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# Coal Petrology - A shifting role from coal utilization to fuel exploration

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## ABSTRACT

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Coal petrology deals with the study of microscopically recognizable remains of vegetal source matter, termed 'macerals', which for convenience are classified and categorized into three main groups- vitrinite ($O_2$-rich), liptinite ($H_2$-rich) and inertinite (C-rich). Each maceral being specific in its origin, evolution and environmental conditions during genesis has tremendous interpretative value. Vitrinite-rich coals form in anaerobic (wet-reducing) condition, whereas aerobic (dry-oxidative) condition results into the formation of inertinite-rich coals. Macerals of the liptinite group originate in acidic-wet conditions of swamp. Optical properties (reflectance and fluorescence) and quantitative estimations of coal micro-constituents overall reflect the chemical properties and thus help in various interpretations. The studies are convincingly utilized to predict the suitability of coal for specific economic and industrial purposes. Currently, the petrological investigations are being utilized to interpret the potentiality of coal for methane that originates during the time and pressure induced diagenetic and catagenetic stages of coal formation.

**Key-words**—Coal, Maceral, Maturity, Utilization, Fossil fuel exploration.

## कोयला शैलविज्ञान की कोयला उपयोग से ईंधन अन्वेषण में बदलती भूमिका

अल्पना सिंह एवं बी.डी. सिंह

## सारांश

कोयला शैलविज्ञान का सरो कार वनस्पति उद्गम पदार्थ के सूक्ष्मदर्शी के रुप से स्वीकार्य अवशेष के अध्ययन से है, 'मैसेरल' शब्द, जो कि सुविधा के लिए तीन समूहों में वर्गीकृत व श्रेणीबद्ध हैं- विट्रीनाइट ($O_2$-प्रचुर), लिप्टीनाइट ($H_2$-प्रचुर) और इनर्टिनाइट (C-प्रचुर)। उत्पत्ति के दौरान प्रत्येक मैसेरल का अपने उद्गम, विकास एवं पर्यावरणीय स्थितियों में विशाल व्याख्यात्मक महत्व है। विट्रीनाइट-कोयले अवायवीय (आर्द्र-न्यून) स्थिति में बनते हैं, जब कि वायुजीवी (शुष्क-ऑक्सीकर) स्थिति के परिणाम इनेर्टिनाइट प्रचुर कोयले शैलसमूह बनते हैं। दलदल की अधिसिलिक-आर्द्र स्थितियों में लिप्टिनाइट समूह के मैसेरल उत्पन्न होते हैं। कोयला सूक्ष्म-संघटकों के प्रकाशीय गुणधर्म (परावर्तकता एवं प्रतिदीप्ति) और मात्रात्मक अनुमान समग्र रुप से रासायनिक गुणधर्मों को प्रभावित करते हैं तथा इस प्रकार विभिन्न व्याख्याओं में सहायता करते हैं। विशेष आर्थिक एवं औद्योगिक उद्देश्यों हेतु कोयले की उपयुक्तता अनुमानित करने को ये अध्ययन विश्वासोत्पादकता से प्रयुक्त होते हैं। वर्तमान में शैलविज्ञान संबंधी अन्वेषण कोयले में मीथेन की संभाव्यता की व्याख्या करने में प्रयुक्त हो रहे हैं जो कि कोयला शैल समूह में काल व दबाव प्रेरित प्रसंघाती तथा प्रतिविकास अवस्थाओं के दौरान उत्पन्न होती है।

**संकेत-शब्द**—कोयला मैसेरल, परिपक्वता, उपयोग, जीवाश्म ईंधन उत्खन्न।

## INTRODUCTION

COAL petrology deals with the microscopically recognizable organic remains in coal and lignite, comprising plant remains (spore-pollen, seed, leaf cuticle, stem wood, root, resin, etc.) of pre-historic vegetation in various states of preservation. The transformation of vegetal matter into coal, i.e. coalification process, gives rise to organo-petrographic entities termed 'macerals' (both structured and unstructured and wide range of degradational products), which



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are the basic unit of coal. The investigations on total organic matter classified and categorized into three main maceral groups— vitrinite, liptinite (exinite) and inertinite, based on their origin, optical and chemical properties, form the basis of organic petrology (Stach *et al.*, 1982; Taylor *et al.*, 1998).

Formation of various coal macerals is the result of their varied origin and difference in the rate of subsidence of swamp. Vitrinite and inertinite originating from similar vegetal source [humic substances (form lignin and cellulose) of woody fraction], differ with respect to their geneses in different environmental conditions of swamp. Higher aromatic oxygen-rich vitrinite generates in aquatic, reducing environmental conditions of swamp experiencing faster rate of subsidence. Whereas, relatively carbon-rich inertinite forms in dry-oxidative conditions and slow subsiding swamp. Higher aliphatic and hydrogen-rich liptinite macerals having their origin from hydrogen-rich plant parts, viz. spores-pollen, cuticle, suberin, resins/ waxes, fats, and algal and bacterial mass, generate in relatively acidic-wet conditions of swamp (Stach *et al.*, 1982; Teichmüller, 1986, 1987, 1989; Taylor *et al.*, 1998).

Petrological studies on coal macerals are carried out utilizing reflectance and fluorescence microscopic techniques, to obtain information on its vegetal composition and level of coalification (Van Gijzel, 1967, 1975, 1979; Ottenjann, 1982, 1988; Stach *et al.*, 1982; Teichmüller, 1982, 1989; Taylor *et al.*, 1989, 1998). Correlation of macerals to their original plant parts provides information on the habitat and nature of palaeovegetation supplied as the source material for coal formation. Absence/presence and quantitative proportions of each maceral being specific in its origin, evolution and genesis throw light on coal facies to understand source vegetation and environmental and palaeoclimatic conditions.

Special investigations such as– moisture and volatile matter contents, carbon and hydrogen contents, reflectance of vitrinite and calorific value allow to distinguish between several stages of coalification (Alpern, 1987; Alpern *et al.*, 1989), referred to as rank levels, which indicate maturity of coal. Rank values thus, enables to understand the maturity level or stage reached by coal during its formation. Vegetal matter continuously gets enriched in carbon content during

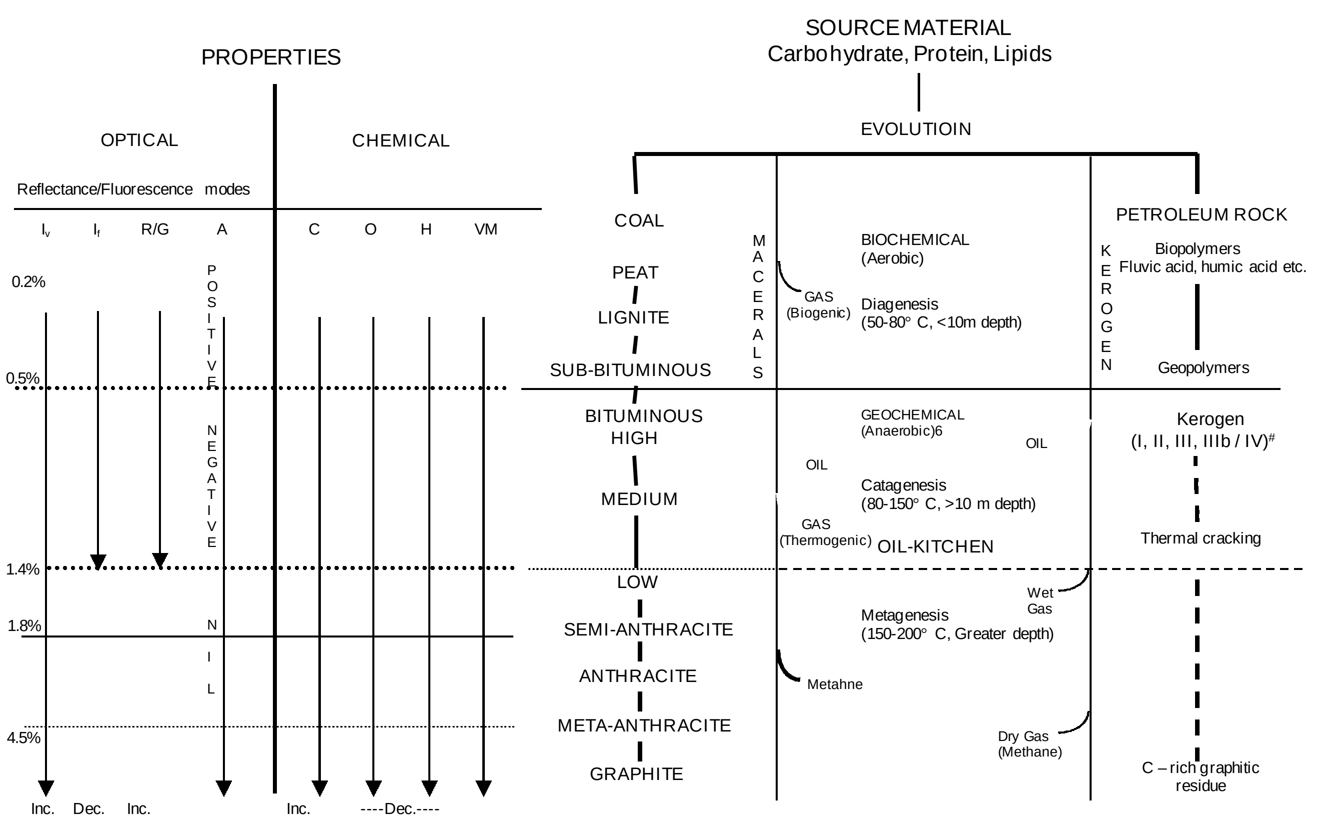


Fig. 1—Schematic presentation of hydrocarbon generation during organic matter evolution in coal and petroleum rocks and their relation with optical (petrological) and chemical properties (after *Stach *et al.*, 1982; #Tissot & Welte, 1984; Brooks, 1981). $I_v$ = Intensity of reflectance, $I_f$ = Intensity of fluorescence, R/G = Red/Green quotient, A = Alteration, C = Carbon, O = Oxygen, H = Hydrogen, VM = Volatile matter, Inc. = Increase, Dec. = Decrease.

the course of transformation. Commenced with peat– the first stage of coalification, and passing through lignite (brown coal), bituminous and anthracite stages of coal, vegetal matter finally but rarely converts into graphite– the pure form of carbon (Fig. 1). Each coalification or maturation stage is specific in its physical and chemical properties. Determination of rank of coal therefore provides information on these aspects.

For maturity determination, maximum intensity of light reflected from vitrinite particle ($R_{o\,max}$ value) and maximum light intensity emitted from liptinite ($\lambda$ max value) in monochromatic incident light (546 nm wavelength) and ratios of maximum intensities of light emitted in red and green (R/G quotient) part of the spectrum on exposure to ultra violet/ blue light excitation (340-390 nm wavelength) is measured and calculated Intensities of lights reflected and emitted have direct relationships with coal maturation. As the maturation of coal increases, $R_{o\,max}$ and $\lambda$ max values increase, however intensity of emitted light at 546 nm decreases and wavelength increases (Ottenjann *et al.*, 1975; Radke *et al.*, 1980). The colour of light emitted shifts towards red part of the spectrum and R/G quotient also increases with increase in rank. Peat, lignite to high-volatile bituminous C coal, and high-volatile bituminous B to medium-volatile bituminous coals show $\lambda$ max values between <500-500 nm, 560-580 nm, and 630-670 nm respectively.

## COAL UTILIZATION

Petrological studies, besides academic interpretations suggest/ predict suitability of coals for various utilizational purposes (Stach *et al.*, 1982; Taylor *et al.*, 1998). Proportions and predominance of macerals together with rank provide an insight into general behaviour of coal in terms of chemical composition. Rank is significant especially when conversion potential of coal is to be understood, since it has a direct relationship with percentage of volatile matter. Low-volatile high rank coals ($R_{o\,max}$ > 1.5%) are generally not amenable for conversion. Rank of coal in common terms indicate ‘grade’ which has importance in technological processes and the maceral composition indicate ‘quality’. Both rank and composition is therefore, important in evaluating utilization potential of coals for specific purposes, because coal can not be used unless it has required organic composition and appropriate rank.

Coals also contain variable proportion of mineral matter, responsible for producing ash, which reduce their utilizational potential. The study of minerals (content, type, association with macerals, etc.) is therefore, important in knowing content of impurities. Studies of coal-mineral association (carbominerite) help in coal beneficiation. Mineral study is extremely essential when coal is to be used for specific purposes, viz. conversion, combustion, etc. Coals with high association of minerals (>30%) are normally outright rejected by the industry users. Evaluated coals as per their suitability can be utilized for the following purposes:

### Combustion (burning)

Coals should have average amounts of carbon, hydrogen, oxygen and volatile matter and a definite calorific value (high) and ash content for burning in thermal power plants for electricity generation.

### Carbonization (coke making)

Coke is needed for steel industry. Coking coals, i.e. coals to produce coke, on heating in absence of air, soften become plastic and form sponge-like mass of pure carbon, called coke. Coking coals must have requisite proportion of fusible macerals (reactive constituents– vitrinite + liptinite = 45-75%), maturation level between medium- to low-volatile bituminous stage ($R_{o\,max}$ 1.10-1.50%), carbon content 70-80%, low proportions of sulphur and phosphorus and not more than 20% ash content (Ghosh, 1969).

### Blending (making coals usable)

Coal blending is a process in which two or more coals are intimately mixed in required ratio to obtain a product of desired proportion. Coals with relatively low mineral matter content, higher maturation (rank) level and other relatively better properties are mixed with poor quality/grade coals for making them usable for the required purposes.

### Liquefaction or Hydrogenation (conversion of coal into oil)

Coals can be converted into synthetic crude oil or syncrude by the technique of liquefaction/ hydrogenation in which enough hydrogen is added in coal– oil mixture or tar to produce oil. Coals having higher proportion of hydrogen-rich macerals (perhydrous or fluorescing vitrinite + liptinites) and lying in between bituminous ranges of coalification ($R_{o\,max}$ 0.5-<1.5%) are suitable for conversion, primarily high-volatile bituminous coals.

### Beneficiation (coal preparation by cleaning processes)

Coal beneficiation reduces inherent mineral content in run-off mine coals. Mineral distribution and concentration analyses help to ascertain the type of methodology applicable for beneficiation.

Global demand for energy has necessitated to explore all the possibilities of coal utilization for energy generation. This led to the development of many new techniques in scientific and technical fields. Petrological studies till now utilized to predict the suitability of coals for various usages and utilizations, is presently adopted to interpret potentiality of coal for methane generation, the highly inflammable gas from coal beds, currently utilized as a energy resource for domestic needs in USA, China, etc. Coal petrological studies are equally effective in evaluating hydrocarbon (oil/gas) generating potential of source rocks. Thus, a great shift in the role of organic petrology from coal utilization to fuel exploration is evident.

## FUEL EXPLORATION

### Coal Bed Methane

Methane ($CH_4$) gas in coal beds, termed as coal bed methane (CBM), generates along with other gases during transformation of vegetal matter into coal (i.e., coalification; Fig. 1) and gets stored in coal itself (Levine, 1993; Rice, 1993). The gas generates at two stages of coalification:

(i) during biologically induced diagenetic stage occurring at shallow depth (<10 m, 50-80ºC temp.) of peat swamp (biogenic methane), and

(ii) during time and pressure induced catagenetic and metagenetic stages occurring at higher temperature (80-200ºC) and greater depths (thermogenic methane).

Besides these stages, methane is also generated after the formation of coal by action of bacteria, etc. Since, gas is generated during coalification it is universally present in all coals, however the amount generated may vary in different coals. Coals also vary in methane retaining and producing capacities. The capacities to generate, retain and produce gas is actually inherited in coal itself, which works as the producer as well as the reservoir rock for methane gas. The variation in these properties therefore, can be attributed to source material/ vegetation forming coal and its degree of maturation.

Petrological investigations on coal may provide the most convincing answers to many CBM related queries as to why coals differ in methane sorption, retention, generation and production capacities. Maceral analyses and rank determination, the two most important petrological parameters for coal evaluation, can also reliably be applied for assessing CBM potentiality of coals. Qualitative and quantitative estimation of macerals and degree of maturation together with cleat and mineral association studies provide an insight to coal for interpreting CBM properties.

*Coal Maceral Composition (Facies)*

Type and proportion of macerals greatly influence CBM properties of coal. Hydrogen-rich liptinite macerals mainly contribute in generation of methane gas. It actually forms the raw material for methane and on degradation/ decomposition (biogenic) and/ or thermal cracking at elevated temperature and maturity generates thermogenic methane. According to Levine (1992), coals with liptinite even in traces are capable of generating methane. Oxygen-rich vitrinite and carbon-rich inertinite macerals are mainly responsible for retention and production of methane, respectively.

Sorption capacity (to absorb/ adsorb and desorb methane) is related to micro-pores development in coal (Levine, 1993; Killingley *et al.*, 1995), which depends on maceral composition and rank. Different macerals vary in their natural pore-systems or phyteral porosity. Vitrinite macerals are more micro-porous as compared to inertinites (fusinite/ semifusinite). Higher proportion of inertinite macerals (especially structured inertinites) therefore, provides lower adsorptive and higher desorptive capacities to coal due to well-developed macro-pore structure (>50 µm in size). On the other hand, vitrinites in dominance provide greater surface area and hence, higher adsorptive and lesser desorptive capacities to coal due to its more micro-porous (<2 µm in size) nature. Thus, maceral composition provides information on sorption behaviour of coal and helps to understand the capacity of coal to produce methane (Levine, 1987, 1992; Lamberson & Bustin, 1993; Mann *et al.*, 1995; Clarkson & Bustin, 1997; Crosdale *et al.*, 1998).

*Degree of Maturation (Rank)*

Coals having requisite maceral composition must also attain a certain level of maturity for the generation of thermogenic methane. The petrological parameter (intensity measurement of reflected light) as mentioned earlier provides the best possible way to estimate the degree of maturation. Extrapolation of obtained rank values on correlation charts give information about coal capacity to generate amount of gas at specific maturation levels (Fig. 2). High-volatile bituminous coals at $R_{o\ max}$ 0.5-0.7% generate early thermogenic methane. Late thermogenic generation of methane in bulk occurs in coals attaining the $R_{o\ max}$ values between 1.1% and 1.4%, and peaks at the boundary between medium- and low-volatile bituminous coal stages (1.4% ≅oil death-line). The late thermogenic generation, however subsequently decreases in coals having higher rank values of $R_{o\ max}$ >1.4%, i.e. in low-volatile bituminous to anthracite coal stages (Fig. 2; Stach *et al.*, 1982; Meissner, 1984; Rightmire, 1984).

The rank values besides providing information on amount of gas generated may give general information on other CBM related properties, viz. coal porosity, moisture content and adsorption/ desorption capacities, having a direct or indirect relationship with rank.

### Cleat Characterization

Cleats in coal are regarded as equivalent to joints in clastic rocks (Diamond *et al.*, 1976; Ward *et al.*, 1984; Condon, 1988; Grout, 1991) or as closely spaced, pervasive fractures (Laubach *et al.*, 1991; Tremain *et al.*, 1991). These, actually are the natural fractures in coals that may be regarded as fine network of pipelines providing drainage for gas/methane to flow. For CBM exploration, cleat study (both mega and micro) is essential for planning exploration and development because of their influence on recovery of methane and the local and regional flow of hydrocarbons and water. A detailed study of micro-cleats (length, breadth, orientation, branching, etc.) under the microscope on polished coal block gives information on

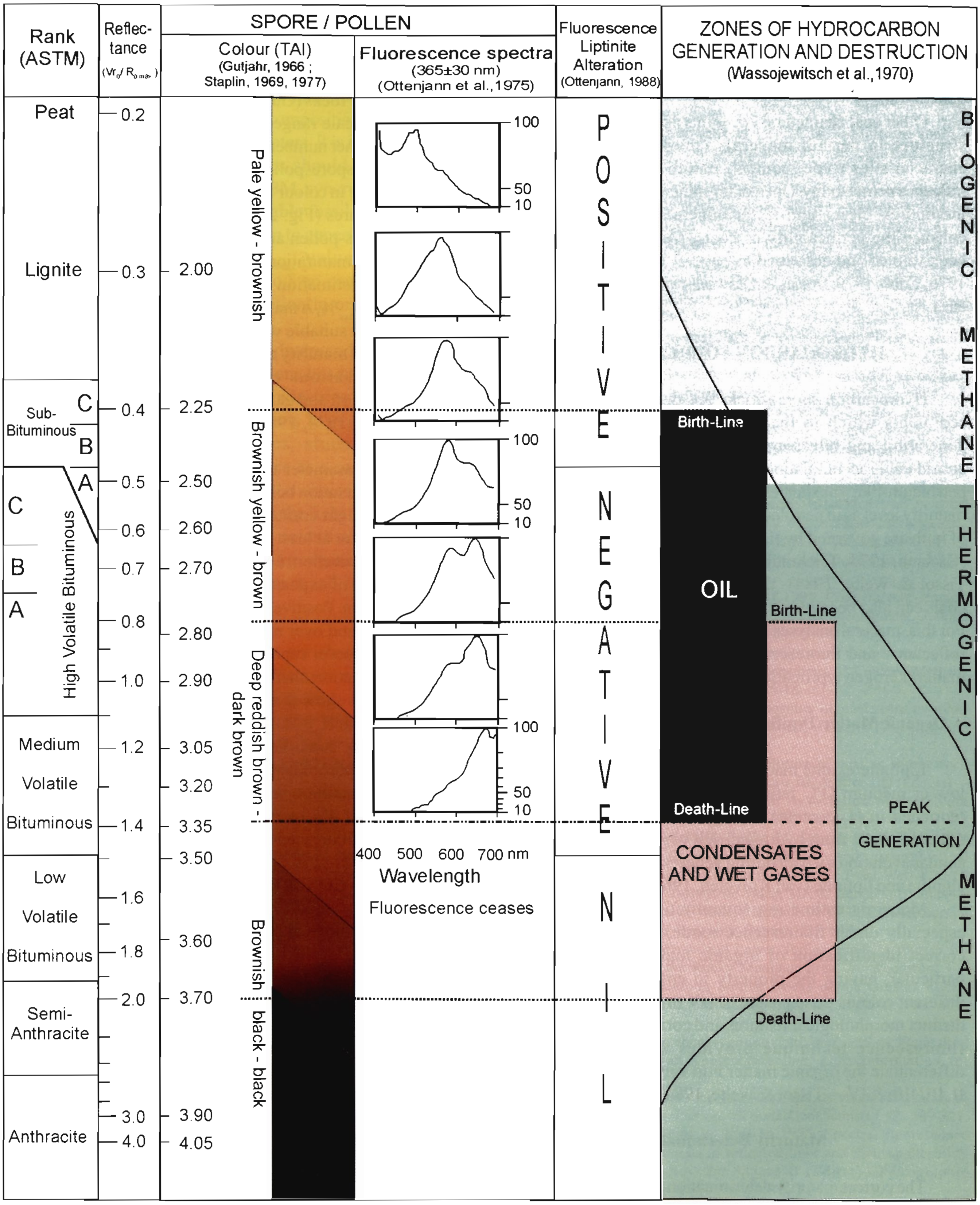


Fig. 2—Optical parameters of organic facies and their relationship with hydrocarbon generation (after Stach *et al.*, 1982; other source: Staplin, 1977; Levine, 1993; Rice, 1993)

permeability or capability of coal to flow methane, which has a direct relation with methane recovery/production. Coals with no or lesser permeability (<0.1 md) are inefficient to produce gas despite having all requisite properties of methane generation.

Other coal characters, viz. joints and fractures, mesopore structure in certain macerals (inertinite), and mineral characteristics (type, content, nature of filling, etc.) also influence permeability. Open or un-mineralized fractures/ joints/ mesopores/ cleats, and lesser mineral content significantly enhance the permeability of coals. Minerals in cleats have been studied and described by several workers (Hatch *et al.*, 1976; Cobb, 1979; Spears & Caswell, 1986; Daniels *et al.*, 1996, etc.).

## HYDROCARBON SOURCE ROCKS

Hydrocarbon source rocks are defined as fine grained sediments which in their natural setting are capable of generating and releasing enough hydrocarbons to form a considerable accumulation of oil or gas (Brooks, 1981). Since, petroleum-like substances also generate in coals at similar maturity level as in petroleum source rocks (Fig. 1) and geneses of both are governed by time and pressure induced processes (Castano, 1973; Teichmüller, 1974, 1986; Stach *et al.*, 1982; Tissot & Welte, 1984), the methods to study and evaluate coals can also be applied to evaluate petroleum source rocks. For this, maceral analyses and maturity estimations under both reflectance and fluorescence modes are suitable for organic matter/ kerogen typification and maturation.

### Organic Matter Typification (Facies & Kerogen types)

Liptinite/exinite macerals exhibiting high H/C ratio and low or medium O/C ratio, represent kerogen type I and II (enriched in $H_2$ content) in source rocks as these kerogen types originate from hydrogen-rich vegetal matter and adopt similar evolutionary path during geneses like those of macerals alginite and liptinite (van Krevelen, 1961; Tissot *et al.*, 1974).

Macerals estimation (quantitative and qualitative), especially under fluorescence mode, enable accurate and correct identification of organic matter, the liptinites in particular, having the property to emit light/ fluoresce in different colours on exposure to UV or blue light. Beside the distinct morphological features and correct identification, the fluorescence technique provides an efficient way to differentiate the organic matter into various kerogen types (I, II, III/ IIIb & IV— Tissot & Welte, 1984).

### Maturity Determination

The correct maturity determination of carbonized material in sediments is extremely important when prospecting for oil/ gas, as it directly provides the inference for the presence or absence of proper source rock. Spores-pollen colour index/ thermal alteration index (TAI), i.e. change in spores-pollen colour with increase in temperature due to carbonization or maturation is routinely used for maturity determination of sediment source rocks (Gutjahr, 1966; Staplin, 1969, 1977).

The TAI scale ranges from 1.00 to 5.00 as proposed by Staplin. The higher number reflects higher temperature to which organic matter (spore/ pollen) were exposed. The spores-pollen exhibit a change in colour from greenish-yellow to black as the sediments matures (Fig. 2). Brownish-yellow to dark brown colour of spores-pollen and TAI nos. between 2.25 and 3.35 indicate proper maturation.

Maturity estimation utilizing petrographic microscopic techniques ($R_{o\,max}$%, $\lambda$ max, R/G quotient, alteration) provides additional most suitable ways. Different correlation schemes between rank (maturity) and oil and gas occurring zones proposed by various coal petrologists provide direct information on oil and gas generating potential of rocks (Fig. 2; Teichmüller, 1974, 1987; Stach *et al.*, 1982; Taylor *et al.*, 1998).

Another parameter to know maturation for oil and gas generation is alteration behaviour, i.e. for the pattern of change in intensity of light emitted on exposure of organic matter to UV/ blue light for at least 10 minutes (Ottenjahn *et al.*, 1982). The negative alteration, i.e. decrease in intensity of light with increasing time of exposure indicate correct maturation level for oil generation. Positive and no alterations respectively point towards under and over maturation of organic matters for oil generation, however capable of gas generation (Figs 1, 2).

The correlation charts of various maturation parameters with oil and gas show that oil generation begins at $R_{o\,max}$ 0.4-0.6% and stops at $R_{o\,max}$ 1.4% which are respectively termed as 'birth-line' and 'death-line' for oil (Fig. 2). The maturation parameters are more reliable in defining oil death-line accurately because oil generation completely ceases at the maturation level of $R_{o\,max}$ 1.4% or more and organic matters show no alteration and fluorescence properties.

## CONCLUDING REMARKS

Thus, petrological parameters, till now conventionally utilized for coal evaluation, are reliable and can be utilized effectively in fossil fuels (CBM and oil/ gas) exploration with the main advantage that the study is carried out on original material, as it does not destroy the original nature and properties of organic matter during sample preparation as against the chemical treatment in other parameters.

There are sizeable reserves of coal and lignite in the country, which could host vast quantities of hydrocarbons (especially CBM). The available geological informations indicate, prima facie, that congenial conditions exist in Indian coalfields for the production of coal bed methane. As an alternative and clean source of energy CBM has become a national agenda in the present energy scenario and there is a need to expedite and accelerate the exploration and production efforts for CBM. A well-coordinated effort through integrated research and exploration activity is called for commercial recovery of CBM and other hydrocarbon resources from coals in the country. Therefore, in order to understand the interplay of coal rank (maturity) and maceral composition (facies), which are two extremely important parameters, it is imperative that:

- Coal petrographic techniques should be applied for assessing the hydrocarbon (CBM, syncrude, oil and gas) generating potential of invaluable fossil fuels.
- More emphasis should be given to generate CBM related petrological data (viz. $R_{o\ max}$ values, coal facies composition, permeability, etc.) on coals having good prospects for methane generation in order to establish CBM standards.
- Work on coals in reference to hydrocarbon exploration should be oriented to problem-based researches in collaboration with respective industries.
- To fulfill the demand for experts to evaluate country's invaluable energy resources, students should be encouraged to opt Coal Science as a career and efforts should be made to make this career choice more attractive.
- In order to have self-reliance in the field of hydrocarbon, the CBM in particular, coal scientists, hydrocarbon generating (oil/gas) and utilizing organizations in India should work in close co-operation and co-ordination.

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