Proc Indian natn Sci Acad **78** No. 3 September 2012 pp. 457-473

Status Report

Development of Palynology in Fossil Fuel Exploration in India with Emphasis on Recent Significant Contributions from Western-Offshore, Krishna-Godavari Basin and Frontier Areas

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A summarized account of developments in palynological studies and their application in fossil fuel exploration in various petroliferous basins of India is presented here. The high resolution biostratigraphic, palaeogeographic and palaeoenvironmental delineations, sequence biostratigraphy and source rock evaluation studies have greatly helped in developing geological models for exploration. Precise age determination through dinoflagellate cyst study and palynofacies modeling has proved extremely useful in delimiting potential facies for the exploration. Further, high impact fossil fuel exploration related palynological researches have been strengthened at Oil and Natural Gas Corporation Ltd. (ONGC) and Birbal Sahni Institute of Palaeobotany (BSIP) in past several years. The updated informations from Krishna-Godavari and Western Offshore basins are of much significance. A recent research from BSIP showing first record of Type I matured liptinite organic matter from Late Neoproterozoic sediments is of much value, since it has shown the prospects of hydrocarbon exploration in Neoproterozoic sediments of Rajasthan and other similar prospective basins in India. Recent findings of acritarchs and algae suggesting a Cryogenian to Ediacaran age for the pre-Tertiary Sequence of Ganga Basin, point towards an extension of Marwar Super Group sediments. Organic matter maturation studies indicate possibility of hydrocarbons in Ganga Basin. Potential areas in frontier basins have also been identified for extending such researches. A brief account of organic petrological studies performed on solid fossil fuel at BSIP, that can be utilized for source rock evaluation, has also been provided.

Key Words: Palynology; Hydrocarbon Exploration; Petroliferous Basins; Frontier Areas; Organic Petrology

1. Introduction

Palynology is the study of organic walled microfossils preserved in sedimentary rocks, covers a broad spectrum of palynofossils like spores-pollen, acritarchs, dinoflagellates, nannoplankton, diatoms, chitinozoans, scolecodonts, micro-algae, etc. recorded from the terrestrial, marine and various transitional environments. The principles of investigations, morphology and study techniques of various palynofossil groups are available in several publications (Tschudy & Scott, 1969; Venkatachala & Salujha, 1970; Traverse, 1988, 1994; Tyson, 1995; Wood & Gabriel, 1996; etc.). The subject now has vastly diversified and grown into a significant discipline due to its application in solving stratigraphic problems, particularly in fossil fuel exploration.

During last fifty years K.D. Malviya Institute of Petroleum Exploration (KDMIPE) of Oil and Natural Gas Corporation Ltd. (ONGC), Dehradun and Birbal Sahni Institute of Palaeobotany (BSIP), Lucknow have generated a lot of palynological data from various Indian sedimentary basins (Fig. 1). Regional laboratories of ONGC at Vadodara, Sibsagar (Assam), Jodhpur and Chennai; universities of Kolkata, Allahabad and Hyderabad; and Geological Survey of India have also worked in this area. While scientists at BSIP continued developing Precambrian-Cambrian, Gondwana, Cretaceous-Tertiary and Quaternary palynology pursuing morphology, palynostratigraphy, palaeoclimate and evolutionary studies, ONGC focused mainly on the applied aspects. The latter involved building biozonation schemes for dating stratigraphic sequences and correlation of oil Wells in various petroliferous basins.

As a significant development, hydrocarbon source rock evaluation studies have been initiated in late seventies and early eighties at KDMIPE by Venkatachala and his

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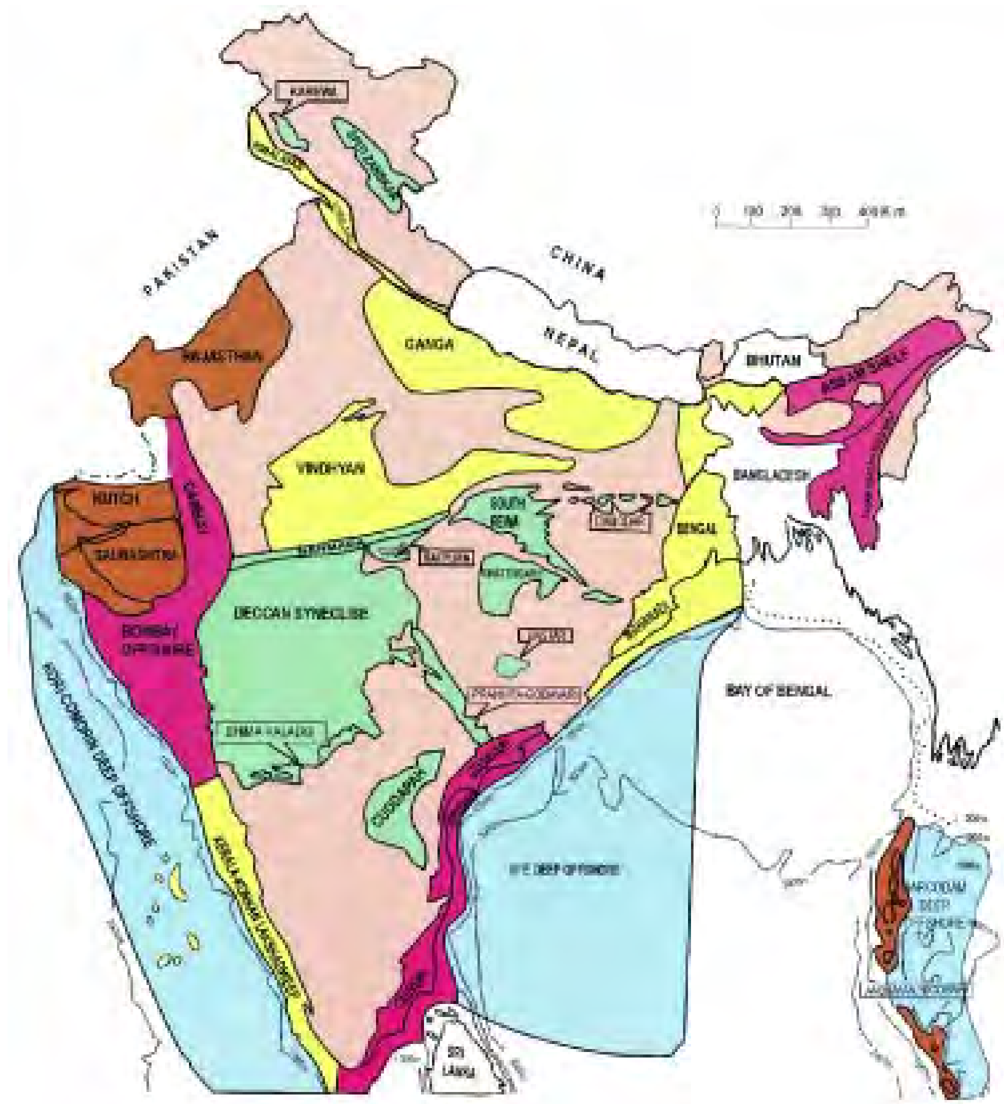

Fig. 1: Sedimentary basin map of India (source Mehrotra *et al*., 2002)

associates (Venkatachala, 1981a, 1981b, 1984). Further advancements continued for source rock evaluation studies integrated with time temperature index and subsidence history in various basins (Swamy & Kapoor, 1997; Swamy *et al*., 1994). These studies are now also being actively pursued at BSIP.

High resolution palynological biostratigraphy based on the studies of dinoflagellate cysts has developed in early eighties (Mehrotra & Sarjeant, 1984a, 1984b, 1984c, 1986, 1987, 1999) and has proved to be extremely useful for biostratigraphers particularly those working in hydrocarbon exploration research, owing to its immense biostratigraphic and palaeoceanographic significance. The studies on nannoplankton, the other important palynological group, have also been pursued at ONGC and BSIP.

Most prolific and useful palynological data from various petroliferous basins of India have been generated and published by Mehrotra and his associates during the last decade. Memoirs of Geological Society of India (Mehrotra *et al*., 2002, 2005, 2008c), Atlases on Mesozoic-Tertiary dinoflagellates cysts from Krishna-Godavari Basin (Mehrotra & Aswal, 2003; Mehrotra & Singh, 2003), and high impact palynological studies in Western Offshore and Krishna Godavari Basin (Mehrotra, 2011; Mehrotra *et al*., 2008a, 2010) are some of the most significant publications.

2. Development of High Impact Palynological Studies

Significant advancements, with regard to applied value of various palynofossil groups in fossil fuel exploration, have taken place during the last several years. The progressive developments of globally recognized bioevents for dinoflagellate cysts and calcareous nannoplankton with their precise stratigraphic ranges in context with high resolution biostratigraphy using last appearance datum (LAD) and first appearance datum (FAD) of stratigraphically valuable species has been applied. Integrated studies on different fossil groups having multifaceted applications in hydrocarbon exploration (Fig. 2) are as follows:

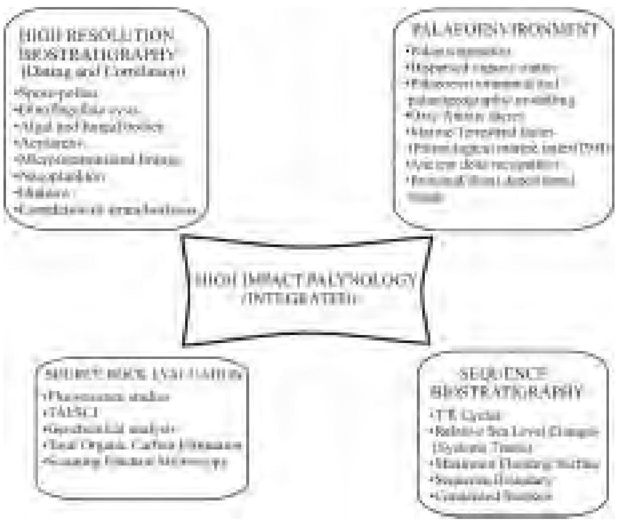

Fig. 2: Integrated approach of high impact palynology in hydrocarbon exploration

Dating of Sediments

Involves determination of precise age of the sediments using spores and pollen, dinoflagellate cysts, acritarchs, calcareous nannoplankton, diatoms and silicoflagellates.

High resolution Biostratigraphy for Finer Zonations

Dinoflagellate cysts, calcareous nannoplankton, silicoflagellates and diatoms are used individually and also in combination to achieve fine time slicing. A high stratigraphic resolution of around 1 million year, based on the dinoflagellate cysts has been achieved in Western Offshore Basin. Correlation of terrestrial and marine sediments has been done on the basis of spores-pollen (for terrestrial sediments) and dinoflagellate cysts, algae and nannoplankton (for marine sediments). Statistical analyses of spores-pollen versus dinoflagellate cyst ratios are used for deciphering various marine transgressive/regressive cycles and identify onlap-offlaps in sequence stratigraphy.

Palaeoenvironment and Palaeogeography

Involves integration of data from the different ecological groups and organic matter types to understand palaeoenvironment. Paleogeographic reconstruction has been done at very fine resolutions of 1 million year and provenance of sediments identified in Mumbai Offshore (Mehrotra *et al*., 2001) and other petroliferous basins.

3. Sequence Biostratigraphy

This is the frontier field of palynological research that has successfully been applied in geological modeling related to the hydrocarbon exploration. It involves identification of sequence boundaries, maximum flooding surfaces (MFS), high-stand systems tract (HST), low-stand systems tract (LST), transgressive systems tract (TST), shelf margin systems tract (SMST) and condensed sections. Application of high resolution sequence stratigraphy requires the ability to recognize key surfaces which record fluctuations in relative sea-level. Raju (2008) compared Cretaceous and Cenozoic sequences of India with global sea-level curves of Haq *et al*. (1987) and further explained sea-level changes in the various Mesoproterozoic to Holocene sediments (Raju, 2006, 2008).

4. Source Rock Evaluation

The main source materials for hydrocarbons are vegetal debris including phytoplankton, marine and terrestrial algae as well as lipid-rich land plant remains. Direct application of these organic matter for identifying hydrocarbon generation potential sequences lies in estimating their types, quantity and maturity (both by visual and spectral analysis) in the sedimentary rocks. There are a number of scales for measuring the degree of thermal alteration index (TAI values), primarily based on the palynofossil colours. The three principle types of organic matters i.e., sapropelic, sporopollenin and mixed assemblages show alteration in their morphological features due to rise in temperature during their burial. Rise in temperature is caused mainly by the overburden of rocks/strata, contact with shear zone or induced by igneous activities in nearby areas.

The colour changes in palynofossils help to estimate the maturity level and thus helps in hydrocarbon exploration. TAI 1 is ascribed to fresh material and an index value of 5 for the thoroughly metamorphosed. The mature main phase of liquid petroleum generation is at TAI range of 2.50 to 3.25. Light oil and gas are obtained by alteration of sapropelic and spore-pollen mixed types of facies at TAI of 3.00 to 3.50. Application of source rock palynological studies relates with the determination of organic matter types and maturation level (Table 1). Integrated study includes identification of source rock potential facies and its comparison with various geological and geochemical parameters for better understanding of source potential (Table 2).

Table 1: Organic matter facies types with dominant hydrocarbon potential (Swamy *et al*. 1994; Source: Mehrotra *et al*. 2002a)

	HUMIC (H)	H> 75% (PC)	
I	a. Humic – Wood (H - W)	Wood + BDT > Charcoal	Very good (gas)
	b. Humic – Charcoal (H - C)	Wood + BDT < Charcoal	Poor
II	SAPROPELIC (S)	S > 75% (PC)	Very good (oil)
	SAPROPELIC HUMIC (SH)	H > 50% (PC)	
III	a. Sapropelic-Humic – Wood (SH - W)	Wood + BDT > Charcoal	Good (gas)
	b. Sapropelic-Humic–Charcoal (SH - C)	Wood + BDT < Charcoal	Marginal (oil)
	HUMIC SAPROPELIC (HS)	H > 50% (PC)	
IV	a. Humic-Sapropelic–Wood (HS - W)	Wood + BDT > Charcoal	Good (oil)
	b. Humic -Sapropelic-Charcoal (HS - C)	Wood + BDT < Charcoal	Marginal (oil)

5. Status in Petroliferous Basins

A brief account of status of exploration palynological studies in commercially producing basins, namely Cambay, Western Offshore, Cauvery, Krishna-Godavari and Assam-Arakan is provided here, based mainly on the work of Mehrotra and his associates (Mehrotra, 2011; Mehrotra *et al*., 2001, 2002, 2005, 2008a, 2008c, 2010). Special attention is being given to the maximum producing Mumbai Offshore Basin, and the most prospective Krishna-Godavari Basin from where an updated account of high impact palynological studies has been published during the last five years.

Cambay Basin

The Cambay Basin is an intracratonic rift graben, developed in the northwestern part of the Indian peninsula. The basin in the subsurface graben has been divided into five blocks viz., Sanchor-Patan Block, Mehsana-Ahmedabad Block, Tarapur-Cambay Block, Jambusar-Broach Block and Narmada-Tapti Block.

Five dinoflagellate bioevents have been identified in the Palaeocene-Early Oligocene succession (Mehrotra *et al*., 1996). Further contributions (Mehrotra, 2011; Mehrotra *et al*., 2002) have proposed three dinoflagellate cyst biozones on the basis of these bioevents. The ascending order of biostratigraphy is based on – *Dapsilidinium assamicum* Assemblage Zone (Danian to Thanetian, 54 Ma), *Glaphyrocysta ordinata* Partial Range Zone (Ypersian, 54-49 Ma), and *Areosphaeridium diktyoplokus* Range Zone (Ypersian to Priabonian, 49-36 Ma). These dinoflagellate zones have also facilitated well correlation in the Gulf area. The resolution of dinoflagellate zones in the interval from Palaeocene to Lower Miocene in Cambay Basin varies from 5.8 to 13.2 Ma; spore-pollen zones show more or less similar resolution for the interval of Eocene to Lower Miocene (Mehrotra *et al*., 2008a).

Source Rock Palynology

Petroleum System— Cambay–Hazad (South Cambay); Cambay–Kadi/Kalol (North Cambay)

The petroleum systems identified in South and North Cambay Sub-basins are as follows:

Hydrocarbon bearing reservoir rocks in the South Cambay Basin are mainly in deltaic sandstones of Middle Eocene-Early Oligocene. Hydrocarbon generated in Cambay Shale is accumulated mainly in Hazad and Ardol members of Anklesvar Formation capped by the transgressive Telwa and Kanwa shales. In North Cambay Basin, most hydrocarbon-bearing reservoir rocks occur in Kalol and Kadi formations. The Tarapur Shale acted as the regional seal (Chandra *et al*., 2001). The upper part of the Olpad and Anklesvar formations in Gandhar, Nada, Olpad and middle part of the Tarapur Formation in Kalol and Nawagam areas showing dominant Sapropelic-Humic facies with TAI values of 2.50 to 2.75 have been proved mature hydrocarbon reserves. The Olpad and Cambay shale in Gulf of Cambay have rich Humic-Sapropelic facies showing TAI values of 2.50 to 2.75 to generate hydrocarbons (Mehrotra *et al*., 2002).

Mumbai Offshore Basin

It is a pericratonic basin located on the continental shelf of western India, proved for most prolific hydrocarbon reserves. The basin has been divided into six tectono-sedimentary blocks viz., Tapti-Daman Block, Diu Block, Panna Bassein Block, Mumbai High DCS Block, Ratnagiri Block and Shelf Margin Block on the basis of structural configuration and type of sediments. In some areas

Table 2: Parameters for evaluating maturation (source Mehrotra *et al*., 2002)

Colour of palyno-fossils	TAI (Staplin, 1969; Waples, 1985)	VRo % (Staplin, 1969; Waples, 1985)	Temp. at max. of peak S_2 (T MAX)	Spectral wavelength (nM)	Time temp. index (TTI)	Paleo temp °C	Hydrocarbon generation: Oil window	Hydrocarbon generation: Wet gas window	Hydrocarbon generation: Dry gas
Pale yellow-brownish	2.00	0.30	420	460		75	DRY GAS (EARLY CATAGENETIC)		
	2.10	0.34		475					
	2.20	0.38		550					
	2.25	0.40		575	<1	80	CONDENSATE FROM RESINITE		
Brownish yellow-brown	2.30	0.42	430						
	2.35	0.44							
	2.40	0.46							
	2.45	0.48		585			OIL WINDOW		
	2.50	0.50	435	590		95			
	2.55	0.55							
	2.60	0.60	440	600	10				
	2.65	0.65			15	130			
	2.70	0.70			20				
	2.75	0.77		610		145		WET GAS WINDOW	
	2.80	0.85	450		40	160			
	2.85	0.93			50				
	2.90	1.00			75	180			
	2.95	1.07							
	3.00	1.15	460	630	110	190			DRY GAS (THERMOGENIC)
Deep reddish brown-dark brown	3.05	1.19							
	3.10	1.22							
	3.15	1.26							
	3.20	1.30	465						
	3.25	1.33			180				
	3.30	1.36	205						
	3.35	1.39							
	3.40	1.42	470						
	3.45	1.46							
	3.50	1.50	480	655	300	215			
	3.55	1.62							
Brown black-black	3.60	1.75			500				
	3.65	1.87							
	3.70	2.00			900	235			
	3.75	2.25		670					
	3.80	2.50	500		2700	260			
	3.85	2.75							
	3.90	3.00			6000				
	3.95	3.25							
	4.00	3.50	500+	700	12000	290			
	4.05	4.00			23000				
	4.10	4.50			42000				
Black	4.15	5.00			85000				

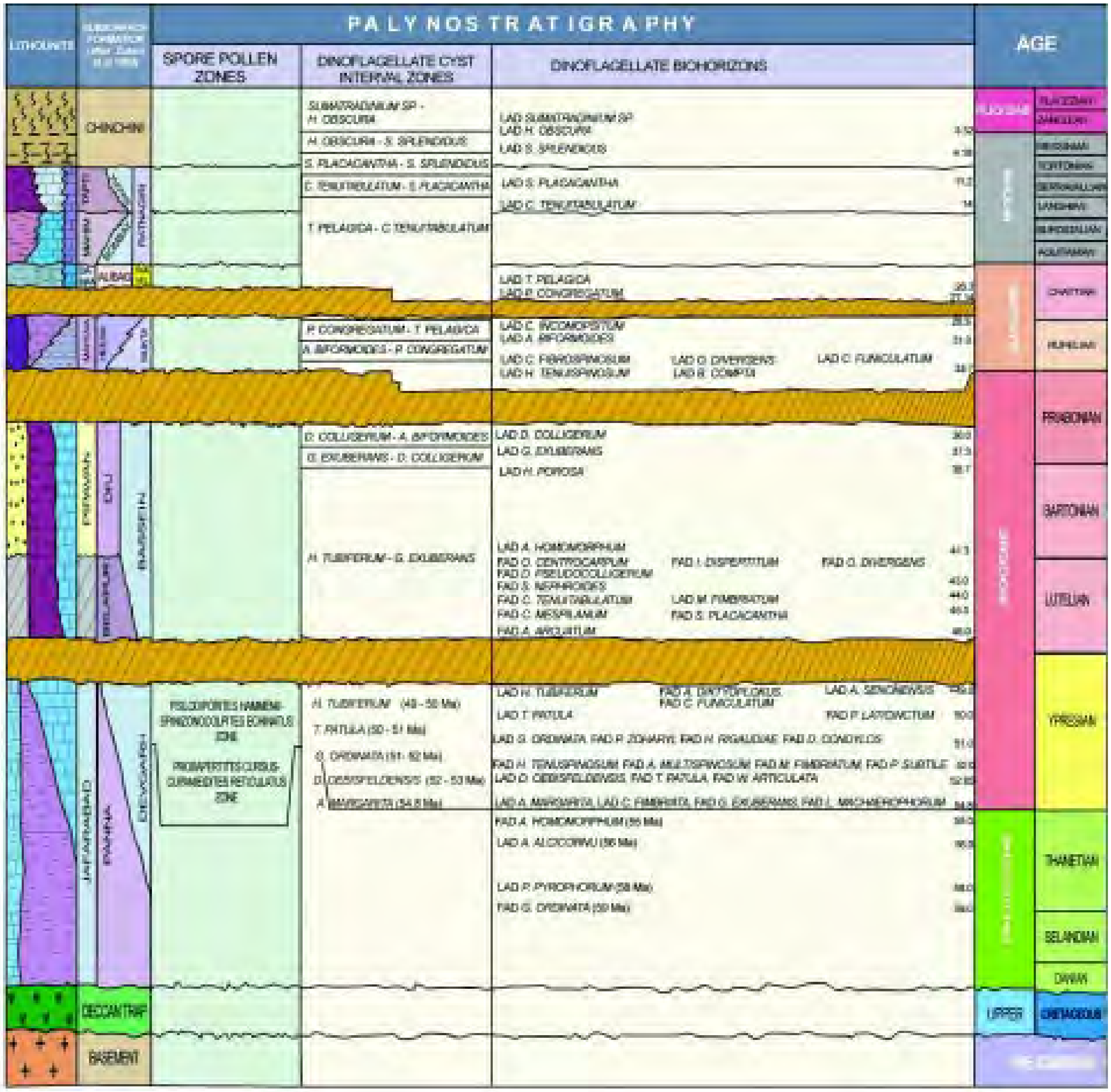

Fig. 3: Generalized lithostratigraphy and palynostratigraphy of Mumbai Offshore Basin (source Mehrotra *et al*., 2010)

Archaean rocks occur below the trap. Overlying the Deccan Trap unconformably, a thick succession of Palaeocene-Miocene sediments is forming one of the major known oil pool reserves (Mehrotra *et al*., 2002, 2008a). Mehrotra *et al*. (2002) gave an account of the stratigraphy and palynology of the basin and its applicability for hydrocarbon exploration. An updated account of high resolution palynostratigraphy, source rock evaluation, palaeoenvironment, palaeogeography and sequence biostratigraphy have been delineated in the Mumbai Offshore Basin (Mehrotra *et al*., 2010). Summarised accounts of these analyses are mentioned below:

The high resolution Cenozoic palynostratigraphy of Mumbai Offshore Basin is presented in Figure 3. A resolution of one million year is achieved for the Panna Formation (49-54.8 Ma), the main source rock of the Mumbai Offshore Basin. Forty-three dinoflagellate biohorizons have been identified in the Cenozoic sequence, facilitating a high resolution correlation of oil-bearing horizons.

The Panna Formation, being the oldest deposits above the Deccan Trap witnessed mainly marginal marine to shallow part of the inner neritic depositional conditions throughout the Early Eocene. Relatively deeper marine conditions prevailed during the deposition of the Bassein Formation. Marginal marine to shallow inner neritic conditions occurred in some areas situated west of Bassein, which continued till the deposition of entire Panna Formation (Kapoor & Swamy, 2007). On the other hand, fluvial depositional setup persisted at the east of Mumbai High, while at southeast an inner neritic depositional environment existed in upper part of the Panna Formation (Fig. 4).

A series of palaeogeographic maps at the interval of one million year have been reconstructed in the Panna Formation (top of Thanetian to Ypersian, 49-54.8 Ma), allowing better understanding and fine tuning of geological models for hydrocarbon exploration (Mehrotra, 2011, Mehrotra *et al*., 2001). Based on the integrated palynological data transgressive systems tract, maximum flooding surface and high stand systems tract have been identified with reference to seismic markers below and above the Panna Formation (Fig. 5), corresponding to the top of Cretaceous and Lower Eocene (Ypersian).

Source Rock Palynology

Petroleum System— Panna–Bombay.

The organic matter maturation in the southeast area of Mumbai High showing TAI values of 2.50 to 2.75 indicate maturity of sediments as a hydrocarbons source. The sands with good porosity and permeability in the up-dip direction may prove to be the targets for exploration (Fig. 6).

Krishna-Godavari Basin

The Krishna-Godavari Basin is a pericratonic basin, developed along the eastern coast of Indian peninsula. A detailed account of the dinoflagellate cyst based integrated subsurface biostratigraphy of the basin is thoroughly illustrated (Mehrotra, 2011; Mehrotra *et al*., 2002, 2008a, 2010). These works are based primarily on Mesozoic (Mehrotra & Aswal, 2003) and Cenozoic dinoflagellate cysts (Mehrotra & Singh, 2003). Mesozoic dinoflagellate data based on the study of cores and cuttings of nine selected Wells is tied up with foraminiferal zones (Raju & Ramesh, 1998) and the Cenozoic dinoflagellate zones have been tied up with foraminiferal biostratigraphy (Raju, 1995) accompanied with spore-pollen assemblage zones (Rawat *et al*., 1991) from the East-Coast of India. Eighty-two dinoflagellate biohorizons have been identified in the subsurface in the Mesozoic-Tertiary of K-G Basin with a stratigraphic resolution of 1 Ma at most of the stratigraphic levels (refer Mehrotra, 2011).

Source Rock Palynology

Petroleum Systems— Krishna/Golapalli-Kanukoollu (West Godavari); Palakollu-Pasarlapudi (East Bombay); Vadaparru-Ravva (Offshore).

The Early Cretaceous sequence in Endamuru and Kommugudem areas has been identified with good source potential on the basis of dominant Humic-Sapropelic-Wood facies, rich organic matter and matured sequence (TAI value 2.50). The Late Cretaceous sediments in Razole and Amalapuram areas have been rated as marginal to good source potential. The Palaeocene sequences in Bhimanapalli constituted mainly of Sapropelic facies with TAI value 2.75 have considered good source potential to generate hydrocarbons. The potential source rock facies in Wells KMG-MDP-DKR-END have been plotted on the basis of organic matter richness and maturity (Fig. 7). Good source potential facies for oil and gas is recognized in Wells KMG-A and END-A, and moderate potentiality in Well MDP-A.

Cauvery Basin

This is a pericratonic basin situated in the southeastern part of Peninsular India between Pondicherry in the north and Tuticorn in the south. It also extends offshore into Bay of Bengal, Palk Strait and Gulf of Mannar. Sediments ranging in age from Upper Jurassic to Pliocene are exposed near the western margin of the basin, whereas eastern parts are covered by the alluvium. The exploratory drilling by ONGC began in the sixties, revealing presence of thick Cretaceous and Tertiary sedimentary successions. The Cauvery Basin has been further divided into subbasins viz., Ariyalur-Pondicherry, Tranquebar-Tanjore, Nagapattanam, Ramnad-Palk Bay, and Gulf of Mannar.

Mehrotra and Sarjeant [1984a, 1984b, 1984c, 1986) illustrated morphological details of dinoflagellate cysts recorded from the shallow Well Periyavadavadi-1, which are: *Hystrichodinium pulchrum, Fromea amphora, Muderongia mcwhaei, M. tetracantha, Wallodinium anglicum, Tanyosphaeridium isocalamum, Dingodinium cerviculum, Batiacasphaera* cf *macrogranulata, Polygonifera eisenackii* and *Imbatodinium fractum*. Based on dinoflagellate cysts and spores-pollen data, a Valanginian to Aptian age for the strata occurring between 75 and 155 m depth is suggested (Rawat *et al*., 1991). The resolution of dinoflagellate assemblages for the interval from Neocomian to Lower Eocene varies from 5.8 to 10.2 Ma. The spore-pollen zones occur in interval from Turonian to Miocene is varied between 3.3 to 20.8 Ma resolutions.

Fourteen palynozones are identified in the Upper Jurassic Lower Cretaceous and Palaeocene-Miocene subsurface sediments (Venkatachala & Sharma, 1974). The

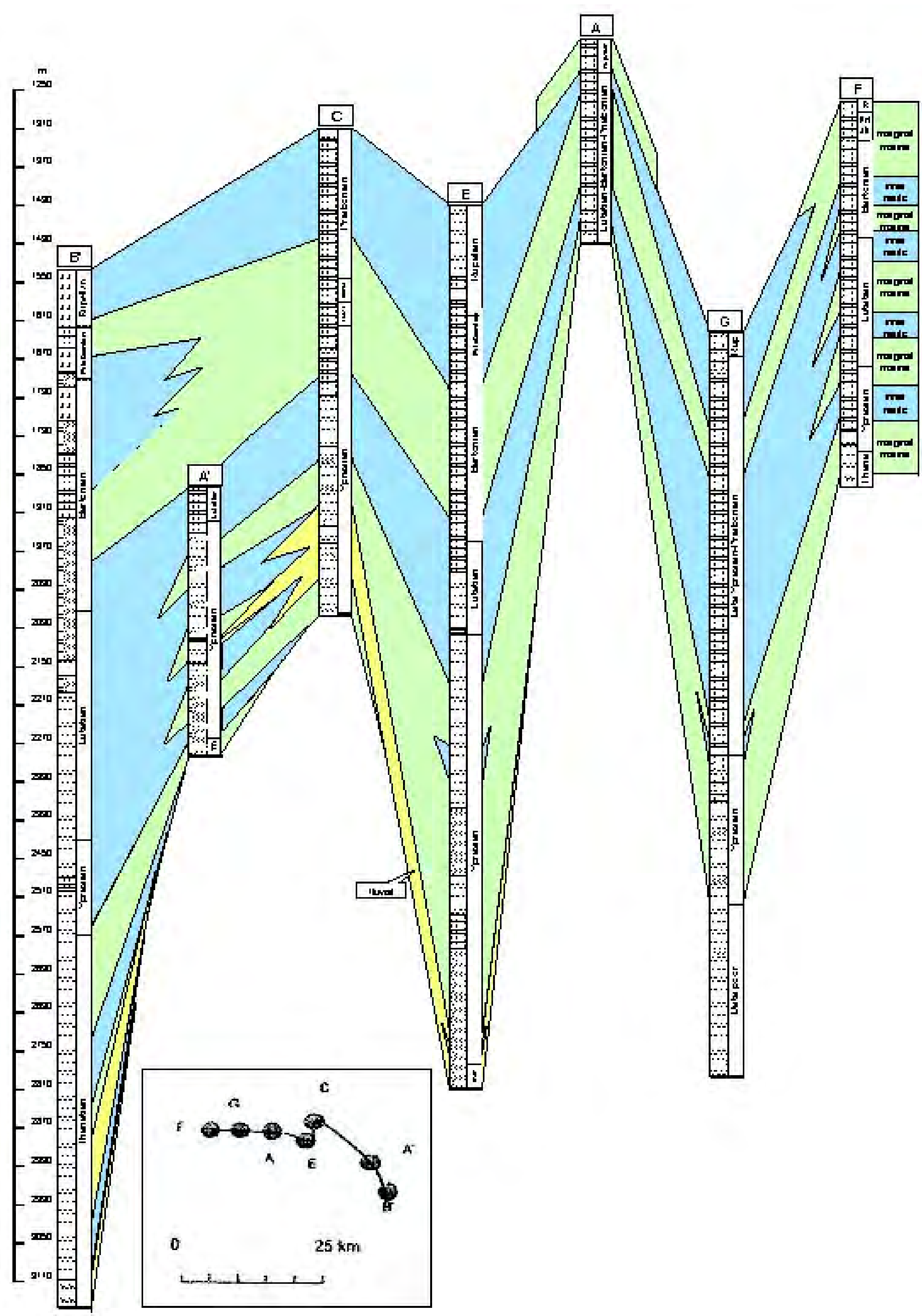

Fig. 4: Depositional environments across the studied wells in Mumbai Offshore (source Mehrotra *et al*., 2010)

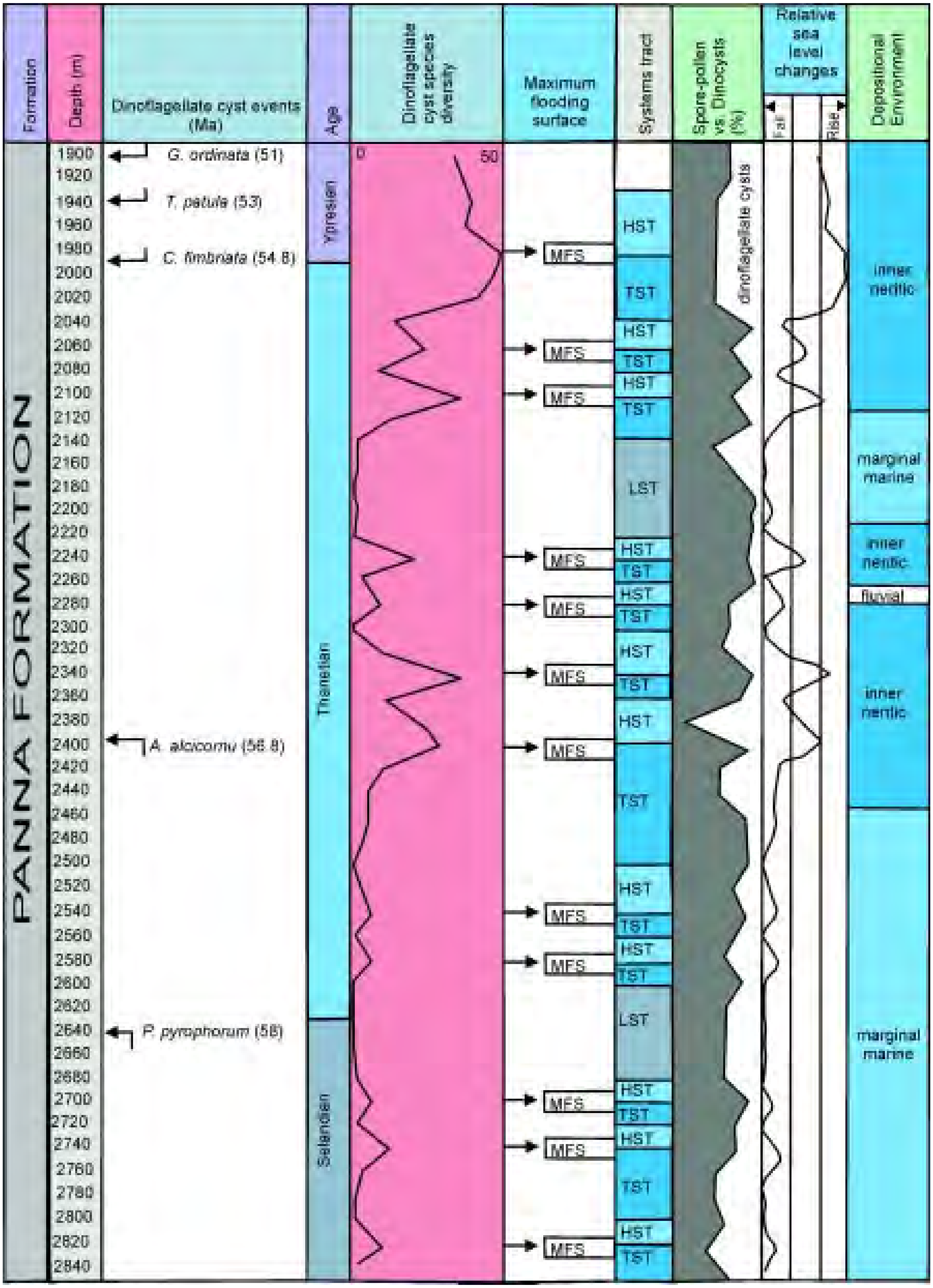

Fig. 5: **Dinoflagellate events, mfs., systems tract, depositional environment and relative sea level changes in well UB (updated after Mehrotra *et al.*, 2002; source Mehrotra *et al.*, 2010)**

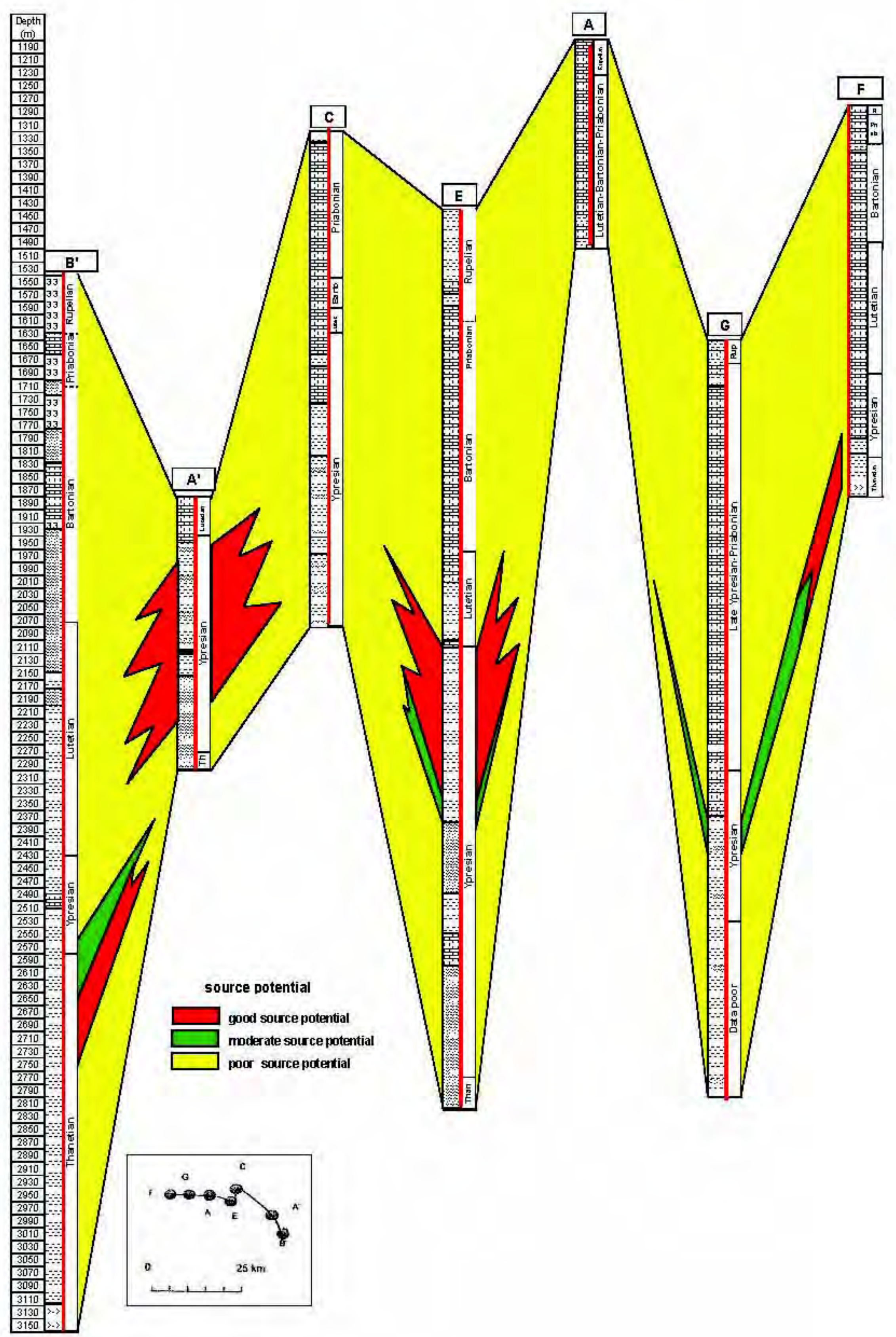

Fig. 6: Section showing source rock potential facies in wells drilled in Mumbai Offshore (source Mehrotra et al., 2010)

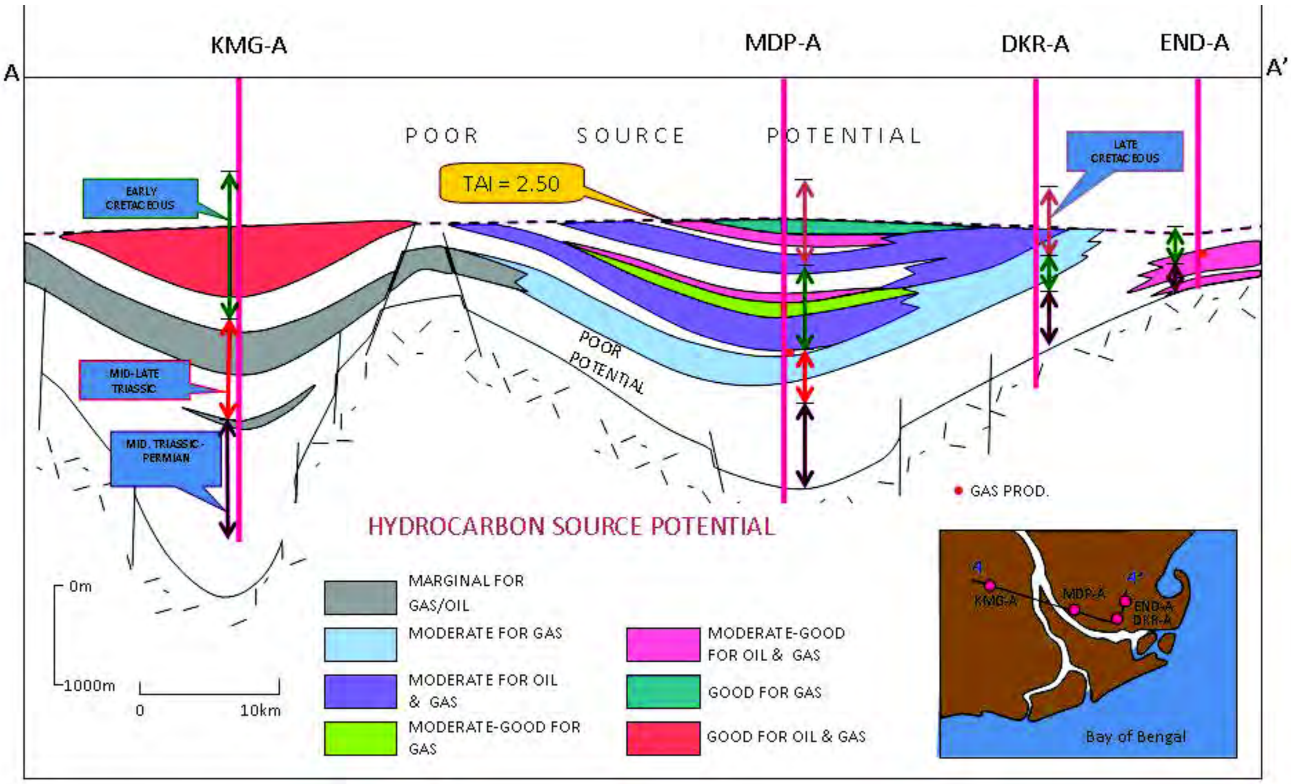

Fig. 7: Section along A–A' showing source rock potential facies in K-G Basin (source Mehrotra *et al*., 2010)

ascending order of palynozones are: *Callialasporites segmentatus* Zone (Late Jurassic: Tithonian); *Microcachryidites antarcticus* Zone (Neocomian); *Coptospora cauveriana* Zone (Aptian-Early Albian); *Rouseisporites reticulatus* Zone (Late Albian to Early Cenomanian); *Constantinisporis jacquei* Zone (Early Santonian); *Cretoriporites cauveriensis* Zone (Late Senonian); *Scollardia conferta* Zone (Maastrichtian); *Proxapertites hammenii* Zone (Palaeocene); *Psilodiporites hammenii* Zone (Lower Eocene); *Anacolosidites trilobatus* Zone (Middle Eocene); *Margocolporites sahnii* Zone (Upper Eocene); *Margocolporites cauveriensis* Zone (Oligocene); *Lacrimapollis pilosus* Zone (Early Miocene); *Tricollareporites echinatus* Zone (Middle to Late Miocene).

Source Rock Palynology

Petroleum System— Andimadam-Bhuvanagiri (Ariyalur-Pondicherry); Andimadam-Nannilam (Tranquebar and Ramnad); Andimadam-Neravi (Nagapatnam).

The Cretaceous and Palaeocene sequences at the Ramnad–Palk Bay Depression and Ariyalur-Pondicherry Depression are Sapropelic facies with adequate maturity (TAI values 2.50-3.00). These sequences have been rated as good hydrocarbon source potential. The Sattapadi Shale has dominantly Sapropelic-Humic facies (TAI value 2.75), while Adiyakkamangalam and Tiruvarur areas exhibit moderate to good source potential to generate gas.

Assam-Arakan Basin

The Assam-Arakan Basin includes Assam Plains, Cachar, Meghalaya, Nagaland, Mizoram, Manipur, Tripura and parts of Arunachal Pradesh. It also extends into Myanmar and Bangladesh. Tectonically, the Assam-Arakan Basin is subdivided into seven blocks– (i) Shillong and Mikir Massifs, (ii) Eastern Himalayan Frontal Fold Belt, (iii) Mishmi Hills Platform areas of Upper Assam, (iv) Dhansiri Valley and South Shillong Front, (v) Schuppen Belt, (vi) Fold Belt comprising Patkai and Kohima Synclinoria, Tripura-Cachar-Mizo folds, and (vii) Eastern zone of Nagaland-Manipur including Ophiolite belt (Pandey & Dave, 1998). Stratigraphy and palynology of various blocks, defined on the basis of spores-pollen and dinoflagellate studies (Mehrotra *et al*., 2002, 2008a), have proved useful in dating, biozonation and correlation of Late Cretaceous to Cenozoic surface and subsurface sediments in Upper Assam, South Shillong and Tripura-Cachar blocks.

High resolution dinoflagellate and spore-pollen data has been generated and applied for establishing biozonation and correlation in hydrocarbon exploration. In South Shillong Plateaus dinoflagellate cyst zones are recognized in the interval from Campanian to Oligocene with resolution between 3.3 to 17.8 Ma. The spores-pollen zones are also recognized with similar resolution in Campanian to Pliocene sediments of Upper Assam Shelf. Comparatively a better resolution (1-12.2 Ma) is achieved through dinoflagellates cysts in the Maastrichtian to Oligocene deposits. The spores/pollen zones are also recognized in Maastrichtian to Pliocene sediments with similar resolution. In Schuppen and Tripura-Cachar Fold Belt the dinoflagellate cysts are rare and restricted to the Oligocene sediments only. On the other hand, spores-pollen zones are recognized with poor resolution in the Paleocene to Pliocene and Pleistocene sediments.

Source Rock Palynology

Petroleum Systems— Kopili; Barail-Tipam (Upper Assam).

The Kopili Formation containing Sapropelic-Humic organic matter facies with the maturation value 2.75 in the Mariani area has been considered a good source rock. Here, the shale sequences of Sylhet Limestone Formation consisting mainly of Sapropelic-Humic (Wood) facies has been considered matured facies with good source potential to generate hydrocarbons.

An updated account of important dinoflagellate cyst biochronohorizons from the Cambay, Mumbai Offshore, Cauvery, Krishna-Godavari and Assam-Arakan basins are tied with foraminiferal biochronohorizons of Indian stages and correlated with standard chronostratigraphy based on the standard planktic foraminiferal zones (Hardenbol *et al*., 1998; Mehrotra *et al*., 2008a).

6. Recent Significant Results from the Frontier Areas

With the declining production from commercially producing basins, the thrust is now on Frontier areas. The depositional conditions and Type I-matured liptinite organic matter in the Gotan Limestone (Late Neoproterozoic) in Rajasthan Basin is of much significance in hydrocarbon exploration (Mehrotra *et al*., 2008b). This shows good prospects for hydrocarbon exploration in the Neoproterozoic sediments over other contemporaneous basins of India. The Sapropelic type of organic matter and biota consisting mainly of acritarchs (Leiosphaeroids), algal filaments and amorphous algal thallus (Fig. 8), displaying TAI values of 2.25 to 2.45, suggest the onset of maturation. The evaluated sediments are considered as of moderate source potential. However, sediments occurring along the down dip direction in the vicinity of the area may have hydrocarbon source pool with enriched organic matter with higher TAI values. Extensive and integrated geoscientific studies on the exposed Neoproterozoic sediments are essential in the region to determine the thickness and geographic extent of source rocks. To substantiate above, subsurface mapping of potential source rock through generation of Well data should necessarily be considered.

A joint work of BSIP and ONGC in the Ganga Basin defining "Noteworthy occurrences of biological remains from the pre-Tertiaries successions and their relevance to biostratigraphy" has been explained in detail (Mehrotra *et al*., 2011). The results suggest a diversified biological assemblage of both macro- and microfossils consisting of acritarchs, algal colonies, filaments and multi-cellular thalloids structures (Cyanophyceae, Chlorophyceae and Rhodophyceae), vase shaped microfossils (=Chitinozoa) and insect larvae: *Helaeomyia petrolei* (=*Psilopa*, Coquillet, colonial alga *Pediatrum* and other thalloid algae displaying their maturity values within 2.5 to 3.5. Occurrence of oil fly larvae indicates possibility of hydrocarbons in Ganga Basin. The recovered assemblage closely resembles with the biota recorded from Cryogenian to Ediacaran sediments, especially from China and Australia. The biotic assemblage is more akin to the organic walled microfossils known from the Neoproterozoic sediments of Marwar Supergroup of Bikaner-Nagaur Basin, already known for containing liquid hydrocarbons. The similarity of recovered biota suggests that the sediments of Marwar Supergroup may have extended up to the Ganga Basin.

7. Concluding Remarks

The available palynological information indicates that it is an extremely significant parameter for generating new geological models and refining hydrocarbon (oil and gas) exploration researches. It is recommended that the future studies should focus on broadening the existing databases on commercially proven basins. Thus, high impact palynological data may improve the scope of finding hydrocarbons in Frontier and Deep water basins. Besides, delineating the hydrocarbon prospects, the palynology has also proved useful in coal and lignite exploration. In near future it may also prove equally useful in shale gas and coal bed methane exploration.

8. Organic Petrology in Source Rock Evaluation

Organic Petrology is a science dealing with the study of microscopically recognizable organo-petrographic entities (macerals) in coals and lignites, formed during the coalification, i.e. transformation of vegetal matter into coal. Petrological studies are carried out by utilizing reflectance and fluorescence microscopic techniques to obtain informations on type of organic matter and degree of maturation (refer Singh & Singh, 2008a). The knowledge

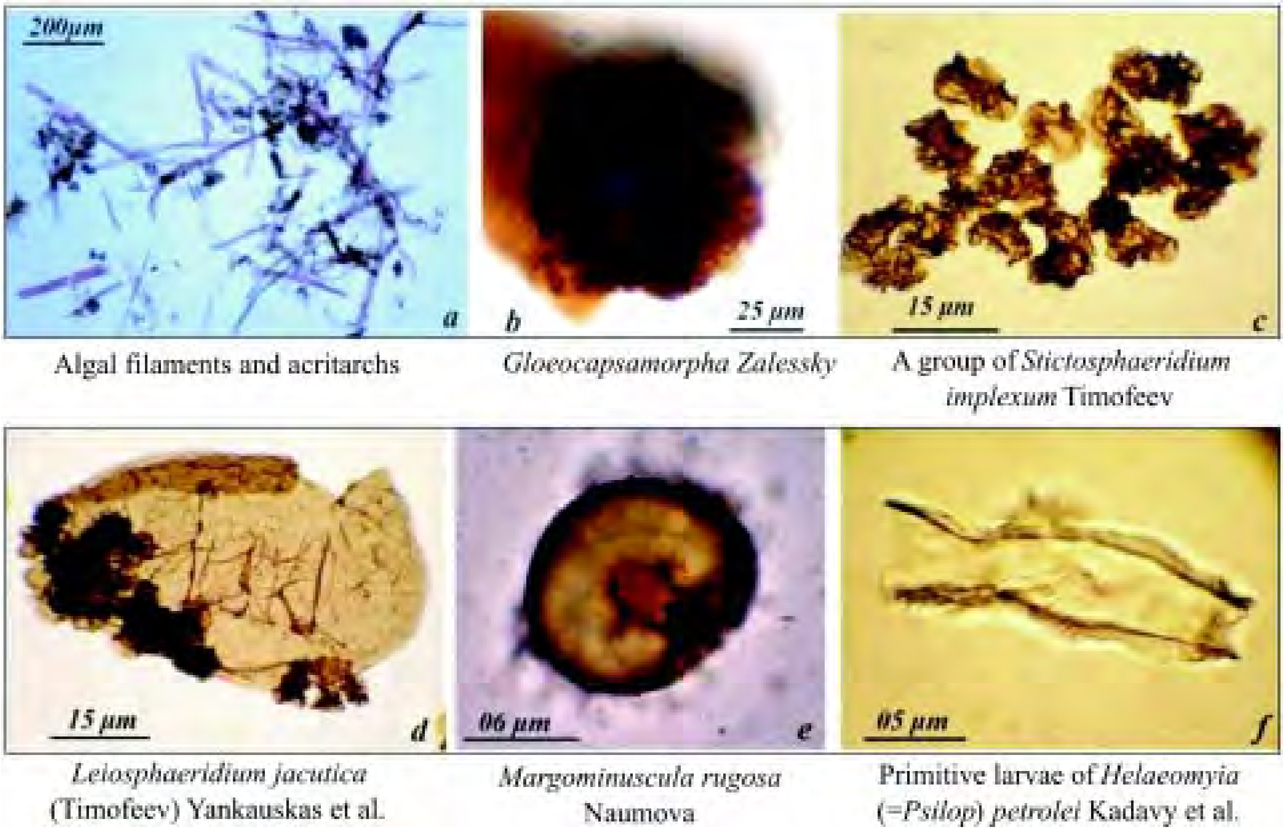

Fig. 8: Microfossils viz., acritarchs, cyanobacterial and larvae of insect isolated in macerated residues from the chert associated in Gotan Limestone Formation, Bilara Group, Marwar Basin

that petroleum-like substances also generate in coal at similar maturity level as in petroleum source rocks, led to the development of petrology as a new branch of science for source rock evaluation. Since, both the coal and petroleum geneses are governed by diagenetic and catagenetic (time and pressure induced) processes (Stach *et al*., 1982; Tissot & Welte, 1984; Teichmüller, 1986; Taylor, *et al*., 1998). Such study can also be applied for coals/lignites to evaluate petroleum source rocks. Each stage of petroleum generation can easily be matched with the maturity of coal, because maturation level of organic matter defines generation and destruction bearing of oil and gas.

The reflectance and fluorescence microscopy form a good parameter for determining type of organic matter/ kerogen and oil/gas generating potential of a source rock. The reflectance parameter has been most widely applied for maturation determination. Since oil and gas proneness, besides maturation, largely depends on organic facies, i.e. type and amount of organic matter in sediments, the scope of petrology has widened especially when the fluorescence microscopy has facilitated easy recognition of oil precursors (liptinites and perhydrous vitrinite). In order to evaluate the potential of a source rock for hydrocarbon generation, the main requirements are:

Sufficient total organic carbon (TOC) content,

Correct organic matter/ kerogen typification, and

Essential maturation level.

Organic petrological studies can reliably be applied for the last two parameters for the evaluation of source rocks potential. The advantage of utilizing coal petrological methods or polished block approach lies in the fact that it does not destroy the original structure.

Organic Matter/ Kerogen Typification

Carbonized organic matter (= kerogen) in sediment can be identified and quantified more accurately using microscopic techniques of coal petrology (Reflectance– using 546 nm light and Fluorescence– using ultra violet/blue light excitation, 340-390 nm). In coal petrological analyses macerals are categorized in three main groups, viz. vitrinite (huminite in lignite), liptinite and inertinite on the basis of their genesis and chemical properties. Vitrinite group macerals are rich in oxygen content, liptinites are rich in hydrogen content, and inertinites are rich in carbon content (Stach *et al*., 1982; Taylor *et al*., 1998). The macerals of vitrinite group having high O/C and low H/C ratio have capacity to generate gas, and those of the liptinite group having high H/C and low O/C ratio have capacity to generate oil. The evolution/ carbonization paths of coal macerals are comparable with the evolution path of kerogens. The kerogen type I and alginite follow the same evolution path, kerogen type II and liptinite follow the another but same path, and kerogen type III and vitrinite follow the intermediate evolutionary path (Van Krevelen, 1961).

Thus, the three maceral groups in coals/lignites are correlatable to kerogen types in petroleum source rocks. The liptinites tend to fluoresce when exposed to blue/UV light. Alginite (dinoflagellate, acritarchs, etc.) correlatable to kerogen type I, and cutinite (cuticles), suberinite (suberin), sporinite (pollen-spores), resinite (resins/waxes), exsudatinite (exsudates), etc. correlatable to type II, having oil generating potential, fluoresce on exposure to UV or blue light and hence can be easily identified and differentiated with other non-fluorescing macerals– vitrinite/huminite and inertinite correlatable to kerogen types III and IV respectively (Fig. 9). Identification and the predominance of kerogen types I, II, III and IV, indicates the oil or gas generation potential of source rocks. Morphological features further enable to identify the type of source material (equatic/terrestrial). Good prospects of hydrocarbon generation in Indian coals/lignites (of vitrinite/ huminite reflectance: 0.30-0.85%) are evident as assessed on the basis of macerals/ kerogen types (Singh & Singh, 2008b), as per the following results:

Permian Gondwana coals: Kerogen II– predominance of liptinites in particular the sporinite, and perhydrous vitrinite + bituminite (humosapropelinite) and collodetrinite (sapropelinite II); Kerogen I & II– dominance of liptodetrinite.

Tertiary coals: Kerogen II– extremely high amount of perhydrous vitrinite; Kerogen I & II– very high amount of liptodetrinite; Kerogen II– fair representation of resinite.

Tertiary lignites: Kerogen II– abundance of resinite; Kerogen I & II– very high proportion of liptodetrinite; Kerogen I– presence of alginite (high in Kutch Basin); fair representation of perhydrous huminite.

The organic matter in sediments having potential to generate hydrocarbon must reach a certain level of maturation in order to generate oil/gas.

Maturation Level or Degree of Carbonification

The correct maturity determination of carbonized matter in sediment is extremely essential to know the oil/gas prospects, as it directly provides the inference for the presence or absence of proper source rock. With the fact that organic matter in coals/lignites and source rocks undergo diagenetic and catagenetic alterations in similar way (Stach *et al*., 1982, Tissot & Welte, 1984; Taylor *et al*., 1998) releases gas and oil. Their maturity estimation, on the basis of petrographic microscopic techniques for solid fossil fuels (R_r%, λ max, R/G quotient and alteration),

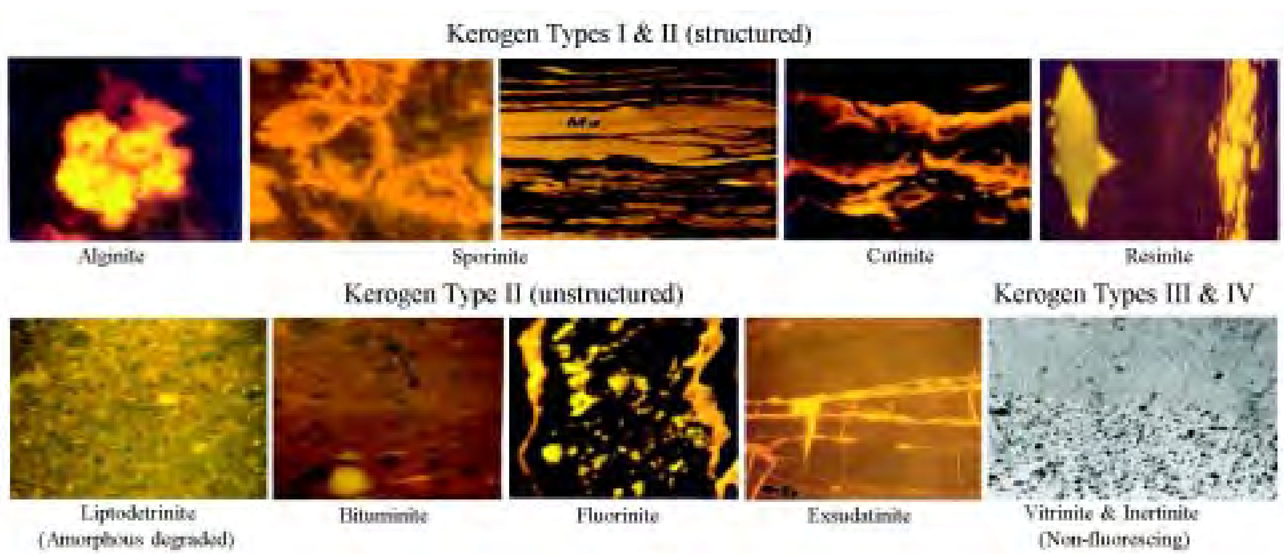

Fig. 9: Liptinite/Kerogen types (structured and unstructured) in Indian coals/lignites

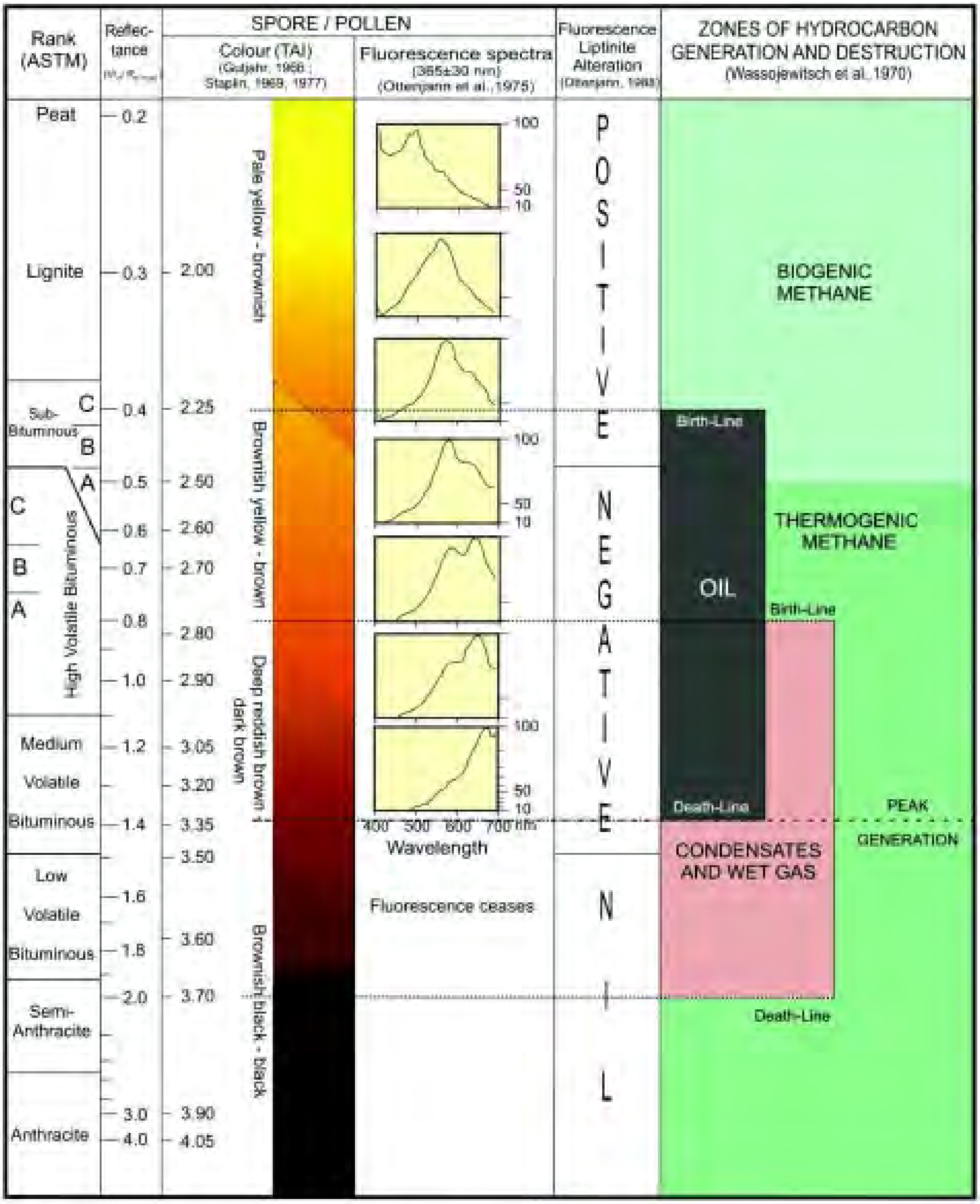

Fig. 10: Optical parameters of organic facies and their relationship with hydrocarbon generation (a modified presentation; Singh and Singh, 2008a)

provide the most suitably way to know the maturation level of source rocks. In hydrocarbon source rocks, catagenetic stage (vitrinite reflectance values: 0.5-1.4%) is the main stage of hydrocarbon generation, where insoluble kerogen formed earlier during diagenetic stage gets converted into oil. The higher reflectance values (>1.4-2.0%) however, indicate the formation of condensates and wet gases.

The alteration behavior, i.e. the distinct and rapid change in the intensity of light reflected from liptinite macerals when irradiated with blue or UV light (short wavelength 360-390 nm) provides another parameter (Ottenjann *et al*., 1982). The alteration behaviors of macerals are in fact related to chemical changes and provide information on maturity of organic matter. The positive alteration (increase in the intensity of reflected light with increase in exposure time), and no alteration (no change in the intensity), respectively indicate immature/ under and over maturation of organic matter for the generation of oil. The negative alteration (decrease in the intensity of light with increasing exposure time) however, suggests correct maturation level for the generation of oil. The correlation charts of various maturation parameters (Fig. 10) show that oil generation begins at reflectance (R_r) of 0.4-0.6% and ceases at 1.4%, which are respectively termed as 'birth-line' and 'death-line' for oil. The maturation parameters are more reliable in defining the death-line accurately as oil generation completely stops at the maturation level of R_r 1.4%, and organic matter do not show fluorescence and alteration properties.

9. Acknowledgements

The authors are thankful to Geological Society of India for permission to reproduce several figures and tables from authors' (NCM) previous publications as referred in the text. Technical assistance provided by Mr. Madhukar Arvind of BSIP in the preparation of manuscript is thankfully acknowledged.

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