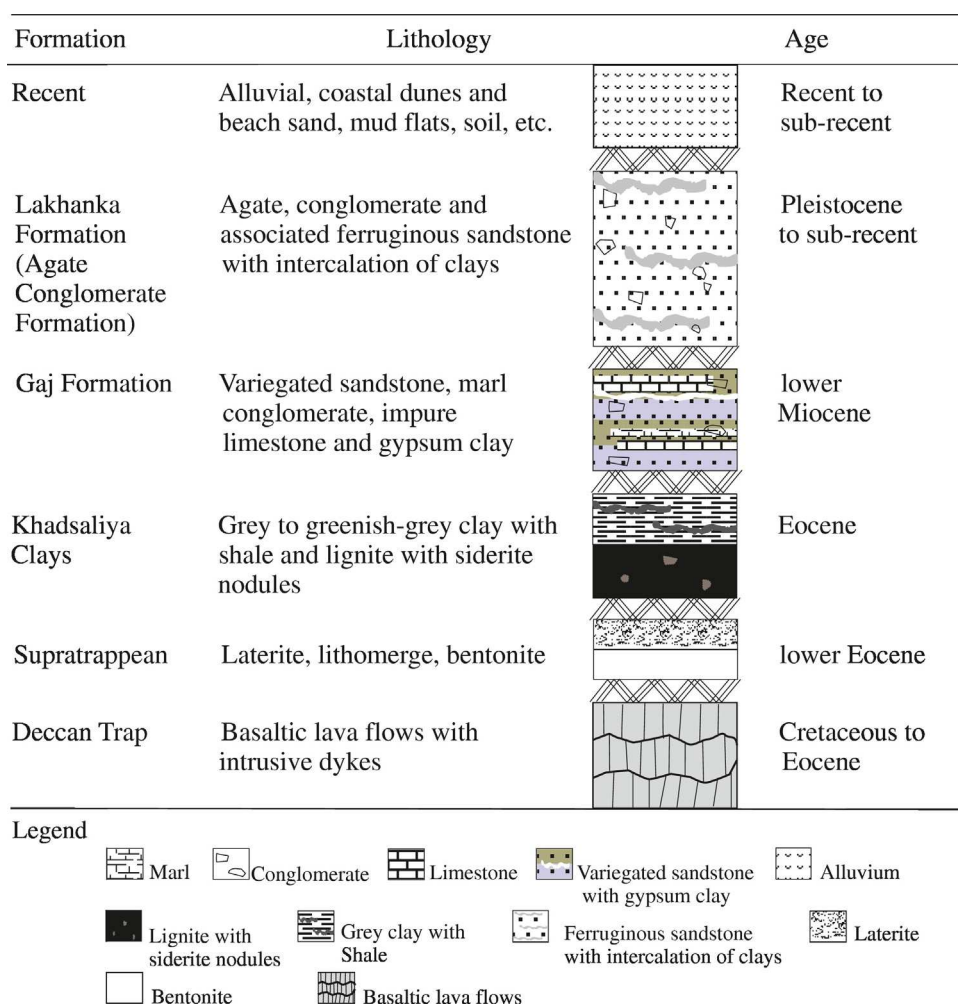


Fig. 2. Generalized lithostratigraphic succession in the study area (modified after Thakur et al., 2010).

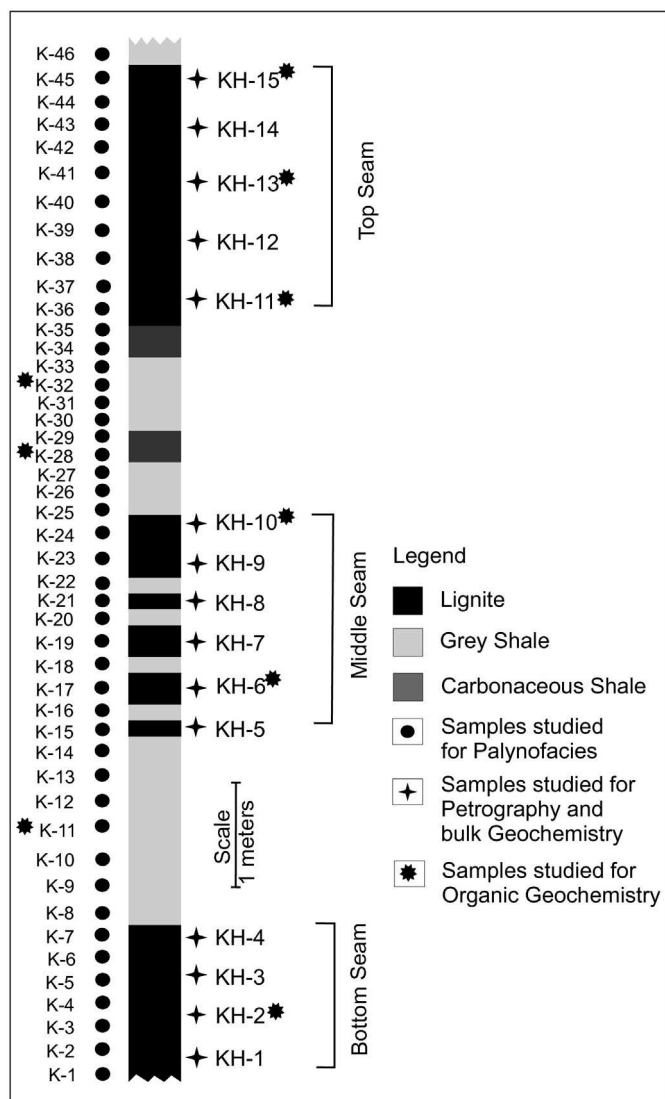


Fig. 3. Lignite seam section in the Khadsaliya mine along with the distribution of studied samples.

Batten and Stead (2005). The observation was made under transmitted white and blue lights, and a minimum of 300 counts were taken for the quantitative estimation of particulate organic matter as suggested in Mendonça Filho et al. (2010, 2011). The absolute and relative proportions, state of preservation, and size of organic matter were taken into consideration for palynofacies analyses. The particulates of organic matter were counted in three main groups – phytoclasts, palynomorphs, and amorphous organic matter (Mendonça Filho et al., 2002, 2011; Tyson, 1995).

3.3. Biomarker analysis (GC–MS)

The extraction of lignite and shale was performed starting with the powdering of the samples into very fine powder using a brass mortar. The soluble organic matter was extracted with dichloromethane:methanol (9:1) mixture from oven-dried powdered samples by ultrasonication for 30 min. Subsequently, asphaltenes were removed by precipitation using excess of *n*-hexane (40 ml). The fractionation was accomplished by passing the extract through a chromatographic column, containing activated silica gel, using *n*-hexane (for saturates) and dichloromethane:hexane in the ratio 1:4 (for aromatics). Here in the study, only the analysis of

saturated fractions has been performed. The analysis was carried out using an Agilent 7890A Gas Chromatograph (GC) interfaced to Agilent 5975C Mass Spectrometer (MS). The GC was fitted with a HP-5MS fused silica capillary column (30 m × 0.25 mm i.d., 0.25 μm film thickness), and helium (He) was used as the carrier gas at a flow rate of 1 ml/min. During each analysis, the GC oven temperature was held at an initial 40 °C for 5 min, and then ramped to 310 °C at 4 °C/min, which was held for a final 5.5 min. Full scan (*m/z* 50–550) 70 eV mass spectra were acquired with a source temperature of 300 °C. Data processing is done using Chemstation software. Peak assignments were based on GC retention time and mass spectral data including comparison to MS library and published mass spectra.

3.4. Rock-Eval pyrolysis

Rock-Eval pyrolysis was conducted using a “Turbo” Rock-Eval-6 pyrolyser manufactured by Vinci Technologies®. The pyrolysis method consists of a programmed temperature heating (in a pyrolysis oven) in an inert atmosphere. The Rock-Eval instrument was first developed by Institut Français du Pétrole (IFP) in 1977 to perform anhydrous, open system pyrolysis (Espitalié et al., 1977). However, the procedure of the analysis is elaborated by Lafargue et al. (1998). The samples were first pyrolysed under an inert N₂ atmosphere and the residual carbon was subsequently burnt in an oxidation oven. The amount of hydrocarbons released during the pyrolysis was detected with a flame ionisation detector, while online infrared detectors measure continuously the released CO and CO₂. The samples were first pyrolysed from 100 °C to 650 °C at a rate of 25 °C/min. The oxidation phase starts with an isothermal stage at 400 °C, followed by an increase to 850 °C at a rate of 25 °C/min to burn out all the residual carbon.

3.5. Proximate analysis

The proximate analysis involves the determination of moisture, ash, volatile matter and fixed carbon contents in weight percentage. The analyses were performed by taking 70 mesh size lignite powders of representative samples, and using micro-balance, oven (for moisture content) and muffle furnace (for ash and volatile matter yields) as per the specifications of Bureau of Indian Standard (BIS, 2003). Fixed carbon content in the lignite samples were calculated by subtracting the sum of ash yield, volatile matter yield and moisture content from 100. The Leco AC 350 GCV Analyser was used to determine the calorific value. Bulk quantities of the lignite samples weighing 100 g were individually crushed to finer sizes in 3–4 stages, and reduced to –212 μm (BSS mesh No. 72, Bureau of Indian Standards IS: 1350; BIS, 2003). ASTM D 2015 (1996) standard was used for the determination of gross calorific values of the samples.

3.6. Ultimate analysis

The ultimate analysis involves the determination of elemental carbon, hydrogen, nitrogen, oxygen as well as sulphur in weight percent. The analysis of lignite samples was performed on Elementar Vario EL III-CHNS Analyser using standard procedure (ASTM Standards: D3177-89, D3178-89, D3179, 1993a, 1993b, 1993c). For this purpose, samples were prepared by the manual crushing in laboratory. The procedure given by Bureau of Indian Standards IS:1350 was followed (BIS, 2003). The sample (approx. 10 mg) was put in tin foil, and kept in CHNS analyser for each set of element to be calculated. The percentage of oxygen was calculated by subtracting the sum of percentage of carbon, hydrogen, nitrogen, ash, and sulphur from 100.

4. Results

4.1. Petrographic characteristics

The studied lignites of Khadsaliya new mine are compact, amorphous textured and dark brown in colour. Table 1 provides the frequency distribution of various macerals and associated mineral matters estimated in the lignites. The representative photomicrographs of various macerals are shown in Fig. 4.

4.1.1. Huminite group

The lignite is mainly composed of huminite group of macerals (av. 60 vol.%). Huminite consists predominantly of telohuminite (structured: ulminite + textinite, av. 33%) and detrohuminite (detritus: attrinite + densinite, av. 23%). The telohuminites are chiefly represented by ulminite maceral (av. 30%), while the detrohuminites are constituted mainly by densinite maceral (av. 15%). A low content of gelohuminite (the gelified huminite) is also recorded, which is represented by the corpohuminite maceral (av. 4%). Overall, the frequency of huminite group is almost similar throughout the seam sections with slightly increasing tendency in the Middle seam section. Certain fractions of the huminite group fluoresce (with weak intensity in dark reddish-brown or brown colour) either due to relicts of cellulose and/or by resinous impregnations. In the Top seam, the proportion of fluorescing or perhydrous huminite is higher (av. 24%) than its concentration in the Middle (av. 22%) and Bottom (av. 15%) seams.

4.1.2. Liptinite group

The liptinites are represented by sporinite, cutinite, resinite, suberinite, fluorinite, and liptodetrinite. These macerals appear relatively darker in colour than huminite, to black in normal incident light and fluoresce (under blue light excitation) in different colours (yellow to yellowish-brown) and intensities. The liptinite content in the studied lignites varies between 9 and 24 vol.% with higher concentration in the Top seam compared to the Bottom and the Middle seams. Liptinites are constituted chiefly by the liptodetrinite (av. 5%) and resinite (av. 4%) macerals, followed by the sporinite, cutinite and suberinite, respectively. Bituminite is also recorded along with the sporadic fluorinite (associated with cutinite). The bituminite is mostly accounted for by the perhydrous huminite.

4.1.3. Inertinite group

The group is mainly represented by funginite, semifusinite, and inertodetrinite along with sporadic occurrence of micrinite. Most common maceral funginite (fungal sclerotia) occurs as oval and elliptical bodies. Single- to multi-celled fungal spores (teleutospores) are common. Greyish-white semifusinite, characterized by well-preserved cell structure, is also common. Inertodetrinite occurs as fragmentary pieces of semifusinite/fusinite and funginite. The group maceral has low concentration (av. 9 vol.%) and has no definite trend in distribution.

4.1.4. Mineral matter

It shows moderately high concentration (av. 14 vol.%) constituted dominantly of clastic (clay and quartz) and sulphide (pyrite) minerals along with the sporadic occurrences of carbonates (calcite, siderite). The clastic minerals, occurring as granules, lumps and bands, are intimately associated with almost all the macerals. Pyrite (range: 1–8%, av. 5 vol.%) occurs in various forms, whereas massive (Fig. 4j), framboidal (Fig. 4k–l), and disseminated forms are most common.

4.1.5. Rank of lignites

Rank of the lignites has been determined by random reflectance (R_r) measurements on huminite (ulminite) particles. The calculated mean values range from 0.30 to 0.38% (av. 0.34%, Table 1) for the seams. The values classify these lignites as 'brown coal' (German Standard) or 'lignite' (Stach et al., 1982) or as 'low rank B (lignite B)' (as per ISO-

11760, 2005), and fall in the early diagenetic zone of methane generation (Taylor et al., 1998). The reflectance results show slightly increasing trend with depth of the seam.

The overall tendency in maceral composition of the lignites from Khadsaliya new mine is similar as in the previous study of lignites from the old mine section (Thakur et al., 2010). However, the rank of the lignites of new mine section is found to be relatively higher than the old mine section.

4.2. Palynofacies characteristics

Combaz (1964) introduced the term 'palynofacies' for the total assemblage of microscopic organic constituents present in a sediment/rock, and that withstand the acid treatments of normal palynological preparation procedures. The modern palynofacies concept was introduced by Tyson (1995). The particulate organic matter recovered from the studied Khadsaliya samples are illustrated in Fig. 5. The palynofacies analysis reveals that the samples (lignite and shale) have yielded all the three groups of particulate organic matter—phytoclasts, palynomorphs and amorphous organic matter (Table 2).

4.2.1. Phytoclasts

In the studied samples, phytoclasts (tissues derived component) are the predominant organic matter; constituting an average of 69%. The non-opaque phytoclasts (av. 38%) show dominance over the opaque (av. 31%). Among the non-opaque phytoclasts, cuticles are in abundance (av. 20%), while the biostructured (av. 9%) and non-biostructured (av. 8%) organic matters are in lesser proportions. The biostructured phytoclast and cuticles presence are suggestive of proximity to the source area (Tyson, 1995). The equant, lath-shaped and corroded types of opaque phytoclasts are more common; indicating an aerial oxidation during the deposition.

4.2.2. Amorphous organic matter

AOM is the subdominant group (av. 26%) in the samples. The AOM consists of all particulate organic components that lack a distinct and recognizable outline, and which does not infer its biological affinity. These components include phytoplankton-derived AOM, bacterially-derived AOM, higher plant resins, and amorphous products of the diagenesis of macrophyte tissues (Mendonça Filho et al., 2011; Tyson, 1995). In the studied samples, this group is mainly represented by the amorphous products, and the AOM subgroups (av. 25%), while the resin subgroup (av. >1%) occurs only as an accessory component.

4.2.3. Palynomorphs

The group is the least abundant (range: nil–8%) of the three main organic matter (kerogen) groups in the samples. Palynomorphs are represented by the terrestrial palynomorphs (spores and pollen grains - collectively known as sporomorphs), marine phytoplankton (dinoflagellate cysts), and zooplankton (inner linings of microforaminifera). In the studied samples, palynomorphs include both the continental (terrestrial and aquatic, av. 4%) as well as the marine (av. 0.4%) components. The palynomorphs of the families Annonaceae, Arecaceae, Meliaceae, Matoniaceae, Bombacaceae have been documented. Nevertheless, identification of the palynomorphs genera is beyond the scope of this study.

Based on the estimation and distribution of particulate organic matters, two palynofacies are recognized in the lignite-bearing Khadsaliya sequence (Fig. 6):

The palynofacies-I is typified by the clear dominance of phytoclasts (av. 74%), while the AOM (av. 21%) and palynomorphs (av. ~5%) are represented in fewer proportions. Such composition is encountered in the sample nos. K-1–7, 10, 11, 13, 17–21, 23, 26–30, 32–37, 43–45. The non-opaque phytoclasts (av. 37%) are represented mainly by the cuticles (21%) with very high degree of preservation, besides the lath-shaped woody material, structureless membranes, and along with fungal filaments. The corroded and equant opaques are common. The AOM

Table 1

Maceral contents (vol.%), mineral matter content (vol.%), ulminite reflectance (Rr%) and petrographic indices (GI, TPI, GWI, VI) of the studied Khadsaliya lignites

Sample no.	Bottom seam					Middle seam							Top seam					Mine average	
	KH-1	KH-2	KH-3	KH-4	Average	KH-5	KH-6	KH-7	KH-8	KH-9	KH-10	Average	KH-11	KH-12	KH-13	KH-14	KH-15	Average	
Macerals																			
Huminite(H)	57	63	53	56	57	64	60	67	63	57	67	63	59	61	51	54	67	59	60
Telohuminite	35	35	26	26	31	33	36	41	44	29	47	39	23	33	27	23	35	28	33
Textinite	1	1	0	1		8	1	2	4	6	6		3	1	1	1	0		
Ulminite	33	34	26	25		25	34	39	41	23	42		20	32	26	22	34		
Detrohuminite	19	24	25	27	24	27	15	21	13	20	15	19	33	26	23	27	26	27	23
Attrinite	6	7	11	9		9	7	6	6	12	5		10	5	7	7	7		
Densinite	13	17	15	18		18	8	15	8	8	9		23	21	15	20	19		
Gelohuminite	4	3	2	3	3	4	10	5	6	9	5	6	3	2	2	4	6	4	4
Corpohuminite	4	3	2	3		4	10	5	6	9	5		3	2	2	4	6		
Gelinite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Liptinite (L)	21	13	21	15	17	16	16	9	15	19	14	15	17	19	14	17	24	18	17
Sporinite	3	0	2	2		1	2	1	1	2	1		1	0	2	1	2		
Cutinite	1	1	3	3		4	4	3	2	3	2		2	4	2	2	3		
Suberinite	0	1	1	0		0	0	0	1	0	0		1	2	2	2	1		
Resinite	4	3	4	2		3	4	1	5	6	6		5	4	1	4	6		
Alginite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Bituminite	0	1	0	0		2	2	1	1	1	1		0	2	1	5	4		
Fluorinite	1	0	1	1		1	1	0	2	1	1		1	1	1	0	2		
Exsudatinitite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Liptodetrinite	11	7	10	8		5	3	3	2	5	3		7	5	4	3	7		
Inertinite (I)	5	6	13	7	8	12	9	11	9	11	10	10	14	15	7	8	6	10	9
Semifusinite	0	0	1	0		1	0	1	0	0	1		1	1	1	0	1		
Fusinite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Funginite	2	3	9	5		9	7	9	5	8	7		12	11	2	6	3		
Secretinite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Macrinite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Micrinite	0	0	0	0		0	0	0	0	0	0		0	0	0	0	0		
Inertodetrinite	2	3	4	2		2	2	1	4	4	2		2	3	4	2	2		
Mineral matter (Mm)	18	18	13	22	18	8	15	13	14	13	9	12	10	6	28	21	3	14	14
Others	14	11	10	16		4	9	6	5	9	2		9	2	21	17	2		
Pyrite	4	7	3	6		4	6	7	8	4	7		1	4	7	4	1		
Fluorescing H	15	15	17	14		17	10	16	29	33	25		19	25	21	26	27		
Non-fluorescing (H)	42	49	35	42		47	50	51	33	24	42		40	36	30	28	39		
Total Fluorescing (H + L)	35	28	38	29		33	26	25	44	52	39		36	44	35	43	52		
Non-fluorescing (H + I + Mm)	65	72	62	71		67	74	75	56	48	61		64	56	65	57	48		
H (mmf %)	69	77	61	72		69	71	77	73	66	73		66	64	71	69	69		
L (mmf %)	25	16	24	19		17	19	10	17	21	16		19	20	19	21	25		
I (mmf %)	6	7	15	9		13	10	12	10	13	11		16	16	10	10	6		
Rr mean %	0.34	0.36	0.36	0.38	0.36	0.33	0.32	0.3	0.31	0.31	0.34	0.32	0.34	0.34	0.33	0.36	0.35	0.34	0.33
GI	4.07	3.81	1.73	2.72	3.08	1.63	3.09	3.06	2.98	1.36	2.63	2.46	1.74	2.66	2.74	2.83	4.43	2.88	2.77
TPI	1.79	1.43	0.96	0.98	1.29	1.28	2.66	2.07	2.98	1.56	3.18	2.29	0.75	1.22	1.06	0.92	1.46	1.08	1.62
GWI	0.72	0.78	0.76	0.94	0.80	0.80	0.76	0.75	0.54	0.82	0.55	0.77	1.37	0.95	0.99	1.24	0.82	1.07	0.85
VI	1.04	1.06	0.73	0.68	0.88	0.91	1.45	1.45	2.15	0.99	2.33	1.55	0.66	0.98	0.82	0.70	0.98	0.83	1.13

GI (Gelification Index) = Ulminite + Densinite + Corpohuminite + Gelinite / Textinite + Attrinite + Inertinite (Kalaitzidis et al., 2000).

TPI (Tissue Preservation Index) = Textinite + Ulminite + Corpohuminite + Fusinite / Attrinite + Densinite + Gelinite + Inertodetrinite (Kalaitzidis et al., 2000).

GWI (Ground Water Index) = Densinite + Corpohuminite + Gelinite + (Ash / 2) / Textinite + Ulminite + Attrinite (Stock et al., 2016; Kalaitzidis et al., 2000).

VI (Vegetation Index) = Textinite + Ulminite + Suberinite + Resinite + Fusinite + Semifusinite / Attrinite + Densinite + Sporinite + Cutinite + Alginite + Bituminite + Liptodetrinite + Inertodetrinite (Kalaitzidis et al., 2000).

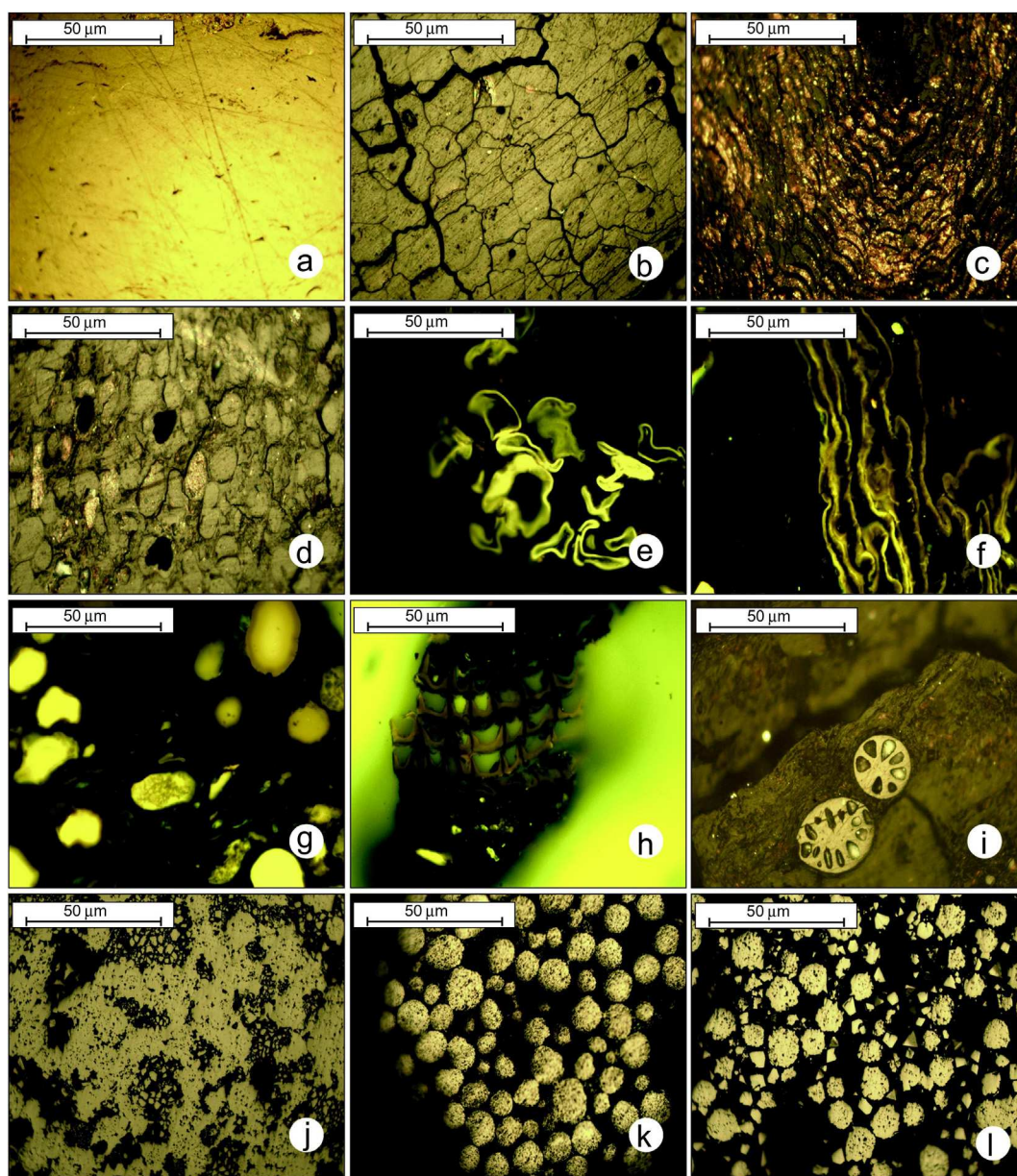


Fig. 4. Representative photomicrographs of macerals and associated mineral matter of the Khadsaliya lignite: a) ulminite, b–c) textinite, d) corpohuminite, e) sporinite (cluster of spores), f) cutinite, g) resinite, h) suberinite, i) funginite, j) massive pyrite, k–l) framboidal pyrite associated with huminite. Photomicrographs taken under incident white light (a–d and i–l) and blue light excitation (e–h).

constituting degraded phytoclasts is indicative of the terrestrial origin of these organic matters. Palynomorphs are mainly composed of the terrestrial palynomorphs (av. 4%), however marine palynomorphs (foraminifer linings and dinoflagellate cysts, av. < 1%) have also been observed.

The palynofacies-II is also characterized by the dominance of phytoclasts (av. 55%), but along with a high amount of the AOM (av. 41%). This type of association is observed in the sample nos. K-8, 9, 12, 14–16, 22, 24, 25, 31, 38–42, and 46. The non-opaque phytoclasts are abundant (av. 42%), and mainly represented by the cuticles (av. 18%) and non-biostructured (av. 12%) organic matters, followed by the biostructured ones (av. 11%). The fungal remains (1%) has also been observed. The granular AOM and fragments of the woody tissues sometimes contained with framboidal pyrite. The terrestrial palynomorphs are relatively higher (av. 4%) in this palynofacies, while the marine palynomorphs are almost absent.

4.3. Organic geochemical characteristics

4.3.1. Biomarker composition

Investigation on the macromolecular composition has been performed on nine samples (six lignite and three shale). The representative TIC (total ion chromatogram) of the saturated fraction is shown in the Fig. 7. The major terpenoids identified in the Khadsaliya samples are given in the Table 3. Various biomarker parameters have also been calculated, and are presented in Table 4.

4.3.1.1. *n*-alkanes and isoprenoids. The selected mass chromatogram (m/z 57) represents the *n*-alkanes and isoprenoids. The hydrocarbon fractions are all dominated by a homologous series of C_{16} to C_{35} *n*-alkanes (Fig. 8). Generally, bimodal *n*-alkane distribution is evident with the dominance of short chain (n - C_{18} , n - C_{20}) and long chain (n - C_{27} , n - C_{29})

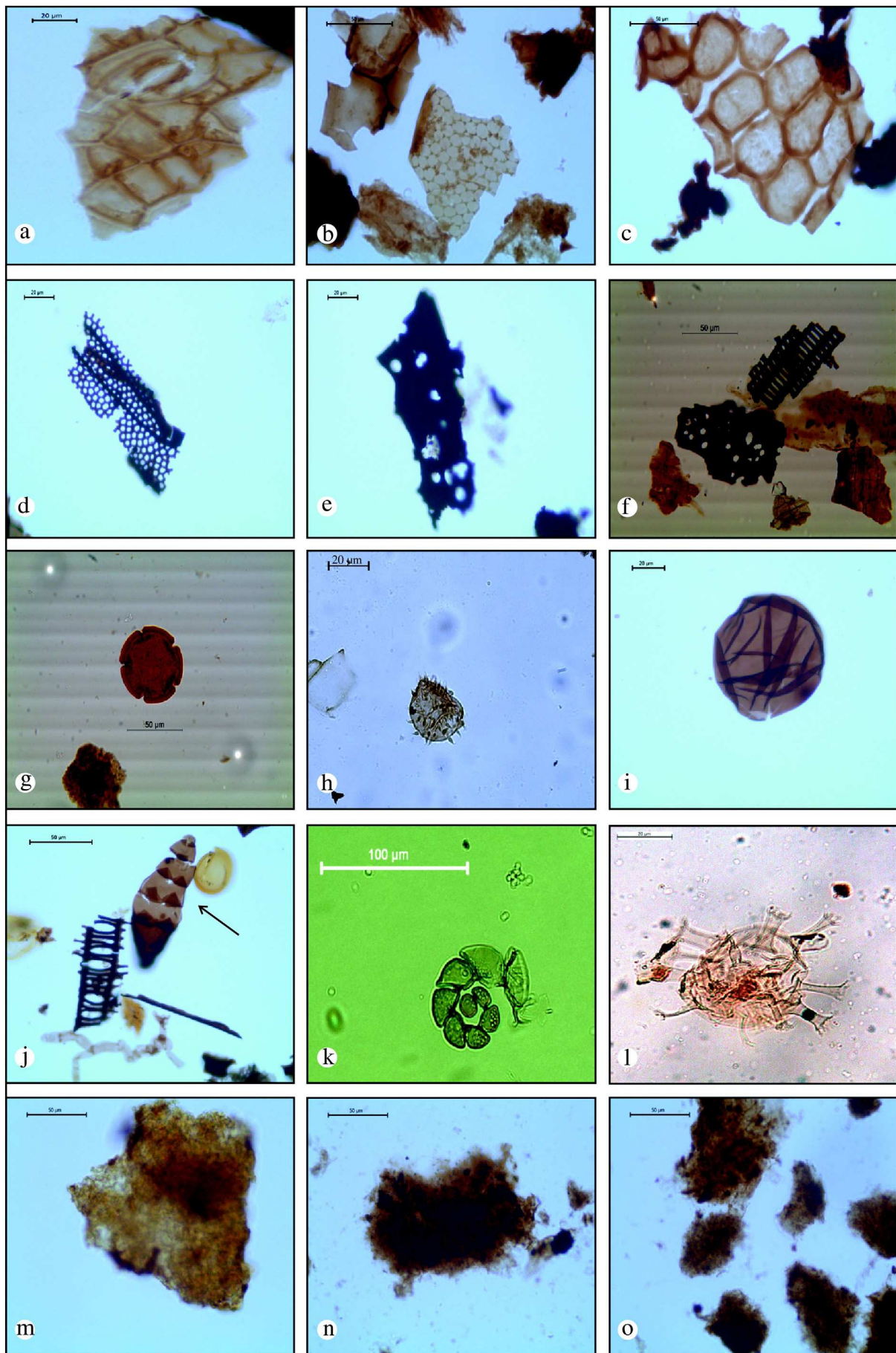


Table 2
Results of palynofacies analysis of the studied Khadsaliya samples.

Sample no.	Phytolasts					Total	AOM		Total	Palynomorphs		Total	Palynofacies type
	Opaque	Non-opaque					AOM	Resin		Terrestrial	Marine		
		Cuticle (%)	Biostructure (%)	Non-biostr. (%)	Fungal (%)								
K-1	72.0	5.0	0.0	9.0	0.0	86.0	9.0	0.0	9.0	3.0	2.0	5.0	I
K-2	74.0	4.0	0.0	8.0	0.2	86.2	9.0	2.0	11.0	1.8	1.0	2.8	I
K-3	75.9	4.5	0.0	5.0	0.4	85.8	8.7	0.6	9.3	3.2	1.7	4.9	I
K-4	73.8	5.6	0.0	6.8	0.0	86.2	9.2	1.2	10.4	2.4	1.0	3.4	I
K-5	66.2	4.7	0.0	5.2	0.0	76.1	18.0	2.2	20.2	2.2	1.5	3.7	I
K-6	64.2	5.4	0.8	5.2	0.0	75.6	18.2	0.0	18.2	4.2	2.0	6.2	I
K-7	51.2	14.6	0.0	8.8	2.1	76.7	16.1	2.2	18.3	3.5	1.5	5.0	I
K-8	39.1	19.0	0.0	7.0	0.0	65.1	29.0	0.0	29.0	5.9	0.0	5.9	II
K-9	15.2	18.7	10.0	16.5	1.2	61.6	35.4	0.0	35.4	3.1	0.0	3.1	II
K-10	23.5	37.2	11.0	5.6	1.0	78.3	18.4	0.0	18.4	3.4	0.0	3.4	I
K-11	22.6	37.5	9.9	8.1	0.0	78.1	15.6	2.3	17.9	4.0	0.0	4.0	I
K-12	10.2	16.4	10.3	18.2	0.5	55.6	40.0	2.0	42.0	2.3	0.0	2.3	II
K-13	14.3	20.8	22.9	6.7	1.2	65.9	25.2	2.6	27.8	6.3	0.0	6.3	I
K-14	12.6	8.1	16.6	17.4	1.0	55.7	36.0	2.0	38.0	6.3	0.0	6.3	II
K-15	10.2	10.0	23.5	11.3	1.0	56.0	37.0	3.8	40.8	3.2	0.0	3.2	II
K-16	10.1	10.5	24.6	8.9	1.5	55.6	34.2	1.9	36.1	8.3	0.0	8.3	II
K-17	18.9	22.8	18.7	3.0	1.0	64.4	30.0	2.9	32.9	2.7	0.0	2.7	I
K-18	32.5	36.5	6.1	7.8	2.1	85.0	10.0	1.7	11.7	3.4	0.0	3.4	I
K-19	22.3	18.9	19.4	6.7	1.2	68.5	26.2	2.0	28.2	3.4	0.0	3.4	I
K-20	22.0	17.4	20.4	7.2	1.0	68.0	24.0	2.5	26.5	5.5	0.0	5.5	I
K-21	19.8	26.5	19.5	5.8	0.5	72.1	23.1	0.0	23.1	4.8	0.0	4.8	I
K-22	5.2	18.6	2.8	16.8	0.0	43.4	51.1	2.6	53.7	2.9	0.0	2.9	II
K-23	35.8	22.6	7.1	7.1	1.2	73.8	22.8	0.0	22.8	3.4	0.0	3.4	I
K-24	14.3	10.8	7.4	16.8	1.0	50.3	45.2	2.0	47.2	2.5	0.0	2.5	II
K-25	12.6	15.6	10.0	15.2	2.1	55.5	37.0	2.0	39.0	5.5	0.0	5.5	II
K-26	25.3	29.6	17.9	8.9	0.0	81.7	13.9	1.0	14.9	3.4	0.0	3.4	I
K-27	21.0	22.7	22.2	7.4	1.2	74.5	21.1	1.0	22.1	3.4	0.0	3.4	I
K-28	7.8	33.5	30.9	10.5	0.0	82.7	13.0	1.0	14.0	3.3	0.0	3.3	I
K-29	10.5	39.4	10.0	5.8	1.0	66.7	29.9	0.0	29.9	3.4	0.0	3.4	I
K-30	22.9	37.9	6.8	8.5	0.5	76.6	18.0	1.4	19.4	4.0	0.0	4.0	I
K-31	14.2	28.6	3.6	5.3	1.0	52.7	40.1	2.7	42.8	4.5	0.0	4.5	II
K-32	18.5	27.4	11.5	7.4	2.0	66.8	27.5	1.0	28.5	4.7	0.0	4.7	I
K-33	21.6	17.6	17.3	6.8	0.0	63.3	30.0	1.2	31.2	5.5	0.0	5.5	I
K-34	39.5	17.4	0.0	8.0	1.2	66.1	28.0	2.0	30.0	3.9	0.0	3.9	I
K-35	42.9	18.6	0.0	4.9	1.0	67.4	26.7	1.0	27.7	3.8	1.1	4.9	I
K-36	55.1	15.8	0.0	2.3	2.0	75.2	21.0	1.0	22.0	2.3	0.5	2.8	I
K-37	36.3	20.0	23.0	2.9	0.0	82.2	12.0	2.1	14.1	2.7	1.0	3.7	I
K-38	25.8	27.0	11.0	7.1	1.2	72.1	17.0	1.0	18.0	8.1	1.8	9.9	II
K-39	32.6	26.5	0.0	8.1	0.0	67.2	25.1	3.6	28.7	4.1	0.0	4.1	II
K-40	30.2	30.6	0.0	8.2	1.0	70.0	24.5	1.0	25.5	4.5	0.0	4.5	II
K-41	32.5	25.3	0.0	6.2	0.0	64.0	28.0	3.2	31.2	3.8	1.0	4.8	II
K-42	32.9	25.3	2.8	7.8	1.2	70.0	23.0	2.3	25.3	4.7	0.0	4.7	II
K-43	43.6	20.1	3.4	11.5	2.0	80.6	15.0	1.1	16.1	3.0	0.2	3.2	I
K-44	37.8	23.3	5.6	8.5	0.0	75.2	20.0	1.0	21.0	3.3	0.5	3.8	I
K-45	32.5	24.9	0.0	5.7	1.0	64.1	28.7	1.0	29.7	6.0	0.2	6.2	I
K-46	23.0	6.4	0.0	10.0	0.0	39.4	56.0	0.0	56.0	3.7	0.9	4.6	II
Total average	31.0	20.2	8.8	8.4	0.8	69.2	24.9	1.5	26.4	4.0	0.4	4.4	
Av. palynofacies-I	37.3	21.2	8.1	7.0	0.7	74.3	19.9	1.4	21.3	3.9	0.5	4.4	
Av. palynofacies-II	13.0	17.5	10.9	12.5	1.0	54.9	39.1	1.7	40.8	4.2	0.1	4.3	

n-alkanes. However, in sample K-28, short chain *n*-alkanes are relatively low in abundance. All the analysed shale samples showed the abundance of C₂₅ (medium chain) *n*-alkane. The acyclic C₁₉ and C₂₀ isoprenoid hydrocarbons, pristane (Pr) and phytane (Ph) are identified in the samples with a dominance of phytane in all the samples. The Pr/Ph ratios are varying from 0.13 to 2.49. The lignite samples showed the higher ratio than the shales. Other biomarker parameters calculated include CPI (carbon preference index; Peters et al., 2005), TAR (terrigenous/aquatic ratio; Bourbonniere and Meyers, 1996), P_{aq} (proxy aqueous; Ficken et al., 2000), and P_{wax} (proxy wax; Zheng et al., 2007). The CPI varies between 1.34 and 3.58, and the TAR varies from 1.68 to 23.83 for the samples. Although, no variation is seen in the CPI values of lignite and shale, the TAR values are low for lignite than the shale. The P_{aq} varies from 0.61 to 0.87, whereas P_{wax} is between 0.17 and 0.51.

4.3.1.2. Sesquiterpenoids. Sesquiterpenoids are found usually in coal and lignite extracts. These compounds are mostly derived from the essential oils, resins and ambers produced by the higher plants (Wang et al., 1990; Simoneit et al., 1986). In the studied samples, the sesquiterpenoids identified are longifolene-12, 4 α (H)-eudesmane, 4 β (H)-eudesmane, 4-Isopropyl-1, 6-dimethyl-1,2,3,4,4a,5,6,8a-octahydro naphthalene, and some unknown compounds. These compounds were also identified in the nearby Surkha lignite-bearing sequence of the basin (Paul et al., 2015). The main botanical sources of these natural products are Cupressaceae, Compositae (Gymnospermae), and Dipterocarpaceae (Angiospermae) families (Sukh Dev, 1989). However, diterpenoids are absent in these samples indicating the absence of gymnosperm source. Therefore, the presence of sesquiterpenoids in the samples may indicate the presence of Dipterocarpaceae in the source vegetation.

Fig. 5. Representative photomicrographs of palynofacies components: a–c) brown phytoclasts, d–f) opaque phytoclasts, g–h) palynomorphs (sporomorphs), i–j) fungal spores, k) foraminiferal linings, l) dinoflagellate cyst, m–o) amorphous organic matters.

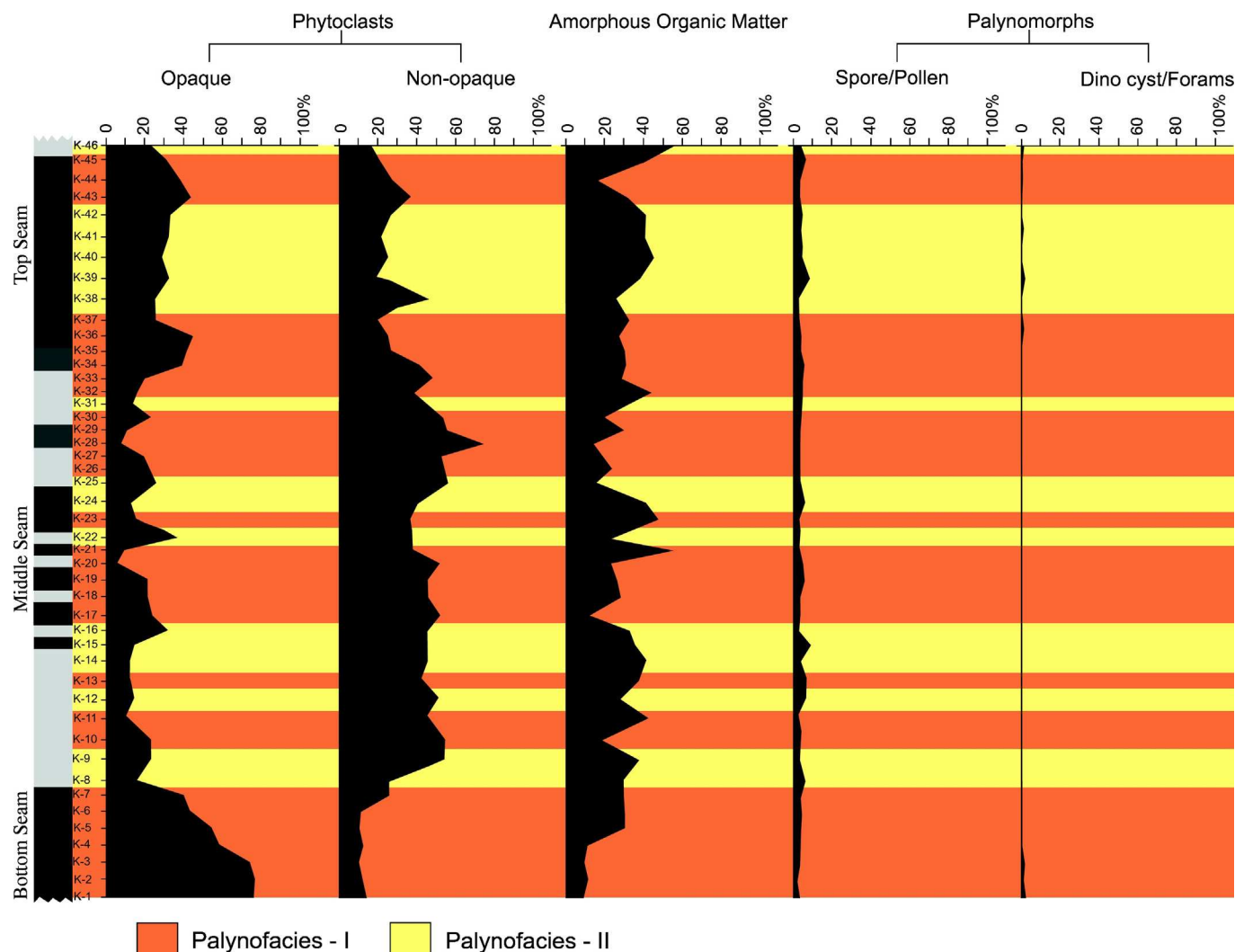


Fig. 6. Vertical distribution of palynofacies components and facies identified in the studied Khadsaliya succession.

4.3.1.3. Triterpenoids. The triterpenoid biomarkers were detected using the characteristic ion fragment m/z -191 (Fig. 9). Most of the compounds identified are pentacyclic triterpenes with substantial amounts of hopanes in all the analysed samples. Although the abundance of individual compounds varies between the samples, 17β (H)-22,29,30-trisnorhopane, 30-norneohop-13(18)-ene, 17β (H), 21β (H)-30-

norhopane, and 17β (H), 21β (H)-homohopane are generally dominant. An overall dominance of norhopane over hopanes is also seen. $\beta\beta$ -hopane is more abundant than its $\alpha\beta$ counterpart. The pentacyclic triterpenoids, other than hopanoids, identified are mostly unsaturated counterparts of oleananes. These compounds, olean-12-ene, olean-18-ene, and olean-2,13(18)-diene(?), are relatively low in abundance.

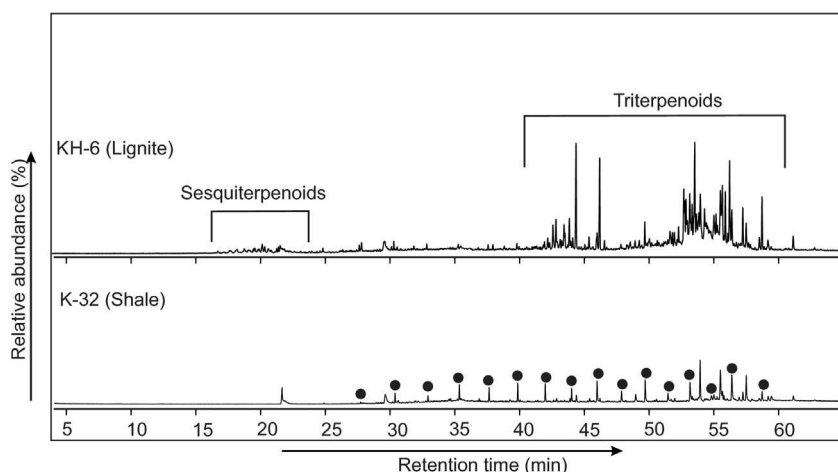


Fig. 7. Representative total ion chromatogram (TIC) of analysed lignite and shale samples from the Khadsaliya succession.

Table 3
Biomarker compounds identified in the Khadsaliya samples.

Peak no.	Compounds	Base peak	Molecular ion
Sesquiterpenoids			
1	Longifolene-12	94	204
2	4-Isopropyl-1,6-dimethyl-1,2,3,4,4a,5,6,8a-octahydro naphthalene	163	206
3	4β(H)-eudesmane	109	208
4	4α(H)-eudesmane	109	208
Triterpenoids			
1	De-A-fernene	231	328
2	De-A-urs-5(10)-ene	109	328
3	De-A-olean-18-ene	177	328
4	De-A-triterpenoid	313	328
5	De-A-Lupane	123	330
6	De-A-triterpenoid	95	330
7	17,21-secohopane (C ₂₅)	191	344
8	Unknown compound	191	398
9	17,21-secohopane (C ₂₆)	191	358
10	22,29,30-Trisnorhopane-13(18)-ene	191	368
11	Unknown compound	190	408
12	17α(H)-22,29,30-Trisnorhopane (Tm)	191	370
13	17β(H)-22,29,30-Trisnorhopane	149	370
14	Olean-2,13(18)-diene?	189	408
15	30-Norneohop-13(18)-ene	191	396
16	Neohop-13 (18)-ene	191	410
17	30-norhopane	191	398
18	Olean-12-ene	218	410
19	Olean-18-ene	204	410
20	Hop-17 (21)-ene	367	410
21	17β(H),21α(H)-30-Norhopane	177	398
22	αβ-hopane	191	412
23	Neohop-13(18)-ene isomer	191	410
24	17β(H),21α(H)-30-Norhopane	177	398
25	17α(H),21β(H)-Homohopane (22 S)	191	426
26	17α(H),21β(H)-Homohopane (22 R)	191	426
27	ββ-hopane	191	412
28	17β(H),21β(H)-Homohopane	205	426
29	17β(H),21β(H)-Bishomohopane	219	440

Tetracyclic 17,21-secohopanes (C₂₅ and C₂₆) are also identified in these samples. Other tetracyclic compounds identified are De-A-fernene, De-A-urs-5(10)-ene and De-A-olean-18-ene.

4.3.2. Rock-Eval pyrolysis and TOC content

The Rock-Eval pyrolysis provides important parameters related to hydrocarbon source potential of the organic-rich sediments. Results of the pyrolysis and TOC analysis of the studied samples are furnished in Table 5.

The free hydrocarbon (S₁) value of the samples ranges from 0.10 to 7.35 mg HC/g. The remaining hydrocarbon (S₂) generation potential of the lignites is found to be widely variable (4.23–261.25 mg HC/g). The S₂ value of shale samples varies between 0.59 and 1.38 mg HC/g,

whereas the S₂ value of carbonaceous shale (sample K-29) is 6.26 mg HC/g. The TOC content of lignites ranges from 16.72 to 54.78 wt.%, whereas the TOC content of shales varies between 0.72 and 0.95 wt.%. The TOC content of the carbonaceous shale is 17.55 wt.%.

The HI value of the studied samples varies between 23 and 477 mg HC/g TOC. Samples with lower HI values could be an indication of the mineral matter influence (Jasper et al., 2009; Littke et al., 1989; Horsfield et al., 1988). The higher HI values are well-corroborated with fair representations of liptinites and fluorescing huminite in the lignite samples (refer Tables 1 and 5). The OI values of the samples are in the range of 33 to 96 mg CO₂/g TOC, except the carbonaceous shale sample, which shows higher OI value (107 mg CO₂/g TOC). The lower OI values may be attributed to the presence of stable oxygen moieties, which are not cracked at the lower coal rank (Varma et al., 2015; Kotarba et al., 2002).

T_{max} (thermal maturity parameter) of the samples varies between 377 °C and 433 °C (av. 418 °C). This clearly suggests that the sequence has passed the early stage of diagenesis. The wide variation in T_{max} values within this about 20 m sequence could be due to maceral composition or influenced by the mineral matter (Jasper et al., 2009). Further, as suggested by Peters (1986), the significant amount of resin (resinite, refer Table 1) may affect the true T_{max} values. HI vs. OI (Fig. 10a), S₂ vs. TOC (Fig. 10b), and HI vs. T_{max} (Fig. 10c) plots collectively indicate that the studied sequence has dominance of a mix of kerogen type III and II. Production Index values (PI: mostly <0.1, the ratio of free hydrocarbon to total hydrocarbons) indicate that the samples are at an immature stage (Peters and Cassa, 1994), and correlate with their huminite reflectance values (0.30–0.38% R_r) which also indicate immature stage.

4.3.3. Proximate parameter

Table 6 summarizes the data obtained from proximate analysis of the studied lignite samples. The analysis reveals that the lignites are high in moisture contents, moderately high in ash and volatile matter yields. The moisture content varies between 11.89 and 24.97% (av. 18 wt.%), whereas the ash yield is ranging in the limit of 18.94 to 35.69% (av. 27 wt.%), with two higher values– 33.36 wt.% (sample KH-9) and 35.69 wt.% (sample KH-11). The volatile matter yield varies between 25.49 and 43.37 (av. 35 wt.%, daf: 56.68–77.25 wt.%), whereas fixed carbon content of the samples ranges from 12.01 to 29.97% (av. 18 wt.%, daf: 22.75–43.32 wt.%). The gross calorific values of the samples vary between 2897 and 5246 cal/g (av. value 3891 cal/g). The fuel ratio, calculated as the ratio between fixed carbon content and volatile matter yield, varies between 0.46 and 0.76.

The moisture content has shown significant negative correlation with the huminite reflectance in the studied lignites (Sia and Abdullah, 2012). Also, the TOC values show good negative correlation with mineral matter contents and ash yields. Fixed carbon content shows a fair positive correlation with the TOC, and ash and volatile matter yields have a negative correlation (Erik and Sancer, 2010). However, a positive correlation between ash yields and mineral matter contents has been observed.

4.3.4. Ultimate parameter

Results of the ultimate analysis of lignite samples are shown in Table 6. The carbon content ranges from 20.33 to 42.86% (av. 30.67 wt.%; daf: 66.62–73.39 wt.%), hydrogen from 4.13 to 5.37 (av. 4.61 wt.%; daf: 3.38–6.30 wt.%), nitrogen from 0.58 to 0.97% (av. 0.77 wt.%; daf: 1.34–2.63 wt.%), sulphur content from 0.76 to 2.02% (av. 1.42 wt.%; daf: 1.84–5.51 wt.%) and oxygen from 27.33 to 39.02% (av. 34.18 wt.%; daf: 16.44–24.50 wt.%). The results (high oxygen, low nitrogen, and relatively moderate sulphur contents) along with the huminite reflectance data classify these lignites under lignite B stage/rank. The carbon content increases with increasing hydrogen content, whereas the oxygen content decreases. The H/C and O/C atomic ratios for the studied samples vary between 0.57 and 1.08, and between 0.17 and 0.28, respectively.

Table 4
Parameters calculated from the distributions of n-alkanes and isoprenoids.

Sample no.	Pr/Ph	CPI	TAR	P _{aq}	P _{wax}	Pr/n-C17	Ph/n-C18
KH-2	0.82	1.34	1.89	0.71	0.33	0.55	0.36
KH-6	2.49	3.58	5.93	0.82	0.26	1.52	0.45
KH-10	0.75	2.94	6.24	0.73	0.36	1.35	0.62
KH-11	0.76	2.04	15.83	0.87	0.17	0.96	0.62
KH-13	0.66	1.63	1.68	0.64	0.44	0.58	0.45
KH-15	0.75	1.51	8.38	0.83	0.19	1.18	0.52
K-11	0.37	2.25	10.50	0.76	0.29	0.62	0.34
K-28	0.13	2.87	23.83	0.74	0.34	0.34	0.34
K-32	0.28	1.74	7.70	0.61	0.51	0.43	0.31

Pr: pristane, Ph: phytane, CPI: carbon preference index, TAR: terrigenous/aquatic ratio, P_{aq}: proxy aqueous, P_{wax}: proxy wax.

CPI = $2(C_{23} + C_{25} + C_{27} + C_{29}) / [C_{22} + 2(C_{24} + C_{26} + C_{28}) + C_{30}]$; Peters et al. (2005).

TAR = $(C_{27} + C_{29} + C_{31}) / (C_{15} + C_{17} + C_{19})$; Bourbonniere and Meyers (1996).

P_{aq} = $(C_{27} + C_{29} + C_{31}) / (C_{23} + C_{25} + C_{27} + C_{29} + C_{31})$; Ficken et al. (2000).

P_{wax} = $(C_{23} + C_{25}) / (C_{23} + C_{25} + C_{29} + C_{31})$; Zheng et al. (2007).

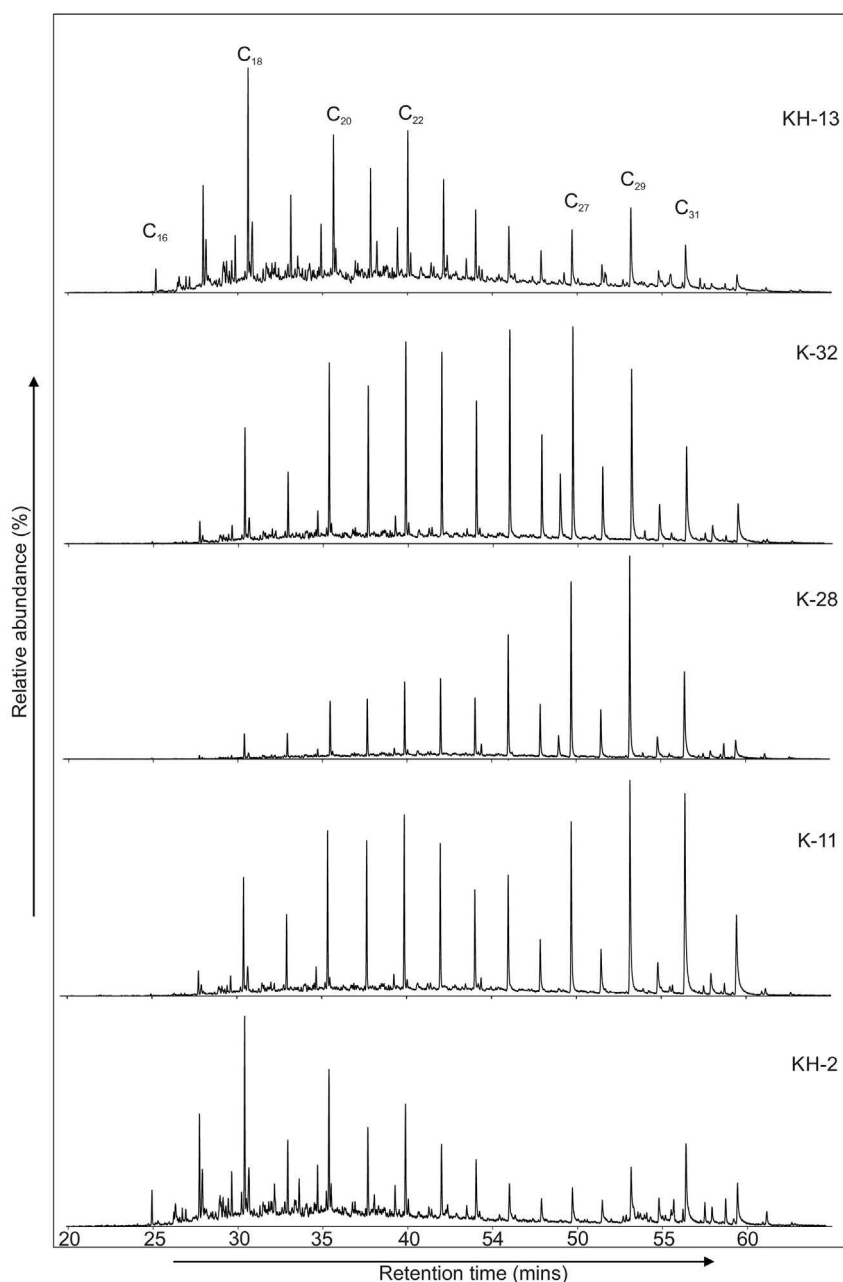


Fig. 8. *n*-alkane distribution according to SIM *m/z* 57 of the samples from Khadsaliya lignite mine. Numbers corresponds to carbons in the *n*-alkane chain.

An attempt has also been made to understand the relationship between lignite quality and hydrocarbon potential. It is found that there is a positive correlation between gross calorific value and TOC content, and also gross calorific values have positive correlations with the carbon contents, fixed carbon contents and volatile matter yields.

5. Discussion

5.1. Palaeoenvironmental conditions

The microconstituents of coal (macerals) carry signatures of their precursors, and the controls of their formation in swamps or wetlands (Taylor et al., 1998; Teichmüller, 1989; Stach et al., 1982). The maceral data (type and amount of macerals) and the coal facies indices (TPI, GI, GWI and VI) derived from it have significance in the reconstruction of peat-forming environment including type of vegetation, ground water and surface water measures, and pH and Eh conditions of mires

(Suárez-Ruiz et al., 2012; and references therein). The palynofacies study has also been used widely for the interpretation of peat precursors and climatic conditions during the development of peat swamps (Carvalho et al., 2006; Batten and Stead, 2005; Mendonça Filho et al., 2002, 2010, 2011, 2012; Batten, 1996a; Tyson, 1995). The particulate organic matter holds a good amount of information on various controls that influence the environment in which it was generated, namely the extent of decay, its burial, degree of degradation, oxic/anoxic environment, proximal/distal relationship to the source, brackish/fresh water environment, etc.

The identification of biomarkers has convincingly been utilized to deduce the depositional environments of organic-rich sediments (Peters et al., 2005). The distribution patterns of *n*-alkanes hydrocarbon and isoprenoids allow depicting the source of organic matter, and also are useful in describing the palaeodepositional conditions. The high abundance of short chain *n*-alkanes (*n*-C₁₈, *n*-C₂₀) indicates a microbial source input (Cranwell, 1977). The *n*-alkanes with a

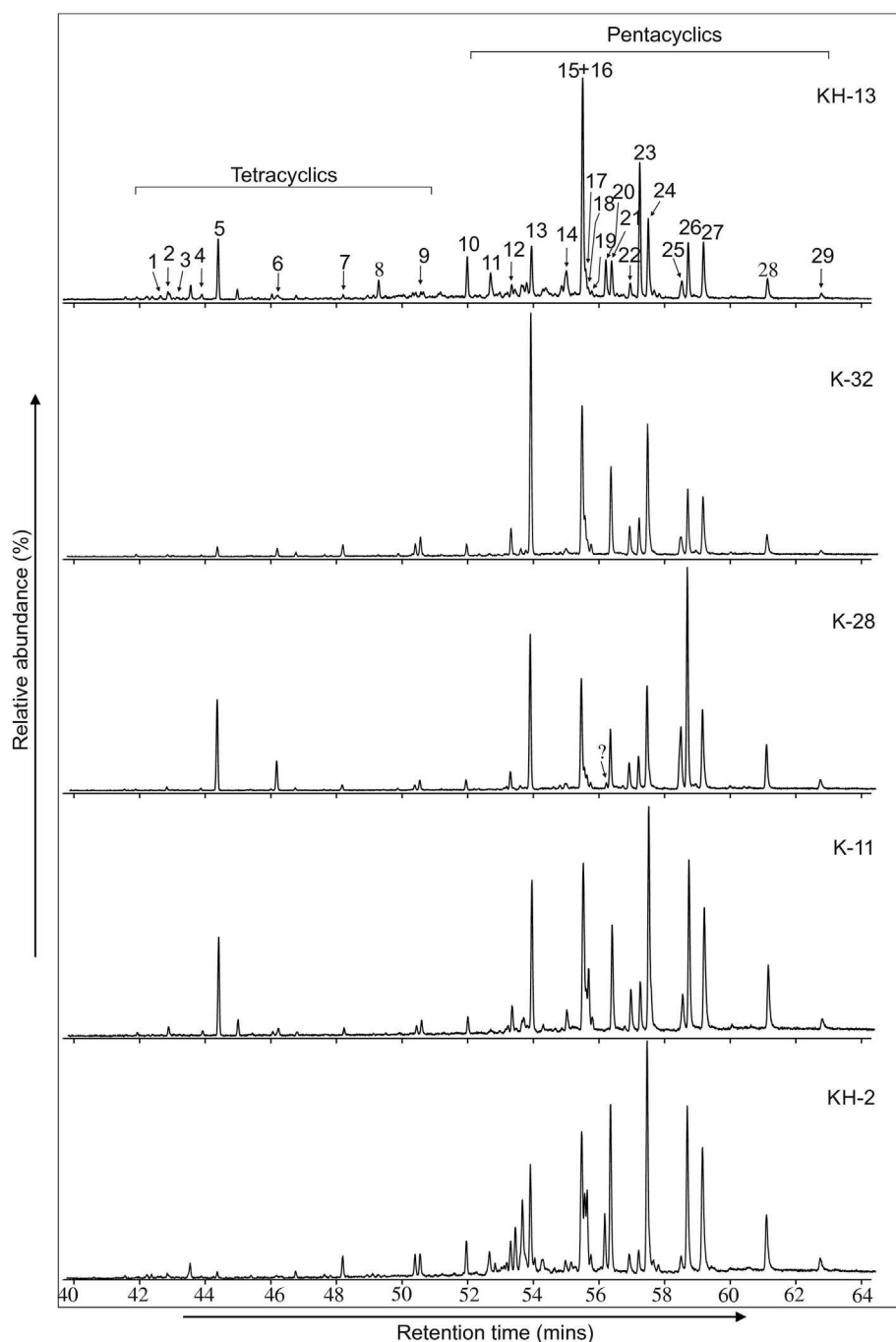


Fig. 9. Triterpenoid distribution in the samples from Khadsaliya lignite mine. Numbers corresponds to compounds referred in the Table 3.

carbon number between C_{15} and C_{25} indicates aquatic source in which shorter chains indicate lacustrine algae, whereas longer chains indicate macrophytes (Ficken et al., 2000, 2002). The Pr/Ph ratio has been widely used to delineate the palaeo-redox conditions existed in the depositional environment (Hughes et al., 1995; Didyk et al., 1978). In addition, proximate and ultimate data also reveal information on the depositional conditions and geologic history of the sequences/seams (Ward, 2002).

The studied Khadsaliya lignites are chiefly composed of huminite, followed by the liptinite, and have low content of inertinite macerals. This suggests the prevalence of anaerobic conditions in the peat-forming mire, probably due to periodic flooding (Erik, 2011; Sýkorová et al., 2005; Flores, 2002). Further, the predominance of telohuminites (ulminite + textinite) indicates woody forest/vegetation. A rich

telohuminites fraction as compared to the detrohuminite (densinite + attrinite) may be related to the fact that lignin-rich wood are structurally better preserved than the cellulose-rich tissues of herbaceous plants during the coalification (Taylor et al., 1998). However, fair representation of detrohuminite could be related to the presence of soft woody tissues of the herbaceous/bushy plants, which eventually forms attrinite and densinite.

Fernene is considered as the biomarker of ferns, which belongs to pteridophytes (Brassell et al., 1980). Therefore, the occurrence of De-A-fernene in the samples indicates the presence of pteridophytes in the source vegetation, while De-A-urs-5(10)-ene and De-A-olean-18-ene invariably suggest the presence of angiosperms. All these corroborate the palaeobotanical records suggestive of growth of herbs and shrubs, including pteridophytes, in and around the basin during Early

Table 5
Results of Rock-Eval pyrolysis and TOC contents of the studied Khadsaliya samples.

Lignite	S1	S2	S3	TOC	T _{max}	Ol	HI	PI	S2/S3	GP
KH-1	2.31	70.28	22.3	36.39	407	61	193	0.032	3.15	72.59
KH-2	5.27	129.79	18.52	40.75	413	45	319	0.039	7.01	135.06
KH-3	1.91	78.67	31.83	39.21	412	81	201	0.024	2.47	80.58
KH-4	2.83	119.29	26.92	49.2	413	55	242	0.023	4.43	122.12
KH-5	0.37	21.29	33.9	40.34	419	84	53	0.017	0.63	21.66
KH-6	1.59	67.69	18.35	31.11	424	59	218	0.023	3.69	69.28
KH-7	0.6	28.98	21.26	34.74	427	61	83	0.020	1.36	29.58
KH-8	0.58	27.2	17.31	26.25	419	66	104	0.021	1.57	27.78
KH-9	0.88	51.24	6.93	16.72	431	41	306	0.017	7.39	52.12
KH-10	0.38	46.98	21.39	35.83	433	60	131	0.008	2.20	47.36
KH-11	0.78	58.37	8.93	21.76	425	41	268	0.013	6.54	59.15
KH-12	1.04	54.93	24.86	37.61	417	66	146	0.019	2.21	55.97
KH-13	0.72	4.23	15.39	18.06	377	85	23	0.145	0.27	4.95
KH-14	1.73	34.75	29.18	30.29	432	96	115	0.047	1.19	36.48
KH-15	7.35	261.25	18.32	54.78	416	33	477	0.027	14.26	268.60
Shale										
K-26	0.1	0.59	0.67	0.72	422	93	82	0.145	0.88	0.69
K-29	0.55	6.26	18.81	17.55	403	107	36	0.081	0.33	6.81
K-31	0.11	1.38	0.53	0.95	429	56	145	0.074	2.60	1.49

S1= free hydrocarbons (mg HC/g), S2= amount of hydrocarbons (mg HC/g), S3= released carbon dioxide (mg CO₂/g), TOC= Total organic carbon (%), T_{max}= temperature maximum (°C), Ol: Oxygen index= (S3/TOC) × 100; (mg HC/gTOC), HI: Hydrogen index= (S2/TOC) × 100; (mg HC/gTOC), PI: Production index= S1 / (S1+S2), S2/S3= Hydrogen richness, GP: Genetic potential= (S1+S2)

Eocene time, as undergrowth in the dense angiospermic forests and back mangroves (Paul et al., 2015; Shukla et al., 2013; Samant, 2000; Guleria, 1991).

Moderate contents of resinite, suberinite, sporinite, and cutinite in the lignites are suggestive of vegetation dominated by the terrestrial higher plants of a forest swamp, as also indicated by the predominance of telohuminites. Consecutively, the abundance of non-opaque phytoclasts in palynofacies assemblages also implies the existence of a fairly dense vegetation cover in the hinterland. The relatively low AOM content in palynofacies-I, along with a high phytoclasts, indicates an increase in terrestrial influx. The presence of resin as rods and blobs indicates the higher plants contribution to the organic matter composition. In addition, a high CPI values (>1) indicates that the organic matter formed from the terrestrial source (Moldowan et al., 1985). However, values equal to 1 may represent insignificant higher plant input (Killops and Killops, 2005). The CPI values of the studied samples are typical for immature and low rank coals with higher plants source. Likewise, the TAR values in the samples (both lignite and shale) are high (>1), and suggests an increased terrigenous input.

The abundance of long chain *n*-alkanes (*n*-C₂₇, *n*-C₂₉) in most of the lignite samples suggests high plant wax input of the terrestrial source

(Eglinton and Hamilton, 1967). The oleanene type of pentacyclic non-hopanoid terpenes identified in the samples is the product of diagenetic transformation of β-amyrin (Otto and Simoneit, 2001; Otto and Wilde, 2001; Rullkötter et al., 1994). These higher plant biomarkers are believed to be originated from the oxygenated triterpenoids in angiosperms (Stout, 1992; Woolhouse et al., 1992; Simoneit, 1986). However, the abundance of detrohuminite macerals indicates the sub-aqueous conditions of mire and also the prevalence of herbaceous vegetation more susceptible to degradation. The P_{aq} ratio between 0.4 and 1 indicates high contribution of submerged or floating aquatic macrophytes, whereas low ratio between 0.1 and 0.4 corresponds to emergent macrophytes (Ficken et al., 2000). However, the ratio <0.1 suggests terrigenous input. A high ratio in all the studied samples admits increased input of the organic matter from aquatic source.

A number of models have been developed for the reconstruction of palaeomire conditions making use of quantitative maceral data/indices as tools (Suárez-Ruiz et al., 2012; and references therein). Diessel (1986) introduced gelification index (GI, the ratio of gelified versus non-gelified macerals), and tissue preservation index (TPI, the ratio between tissue-derived structured and tissue-derived unstructured macerals) for deducing the coal facies. These two indices were modified

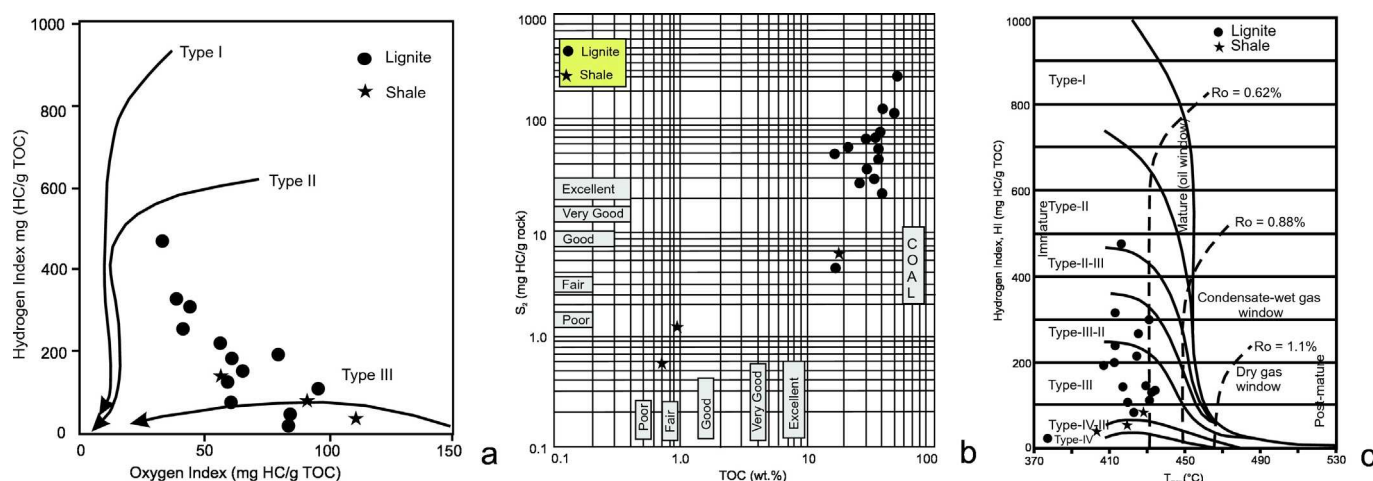


Fig. 10. Rock-Eval data of the samples of Khadsaliya lignites showing a) HI vs. Ol, b) S₂ vs. TOC, and c) HI vs. T_{max} plots.

Table 6
Results of proximate and ultimate analyses of the studied Khadsaliya lignites.

Sample no.	As received basis										Dry basis (db)					Dry ash free basis (daf)										Atomic values				Atomic ratio	Fuel ratio	GCV Cal/g																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
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M: moisture, VM: volatile matter, FC: fixed carbon, H: hydrogen, N: nitrogen, S: sulphur, O: oxygen, wt.: weight, GCV: gross calorific value.

by Kalkreuth et al. (1991), and later by Kalaitzidis et al. (2000) for the low-rank coals/lignites. TPI measures the degree of humification of the peat-forming plant matter, whereas GI quantifies the level of moisture in the peat-forming environment vis-à-vis amount of plant-cell destruction. A high TPI value (>1) reflects equilibrium between the growth and the accumulation of plant materials, rise of water table, and dominance of tree vegetation. A low TPI value suggests either predominance of herbaceous plants in the mire or large-scale destruction of plant tissues as a result of advanced humification (Diessel, 1992). TPI also indicates pH conditions of palaeomires because in a low pH conditions, microbial activity is weak and structural components of plants can be well-preserved and vice-versa (Zhang et al., 2010). High GI value is indicative of a high water level and high gelification.

Calder et al. (1991) proposed a coal facies model based on GWI (ground water index) and VI (vegetation index) indices. Kalaitzidis et al. (2000) modified these indices for low-rank Tertiary lignite. The GWI value indicates the level of ground water (and relative rainfall) during peat accumulation. Mires are usually formed in successive variations between rheotrophic, mesotrophic and ombrotrophic hydrological conditions (Silva et al., 2008; Amijaya and Littke, 2005). GWI values <0.5 suggest ombrotrophic hydrological conditions, whereas values >1 indicate rheotrophic hydrological condition. A mesotrophic hydrological condition is characterized by the GWI values in between 0.5 and 1. The VI is related to the type of vegetation in the mire. It is dependent on the type of peat-forming plant communities (e.g. trees and bushes).

However, predicting the peat mire type and depositional condition on organic petrographic basis alone may be erroneous (Scott, 2002; Wüst et al., 2001; Crosdale, 1993; Dehmer, 1993), and other studies (distribution of associated sediment types, palynology, etc.) should be used for better interpretation (Moore and Shearer, 2003). In the present study, the coal facies indices (TPI, GI, GWI and VI) are calculated using the formulae of Kalaitzidis et al. (2000) and Stock et al. (2016), and the values are listed in Table 1. A high TPI values (mostly above 1, range: 0.92–3.18; Fig. 11) of the lignites indicate preservation of tissues in high ground water table conditions (Dehmer, 1995). Whereas, low TPI value (below 1) is suggestive of optimum water conditions favourable for severe aerobic bacterial decay. Further, a moderate variation in the GI values (range: 1.36–4.43) is suggestive of some fluctuation in redox conditions in the basin, probably due to fluctuations in the water cover. An estimate of the GWI (range: 0.44–1.53) and VI (range: 0.66–2.33) indices point that the peat was deposited under deltaic regime in mesotrophic hydrological conditions with occasional change in conditions close to rheotrophic phase due to the high ground water levels (wetness) in the basin (Fig. 12).

The apparent dominance of phytoclasts organic matter (with better degree of preservation) in the recovered palynofacies assemblages also reflects that the deposition took place in oxygen deficient environments in the immediate vicinity of fluvio-deltaic sources or turbidites (Tyson, 1993, 1995). It is evident by the marginal dysoxic-anoxic basin field (II; palynofacies-I of the study) on Tyson's APP (AOM-Phytoclasts-Palynomorphs) ternary diagram (Fig. 13). The occurrence of high amount of AOM in palynofacies-II suggests that it is preferentially preserved under low oxygen conditions (Tyson, 1995). The AOM generally increases towards offshore basinal settings, where reduced water mixing and relatively low oxygen concentrations allow increased preservation of the less oxidation resistant organic matter (Roncaglia, 2004; Wood and Gorin, 1998; Steffen and Gorin, 1993; Tyson, 1993, 1995; Leckie et al., 1990). According to Kholeif and Ibrahim (2010), the high AOM sediments indicate reducing conditions and increased water column resulting in dysoxic or anoxic bottom conditions. However, enhanced deposition of the AOM in shallow depositional settings could be explained by the upward migration of the oxygen minimum zone, thus providing the low oxygen environment for the preservation of AOM, as indicated by the proximal suboxic-anoxic shelf field (VI) on Tyson's APP diagram.

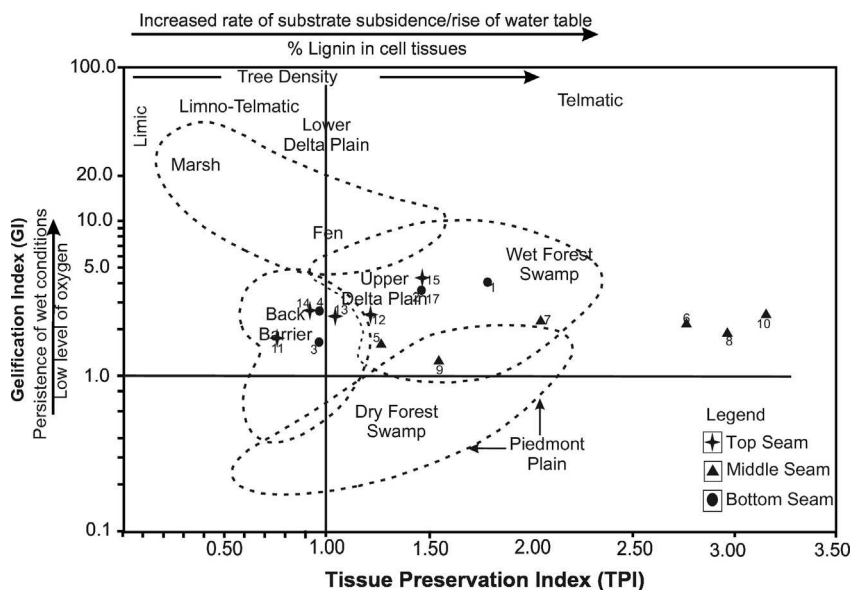


Fig. 11. Facies deciphered from the GI and TPI indices in relation to depositional setting and type of mire.

The AOM shows a weak fluorescence may be due to the bacterial degradation under dysoxic or anoxic conditions, which eventually decreased fluorescence. The bacterial degradation of organic material is supported by the low content of inertinite macerals (formed during aerial exposure of peat), which precludes the possibility of oxidative decomposition. The bacterial activity increases in oxic and alkaline (due to increased pH conditions of water) conditions leading to extensive degradation of organic matters (Taylor et al., 1998). The decomposition products of liptinite get perfused in the huminite forming perhydrous or fluorescing huminite, appreciably represented in all the studied lignite samples. Further, the presence of non-biostructured phytoclasts

suggests that the organic matter may go through to some pre- and post-depositional alterations (Mendonça Filho et al., 2011, 2012; Tyson, 1995). In addition, most of the studied samples showed higher abundance of short chain *n*-alkanes (*n*-C₁₈, *n*-C₂₀); indicating high microbial activity during the formation of these sediments (Cranwell, 1977).

The tetracyclic compounds identified are secohopanes and De-A-triterpenoids. Secohopanes (C₂₅, C₂₆) are considered as the degradation products of hopane precursors formed during the thermal maturation or microbial degradation (Peters et al., 2005). The De-A-triterpenoids identified in the samples are De-A-fernene, De-A-urs-5(10)-ene and De-A-olean-18-ene. These compounds are thought to be formed by the loss of A-ring from 3-oxygenated pentacyclic triterpenoids on photochemical and/or microbially-mediated oxidative reactions (Trendel et al., 1989; Corbet et al., 1980). They are also considered as the product of diagenetic transformation of parent triterpenoids (Jaffé et al., 1996; Jaffé and Hausmann, 1995; Corbet et al., 1980).

The distribution of hopanes and hopenes are characterized by the presence of 17 α (H)21 β (H), 17 β (H)21 α (H) and 17 β (H)21 β (H) isomers with 27 and 29–32 epimers. Abundant 17 α (H)21 β (H)-homohopane (22 R) is common in low rank coals (Stefanova et al., 2005; Burhan et al., 2002; Didyk et al., 1978). The decarboxylation of 31,32-bishomohopanoic acid in soils and peats can eventually leads to the formation of this compound in coals (Killops et al., 1998). 17 β (H)-22,29,30-Trisnorhopane is prominent in some samples. The prevalence of this C₂₇17 β (H)-hopane along with 17 β (H)21 β (H)-homohopane indicates the activity of methanotrophic bacteria (Killops et al., 1998). Hop-17(21)-ene present in the samples is considered as a rearrangement product of diploptene, a common biohopanoid present in a variety of bacterial lineages (Rohmer et al., 1984). It is transformed into hopanes by hydrogenation during diagenesis. The hopanoid distributions generally indicate bacterial origin of sedimentary organic matter (Peters et al., 2005). Abundance of hopanoids in the studied samples indicates considerable contribution from the bacterial biomass into these sediments. Extended hopanes up to C₃₂ is present in all the analysed samples. The bacteriopolyhopanol, a compound present in the prokaryotic cell membrane is found to be the precursor of homohopanes (Roushdy et al., 2010; Ourisson et al., 1984).

In the studied lignite samples, ash contents are comparable with mineral matter contents and vary in same fashion. This could be the result of intense organic matter degradation which would concentrate the

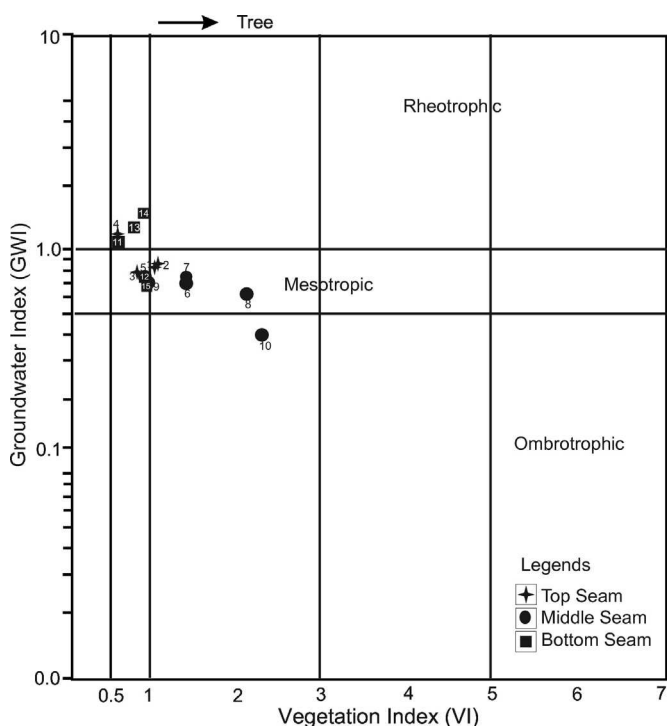


Fig. 12. Diagram of VI and GWI indices of the Khadsaliya lignites showing palaeoenvironment conditions.

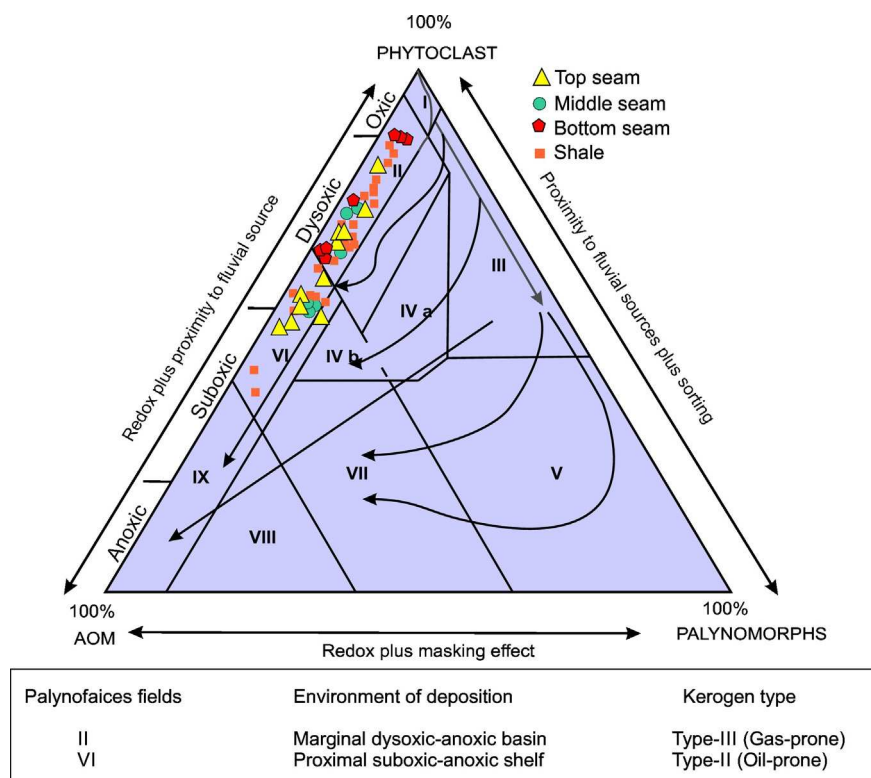


Fig. 13. Ternary diagram of APP (Tyson, 1995) characterizing the kerogen assemblages recovered from the samples and the depositional environments indicated.

inorganic fraction (Davis et al., 2007; Teichmüller et al., 1998). Low to moderate sulphur contents in the deposits are related to a marginal marine and brackish-water environment during deposition (Sachsenhofer et al., 2003). This also points to a moderate water table (mesotrophic) and low pH (Stach et al., 1982) with proximity of the peat to marine water. Low sulphur content is a result of both the limited sulphur input and the lack of sulphate-reducing bacteria in the acidic conditions (Davis et al., 2007; Amijaya and Littke, 2005; Gruber and Sachsenhofer, 2001; Diessel, 1992). Therefore, the sulphur content also indicates that the lignites were accumulated in mesotrophic condition. The principal sulphur source was the marine water. This contention is further supported by the presence of framboidal pyrite in the lignites.

The presence of funginite (and record of fungal elements in the palynofacies) in higher concentrations in the lignites is indicative of warm and humid/moist climatic conditions, but not reaching to the level of oxidation of peat because other macerals of the inertinite group produced by oxidation are exceedingly low in concentrations. Such conditions are favourable for the fungi and luxuriant growth of vegetation in tropical to sub-tropical climate. Frequent occurrences of resinite and suberinite in the lignites could be due to the prevalence of resin-producing angiosperms and mangroves (arboreal plants) in woody forests. The mangrove-mixed angiospermic vegetation and frequent occurrence of framboidal pyrite are suggestive of brackish-water influence during the development of peat in the marshy marginal marine environment (Paul et al., 2015; Samant, 2000). Further, the presence of marine palynomorphs (lining of foraminifers and dinocysts, especially in the palynofacies-I) along with opaque phytoclasts suggest intermixing of marine elements with terrestrial elements in proximal condition. Palynofacies-II is also an indicative of shoreline and brackish/freshwater environment (marginal marine).

The pristane (Pr) and phytane (Ph) compounds are assumed to be derived from the phytol side chain of chlorophyll in phototrophic organisms, although other sources were also suggested (ten Haven et al., 1984). The cleavage of phytol side chain results in the formation of phytol and under anoxic conditions, which is further reduced to

dihydrophytol, and then finally to phytane. Under oxic conditions, the phytol is oxidized to phytenic acid, decarboxylated to pristane, and then reduced to pristane (Peters and Moldowan, 1993). The low Pr/Ph ratio values in the shale samples (av. 0.26) suggests anoxic, whereas higher values (1.04) in the lignite samples suggests suboxic conditions. Further, the abundant $n\text{-C}_{25}$ in shale samples suggest increased aquatic condition. The relatively low abundance of $n\text{-C}_{18}$ in the shale samples comparatively less microbial activity. The plot $\text{Pr}/n\text{-C}_{17}$ versus $\text{Ph}/n\text{-C}_{18}$ (Fig. 14) clearly shows mixed (type II/III) organic matters input under moderate redox conditions.

5.2. Economic potential for hydrocarbon source

The source rock horizons are important for any petroleum system. Source rock potential is controlled by the amount of organic matter

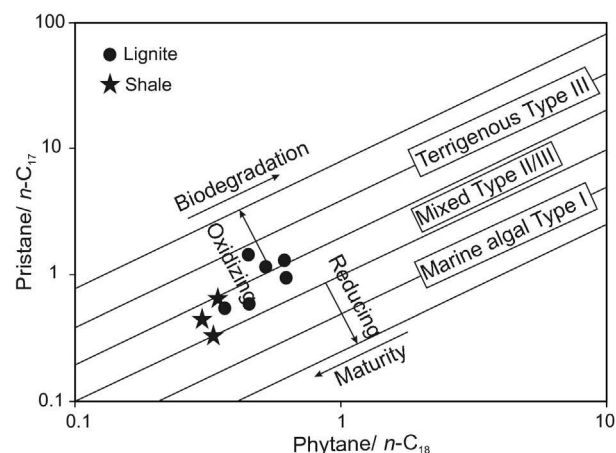


Fig. 14. Pristane/ $n\text{-C}_{17}$ versus Phytane/ $n\text{-C}_{18}$ plot of the Khadsaliya samples.

(kerogen), post-depositional alterations (diagenesis), and degree of thermal maturation. The composition of kerogen determines the genetic potential and the amount of hydrocarbons that can be generated during burial. The petrographic (macerals/visual kerogens, vitrinite/huminite reflectance), palynofacies (kerogen), and geochemical (such as TOC, Rock-Eval pyrolysis) analyses have successfully been utilized to provide the valuable source rock information with a higher degree of accuracy. The thresholds for the source rock quality are based on HI values (Hakimi et al., 2013; Peters and Cassa, 1994). The samples that contain a type III vitrinitic/huminitic kerogen would be expected to generate gas with HI values < 200 but > 50 mg HC/g TOC, whereas samples with HI values higher than 200 mg HC/g TOC can generate oil although their main generation products are gas and condensate. Moreover, samples with HI values > 300 mg HC/g TOC (type II kerogen) may generate oil (Koeverden et al., 2011; Hunt, 1996; Bordenave and Durand, 1993). The type I kerogen (oil prone) commonly possesses HI values of > 600 mg HC/g TOC, while type IV (inert) materials typically have their values lower than 50 mg HC/g TOC.

In this respect, the analysed samples from the lignite-bearing sequence of Khadsaliya new mine consist of high TOC contents (av. 33 wt.%) and the high HI values (av. 188 mg HC/g TOC), and are considerably above the minimum threshold values for hydrocarbon generation. The value of S₂ ranges from 4.23 to 261.25 mg HC/g sample. This range indicates a highly variable source rock potential. Hence, both the TOC and S₂ yields from the samples indicate very good potential source rocks for oil and gas, as it can also be deduced from the HI values that vary from 23 to 477 mg HC/g TOC. The plottings of such values on HI versus OI and S₂ versus TOC diagrams (refer Fig. 10a and b, respectively) reveal that the samples are having kerogen types II and III (mixed oil- and gas-prone). The van Krevelen's diagram plots the H/C vs. O/C atomic ratios, which are used to classify kerogens and informing about the evolution path of organic matter from different organic sources (Erik, 2011). The cross plot of H/C and O/C of the studied samples also indicates that the organic matter constitutes a mix of type II and III kerogens (Fig. 15).

The ratio of S₂/S₃ suggests the quality of the organic matter present. Ratio values lower than 1 indicates absence of generated hydrocarbons (Peters and Cassa, 1994). Most of the studied samples show S₂/S₃ ratio above 1; indicating the potential to generate hydrocarbons. Moreover, the degree of thermal maturation can be evaluated from huminite (vitrinite in coal) reflectance and T_{max} (Peters et al., 2005; Taylor et al., 1998; Hunt, 1996). In the present study, the T_{max} and reflectance values obtained for the lignite samples are 377–433 °C and 0.30–0.38 R_r, respectively. These values suggest an immature stage with respect to the hydrocarbon generation. The presence of 17β(H),21β(H) stereo isomers also indicates that the samples have experienced only a low

thermal maturity (Rohmer et al., 1980; Enslinger et al., 1974). The presence of hop-17(21)-ene and other unsaturated hopanes also suggests the lower level of thermal maturity of these samples.

Thermal maturation of the organic matter has been additionally deduced from the Rock-Eval pyrolysis derived T_{max} versus HI plot (refer Fig. 10c). The zone of oil generation ranges between T_{max} temperature of 435° and 460 °C, and between production index (PI) values of 0.1 and 0.4 (Tissot and Welte, 1984). The PI values (<0.1) of the studied samples point towards the remote chances of *in situ* generation of hydrocarbons from the lignite-bearing sequence of Khadsaliya mine.

Furthermore, the organic matters identified in the palynofacies analysis of the samples are mainly constituted by phytoclasts along with AOM, and low palynomorphs. This also suggests the input of dominantly type III-II admixed kerogens (organic materials; Batten, 1996b; Tyson, 1995). The data is corroborated with the presence of fair amounts of hydrogen-rich macerals (perhydrous/fluorescing huminite + liptinites: 25–52%, Table 1), recognized as visual kerogens, in the lignites. The bacterial degraded hydrogen-rich macerals are considered to be good source of hydrocarbons (Horsfield et al., 1988). Thus, the overall characteristics indicate that the studied lignite-bearing sequence of Khadsaliya new mine has the potential to generate mixed oil and gaseous hydrocarbons upon maturation.

6. Conclusions

A combination of petrographical, palynofacies, and organic geochemical parameters has been applied for detailed characterization of the Khadsaliya lignite deposits from the new mine section. The inferences drawn from the data generated are complimentary to each other. The following findings are highlighted with regard to the thermal maturity, palaeodepositional conditions, and hydrocarbon potential of Early Eocene lignites from the Saurashtra Basin of western India:

- Lignites are dominantly composed of huminite group of macerals followed by the liptinite, and low content of inertinite groups.
- High GI, TPI, and CPI values indicate that lignites were formed from the woody forest (including herbaceous vegetation) in deltaic regime under high ground water conditions and wetness in the palaeomire.
- Biomarkers composition suggests the organic matter contributions from angiosperms, pteridophytes, and product of bacterial activity.
- GWI and VI indices suggest that the peat precursor was subjected to intermittent flooding of the mire, as the maceral data show a shift from mesotrophic to rheotrophic conditions. The high ground water conditions are further determined from the increased TAR values.
- Extrapolation of palynofacies data, Pr/Ph ratios, and Pr/n-C₁₇ vs. Ph/n-C₁₈ plot collectively shows that the studied sequence formed in a varying deposition regime (marginal dysoxic-anoxic basin to proximal suboxic-anoxic shelf environments).
- Lignites are characterized by high moisture contents, high carbon, moderate oxygen, low to moderate sulphur, and relatively moderately high ash yields and volatile matter yields and along with average fixed carbon contents.
- Biomarker composition, huminite reflectance and T_{max} values indicate that the lignites are thermally immature, and coalification extended up to the 'low rank B coal' stage.
- Sufficient TOC contents, H/C–O/C atomic ratios, and normally high HI values along with fair concentrations of phytoclasts and amorphous organic matters, and hydrogen-rich macerals (perhydrous huminite + liptinites) point towards the potential of the studied lignite-bearing sequence to generate a mix of oil/gaseous hydrocarbons (kerogen types II–III) upon maturation.

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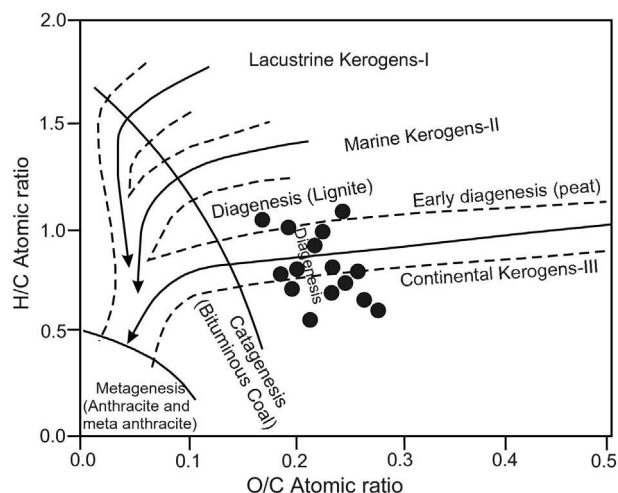


Fig. 15. Atomic H/C vs. O/C plot for the Khadsaliya lignite samples.

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