Palynofacies, maturation and source rock potential in Krishna-Godavari Basin, India

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Studies on palynofacies and thermal alteration index (TAI) were carried out in the subsurface sequence encountered in nine drilled locations of Krishna-Godavari Basin for source rock evaluation of the Late Cretaceous-Tertiary sediments. The dispersed organic matter, as a whole, is considered mostly land-derived. The composition of the organic matter is dominantly mixed type. A higher degree of sapropelization is recorded in Late Cretaceous-Palaeogene sequence as compared to Neogene. The organic maturation as suggested by TAI values indicates that the maturation level of 'Oil Window' (TAI = 2.5) reached in the Late Palaeocene (53-60 Ma) in A, B, F and E locations. Younger levels of maturation are noted as Middle Eocene (43-49 Ma) in C and D and Early Miocene (13-16 Ma) in G, H and I locations. It is further observed that the occurrence of youngest level of 'Oil Window' maturation lies between 80°-100° C, which appears the effective cooking temperature for the kerogen in the basin. Based on palynofacies development and TAI values, the sediments within the mature zone are considered to possess good source rock quality to generate mixed type of hydrocarbons in the maturation range of TAI 2.5 to 3.0.

Key-words—Biodiagenesis, Palynofacies, Krishna-Godavari Basin, Late Cretaceous/Tertiary (India).

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सारांश

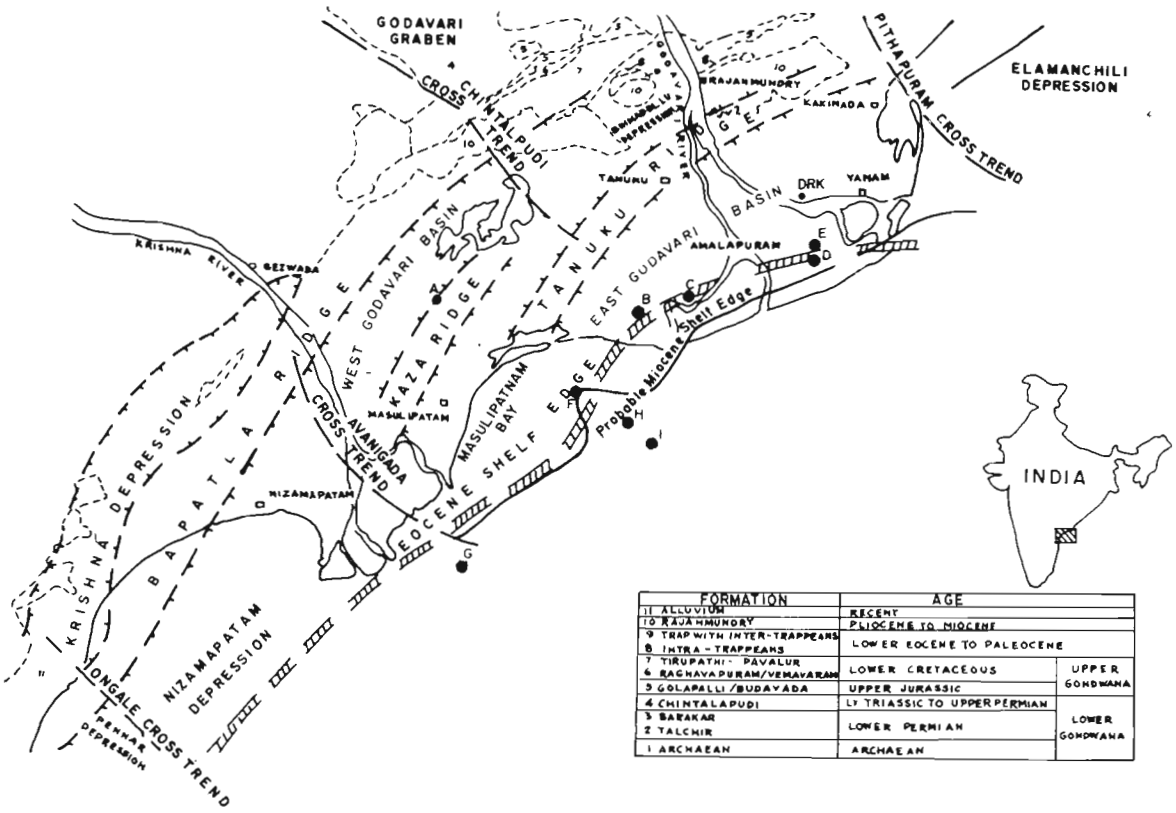
भारत में कृष्णा-गोदावरी द्रोणी में परागाणु-संलक्षणी, परिपक्व एवं सम्भाव्य स्रोत चट्टान

एँम० एँस० रावत एवं सी० एँम० बेरी

अर्नतिम क्रीटेशी अवसादों की स्रोत चट्टान का मूल्याँकन करने के लिए कृष्णा-गोदावरी द्रोणी में नौ विभिन्न स्थानों पर की गई ड्रिलों से उपलब्ध उपसतही अनुक्रम का परागाणविक-संलक्षणी एवं तापीय परिवर्तन सूचक अध्ययन किया गया। कार्बनिक पदार्थ की संरचना मिश्रित प्रकार की है। नवनूतन की अपेक्षाकृत अर्नतिम क्रीटेशी-पुरानूतन कालीन अनुक्रम में उच्चतर डिग्री को सैप्रोपेलाइजन अभिलिखित किया गया है। तापीय परिवर्तन सूचक मानकों द्वारा प्रस्तावित कार्बनिक परिपक्वता से प्रदर्शित होता है कि 'ऑयल विन्डो' की परिपक्वता अर्नतिम पुरानूतन कल्प में ए०, बी०, एँफ० एवं ई० नामक स्थानों पर पूर्ण हो गई थी। जी०, एँच० एवं आई० स्थानों पर प्रारम्भिक मध्यनूतन में तथा सी० एवं डी० में मध्य-मध्यनूतन कल्प में कम परिपक्वता स्तर प्रेक्षित किया गया है। यह भी प्रेक्षित किया गया है कि 'ऑयल विन्डो' का सबसे कम परिपक्वता स्तर 80°×100° सेन्टीग्रेड के बीच विद्यमान है और यही तापक्रम द्रोणी में केरोजन को पक्व करने में प्रभावकारी लगता है। परिपक्व मंडल के अन्दर के अवसादों में 2.5 से 3.0 के मध्य तापीय परिवर्तन सूचक के परिपक्वता-विस्तार में मिश्रित प्रकार के हाइड्रोकार्बनों का निर्माण करने के लिए स्रोत चट्टानी गुणता विद्यमान है।

THE paper embodies the results of source rock palynological study of Late Cretaceous-Neogene sedimentary sequence encountered in the subsurface of onshore and offshore areas of Krishna-Godavari Basin. Drilling in this basin was started in 1978 by Oil and Natural Gas Commission and, so far, over 50 locations have been drilled. This study has been taken up in view of the increasing exploratory activities for commercial hydrocarbons in both onshore and offshore areas.

Earlier palynological studies in the basin are mostly confined to the palynostratigraphy (Sharma *et al.*, 1977; Venkatachala & Sharma, 1982, 1984; Ramanujam *et al.*, 1986; Rawat *et al.*, 1986). Palynofacies and maturation studies, which have attained significant interest in source rock evaluation for hydrocarbons, have not been attempted seriously. Venkatachala (1984) published a short account on organic matter types and maturation in Narsapur well and initiated such studies in this



Text-figure 1—Location and geological map of Krishna-Godavari Basin.

basin. A few unpublished records are those of Berry *et al.* (1984), Sharma and Berry (1984) and Rawat *et al.* (1986). Regional synthesis of palynofacies and maturation data in the basin has not been attempted to-date; this study forms such an attempt on this problem.

GEOLOGICAL SETTING OF KRISHNA-GODAVARI BASIN

Krishna-Godavari Basin occupies most of the coastal plains of Andhra Pradesh on the east coast of India and extends into the coastal water of Bay of Bengal. It covers an area of about 15,000 sq km in onland and 25,000 sq km in the offshore up to 1,000 m isobath. Tectonically, the basin is of the type of divergent continental margin associated with initial rifting and basin filling, then covered by platform-type carbonates and in the final stage, superimposed by the delta system. It is a composite basin comprising various ridges and depressions (Text-fig. 1).

The Archaean and metamorphic complex forms the basement and delimits the basin towards the west and north-west. The basement exhibits the ENE-WSW to NE-SW trend, which is in conformity with dominant trends of Eastern Ghats. Outcrop sedimentary rocks, ranging in age from Permian to Holocene, mainly remain covered under alluvium.

The onland subsurface sequence includes Cenozoic, Mesozoic and Palaeozoic strata. The latter has been encountered in one well of Draksharama area. The Mesozoic sediments of the area have also been penetrated scantily but the Cenozoic sequence is profusedly drilled. Generally, the Late Cretaceous claystones are overlain by a Palaeogene sequence of sandstone-shales and occasional limestones. This is followed by a sand and clay sequence in the Neogene. In the offshore areas, few locations have gone down to Late Cretaceous. A thick, more than 3,000 m sedimentary sequence of Miocene-Recent in the offshore have been found to be composed of siltstone, sands, shaly sands, shales and clays.

The present study is based on the subsurface data of nine locations drilled by Oil and Natural Gas Commission in Krishna-Godavari Basin (Text-fig. 1). The tentative representative locations are as under:

West Godavari Basin

1. Location A (Late Cretaceous-Neogene)

East Godavari Basin

2. Location B (Late Cretaceous-Neogene)

3. Location C (Late Cretaceous-Neogene)
4. Location D (Late Cretaceous-Neogene)
5. Location E (Palaeocene-Neogene)

Masulipatnam Bay Area

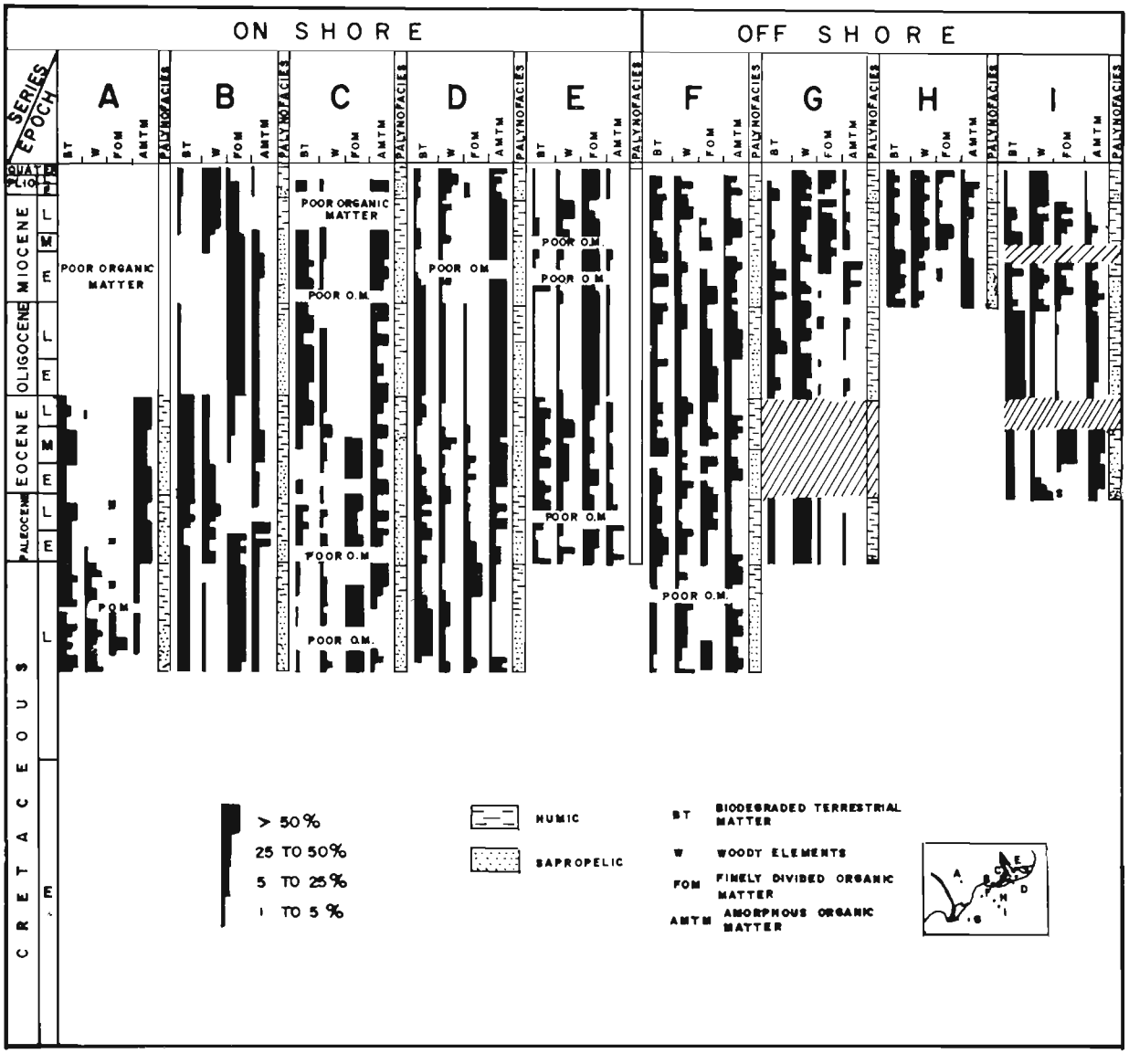
6. Location F (Late Cretaceous-Neogene)
7. Location G (Palaeocene-Neogene)
8. Location H (Neogene-Recent)
9. Location I (Palaeocene-Recent)

METHODS

Based on visual examination, various types of organic matter, as detailed and classified by Masran and Pocock (1981) and Venkatachala (1984), are recorded. However, for the purpose of this study, the total organic matter has been conveniently grouped into four principal types, viz., (i) biodegraded terrestrial organic matter (BT), (ii) woody components (W), (iii) amorphous organic matter (AMTM), and (iv) finely divided organic matter (FOM). These groups are considered of prime interest to interpret the type and potential of organic matter in the source bed for hydrocarbons.

In addition, organic matter types and their quantitative analysis are made according to the method of Terry and Chilinger (1955). To show relative abundance (volume percentage) of organic matter types in the studied sequence and as depicted in Text-figure 2 the following four categories have been considered:

Abundant (A) : 50% or
Common (C) : 25-50%



Text-figure 2—Organic matter types in Krishna-Godavari Basin.

Table 1—Principal organic matter types in Krishna-Godavari Basin

AGE	ORGANIC MATTER	A	B	C	D	E	F	G	H	I	LEGEND
PLIOCENE	BT	POOR ORGANIC MATTER	P	C	T–P	T	P–A	T–C	P–C	T	BT : BIODEGRADED TERRESTRIAL MATTER
	W		A	T	P–A	T	P–A	C–A	C–A	A	W : WOODY ELEMENTS
	FOM		T–C	–	P	A	–	P–A	T–A	–	FOM : FINELY DIVIDED ORGANIC MATTER
	AMTM		T	A	T–A	T	P–A	T–P	T–A	T	AMTM : AMORPHOUS ORGANIC MATTER
	FACIES		H > S	H : S	H > S	S > H	H>S	H>S	H>S	H>S	
MIOCENE	BT		T	C–A	T–C	T–A	T–A	T–A	P–A	T – A	
	W		P–A	T–P	T–C	T–A	T–A	P–A	P–A	P – A	
	FOM		C–A	–	–	P–A	T–A	T–A	T–A		
	AMTM		P–C	A	A	T–P	T–A	T–A	P–C	P – A	
	FACIES		S >H	H : S	S >H	S >H	S : H	H : S	H>S	T – A	
OLIGOCENE	BT		T	P–A	C	T	P–A	P–A		H>S	
	W		–	P	P	T	P–C	P–A		A	
	FOM		A	–	T	A	P–A	T–P		T	
	AMTM		P	P–A	A	T	P–A	T–P		P – C	
	FACIES		S >H	H>S	S >H	S > H	S >H	H >S		T	
EOCENE	BT	P–A	A	P–A	T–C	P–A	P–A			H > S	A : ABUNDANT (>50%)
	W	T	P–C	T–C	T–A	P–A	P–A				C : COMMON (25–50%
	FOM	–	T–P	A	T–C	P–A	P–A			C	P : PRESENT (5–25%)
	AMTM	C–A	T–C	P–A	P–A	T–P	P–A			P – A	T : TRACES (< 5%)
	FACIES	S >H	H>S	S >H	S >H	H >S	S : H			P – A	S : SAPROPELIC
PALEOCENE	BT	P–A	P–A	P–C	P–A	T–A	P–A			C – A	H : HUMIC
	W	T	P–A	T–P	P–C	T–A	T–A	A		S : H	
	FOM	P	C–A	C–A	T–C	C–A	P– A	T			
	AMTM	C–A	P–A	P–A	P–A	P–A	P–A	T			
	FACIES	S>H	H>S	S >H	S : H	S >H	S : H	H > S			
LATE CRETACEOUS	BT	P–A	C	T	P–A		T–P				
	W	P–A	T	T–C	T–C		T–A				
	FOM	P–A	C–A	A	P–A		C				
	AMTM	P	P	T–A	P–A		P–A				
	FACIES	H > S	S >H	S >H	S : H		S >H				

Present (P) : 5-25%
Traces (T) : 1-5%

Thermal Alteration Index (TAI) values were worked out on 1-5 scale of Staplin (1969) based on the colours of spores and pollen. Mature/immature facies were demarcated according to the scheme suggested by Staplin (1977, fig. 10). Accordingly, in the assessment of the maturation, TAI value of 2.5 has been taken to demarcate the youngest level of mature facies.

'Humic facies' comprising terrestrially sourced biodegraded matter and woody elements are dominantly gas-prone which mature at higher level of thermal index as compared to the 'Sapropelic facies' (amorphous and finely divided organic matter) sourced from marine as well as terrestrial organic matter which yield hydrocarbons at comparatively lower level of thermal maturity. These two major organic facies are very significant from the source potential view point.

PALYNOFACIES AND MATURATION

The type of dispersed organic matter from different sequences in the studied locations is recorded under various stages of biodegradation and sapropelization. Based on the occurrence and the relative abundance of four principal categories, the dominant organic facies are determined as shown in Table 1 and depicted through a composite palynofacies diagram (Text-fig. 2).

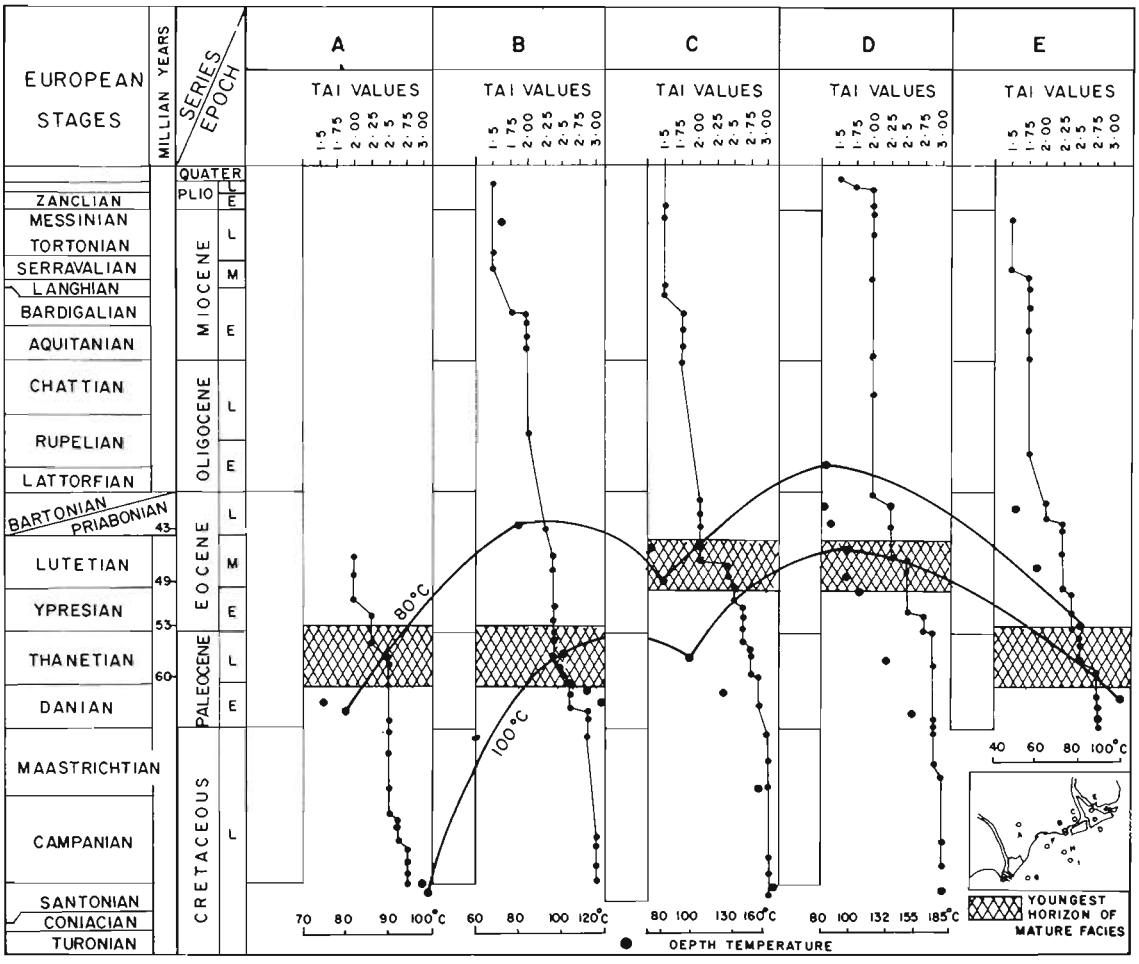
The thermal maturation levels as evaluated by TAI values of fossil pollen grains are depicted through maturation profiles (Text-figs 3, 4). The bottom hole temperatures are also incorporated along the TAI values (Text-figs 3, 4). The data is effectively used to delineate the thermally mature organic facies. The characteristics of organic matter and its maturation in the area of present study are discussed below:

PLIOCENE SEQUENCE

Palynofacies—Humic organic facies dominates; however, a better degree of sapropelization occurs at certain intervals in the onshore region, particularly in the Bhimanapalli area (Text-fig. 2).

Thermal maturation—The low TAI values of 1.25-2.0 would suggest an immature thermal facies.

Source potential—The Pliocene sequence from potential view point is relatively unimportant.



Text-figure 3—TAI maturation profile in the onshore locations of Krishna-Godavari Basin.

MIOCENE SEQUENCE

Palynofacies—The sequence contains a mixed organic facies comprising both humic and sapropelic matter; however, a better humic yield is observed in locations G, H and I (Text-fig. 2).

Thermal maturation—The TAI values range from 1.5 to 2.75. The sequence in Narsapur-Bhimanapalli area on the onland parts shows low TAI values of 1.5-2.0 indicating immature facies. However, TAI values show increasing trends in the locations studied beyond the Miocene shelf edge in the offshore. Based on TAI values, the youngest level of mature facies is recorded in Early Miocene in G, H, I locations (Text-fig. 4).

Source potential—Miocene source potential in onshore locations—A, B, C, D, E and F in the offshore above Miocene shelf-edge, is considered poor due to low maturation. In contrast, the occurrence of higher TAI values of maturation in locations G, H and I, beyond the Miocene shelf edge, as discussed above, is significant and points towards a good source rock maturation in Early Miocene (13-16 Ma) capable of generating hydrocarbons, mostly gaseous ones.

PALAEOGENE SEQUENCE

Palynofacies—The sequence contains organic matter suite dominated essentially by sapropelic matter, though humic matter is also recorded in appreciable amount and forms dominant component at certain intervals in B, C and G areas (Table 1; Text-fig. 2).

Thermal maturation—The TAI values range from 1.75 to 2.75^{+}. Based on TAI data, the youngest levels of mature facies are delineated in A, B, C, D, E and F areas during Late Palaeocene-Middle Eocene time (Text-figs 3, 4).

Source potential—Based on palynofacies and maturation data, a good source rock development is postulated up to Middle Eocene in C and D locations

(Text-fig. 3) and up to Late Palaeocene in A, B, F and E areas. A general enrichment of sapropelized organic matter in A, C, D, E, F areas would indicate a better source potential for both liquid and gaseous hydrocarbons, as compared to B and G areas where sapropelization is not so prominent.

LATE CRETACEOUS

Palynofacies—Late Cretaceous organic matter recorded in A, B, C, D and F areas is classified as sapropelic-humic. Sapropelic type constitutes the major part of the organic matter, although humic elements are also common and form a sizable per centage in A area.

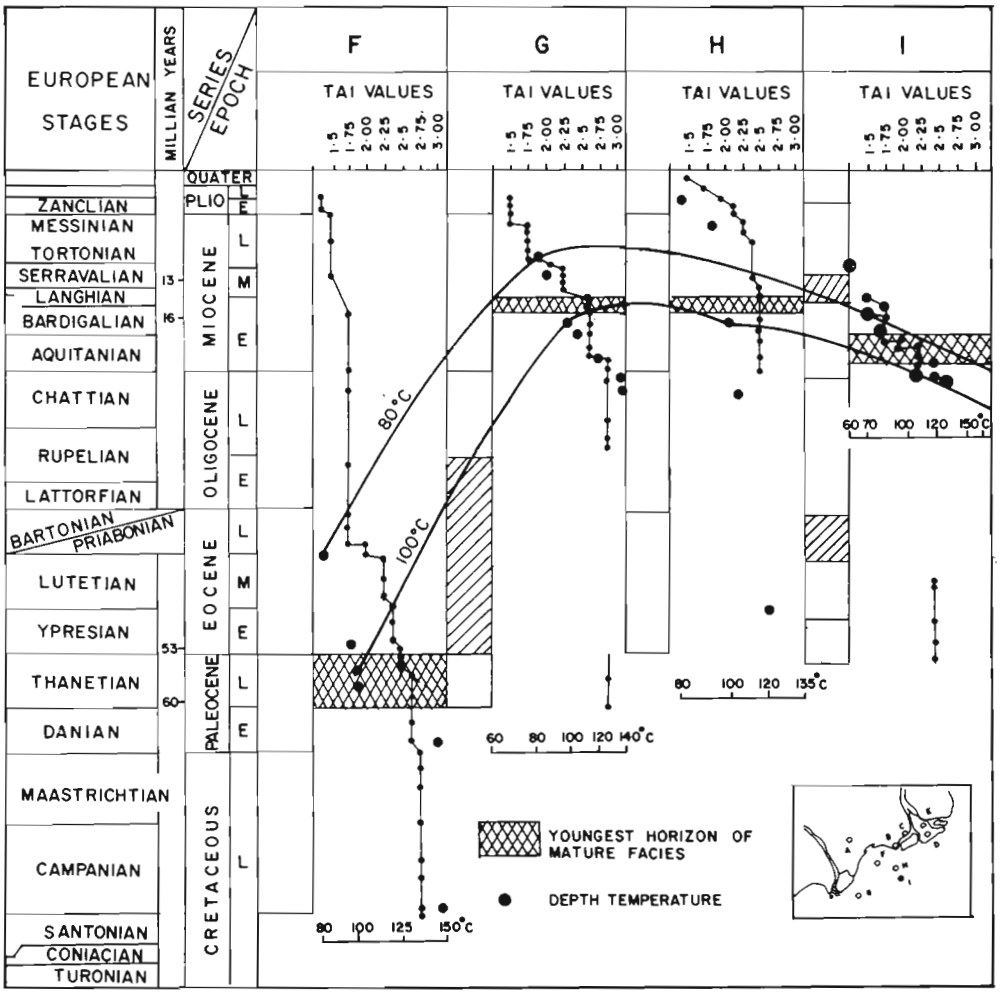
Thermal maturation—The TAI values range from 2.5 to 3.0 showing adequate maturity.

Source potential—The general enrichment of sapropelized matter and adequate thermal maturity would indicate ideal source rock potential for hydrocarbons.

REMARKS AND CONCLUSION

Organic matter—The vegetal dispersed organic matter is considered mostly land-derived. However, occurrence of associated structured marine remains would indicate that a sizable fraction of amorphous matter belongs to marine source. The composition of organic matter is dominantly of mixed type and varies from sapropelic dominant to humic dominant. At times, both humic and sapropelic facies are observed to be nearly in equal proportions.

A comparatively thicker Miocene-Pliocene sedimentary sequence in locations, viz., G, H, and I beyond the Miocene shelf edge, shows dominance of humic organic matter, in contrast to sapropelized type commonly occurring in the areas, such as, B, C, D, E in East Godavari Basin and F situated above the Miocene shelf edge in Masulipatnam Bay. Apparently, the rapid burial of sediments in the areas beyond the Miocene shelf edge has slowed degradation of organic matter reaching the sea



Text-figure 4—Maturation profile in the offshore locations of Krishna-Godavari Basin.

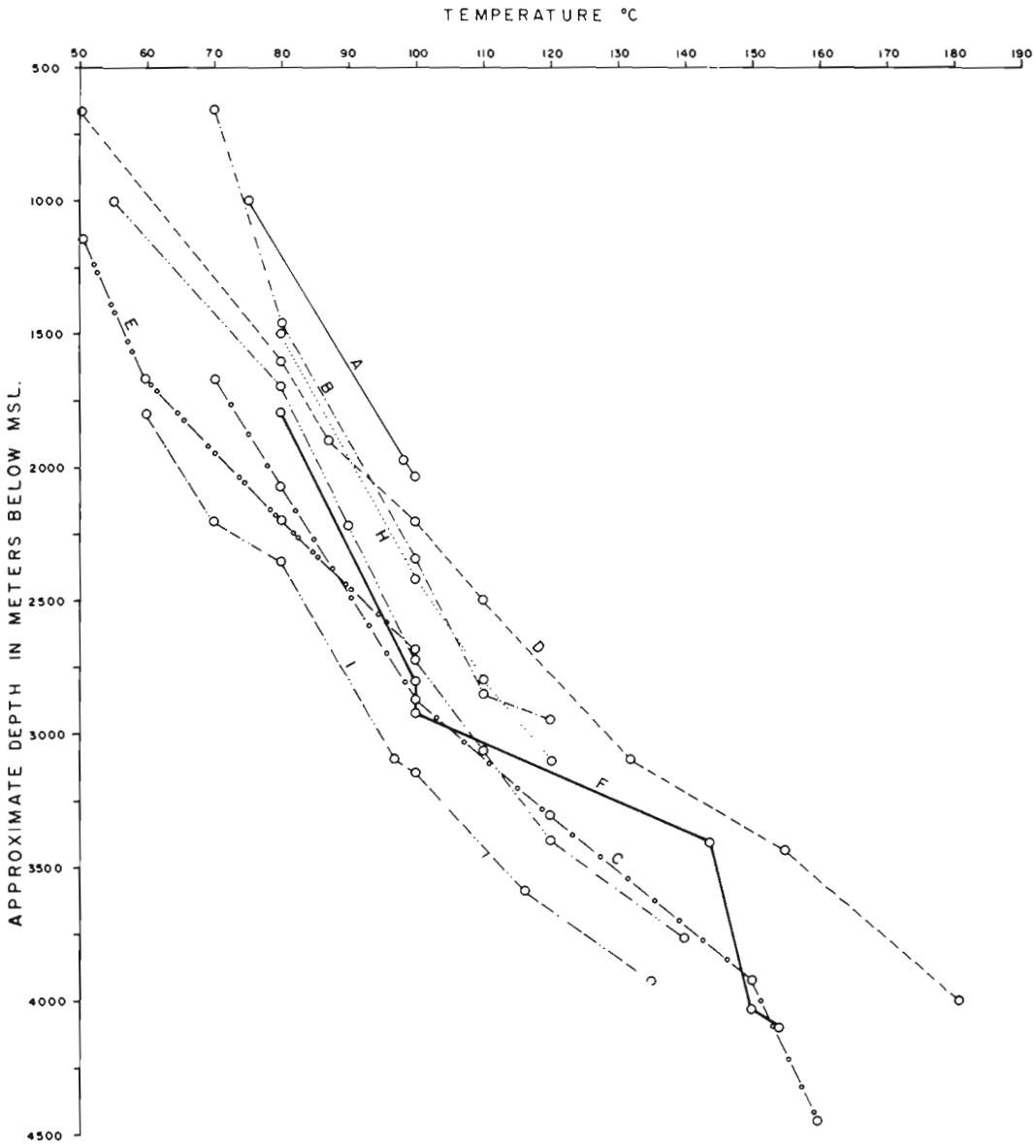
bottom. On the similar line, one may explain a higher degree of sapropelization in the Cretaceous-Palaeogene sequence where sedimentation rate is usually slow.

Maturation—The organic maturation as suggested by Thermal Alteration Index (TAI) values (Text-figs 3, 4) of the organic matter studied in the nine locations indicate the youngest level of mature facies (oil window) at various burial depths in A, B, C, D, E, F, G, H and I locations and has three distinct horizons, restricting the maturation (Text-figs 3, 4).

In certain areas, like A, B, F, E, which are apparently west of Eocene shelf edge, the maturation has reached up to Late Palaeocene (observed intervals: 53-60 Ma). In two of the locations, i.e., C, D, which are below the Eocene shelf edge and above the Miocene shelf edge, the youngest horizon of maturation falls in the Middle Eocene (Interval: 43-49 Ma) (Text-fig. 3).

In the third set of locations, i.e., G, H and I, the youngest level of mature facies reached in the Early Miocene between 13-16 Ma (Text-fig. 4).

The above observations show a quantum jump in time in response to the studied locations *vis-a-vis* the shelf edge. The latter is a plane of active tectonic leverage. It is presumed that the tectonic setting of the locations in their respective positions has affected the maturation history. It is for this reason that the locations beyond the Miocene shelf edge having a chance of continuous sedimentation and



Text-figure 5—Depth/temperature relationship in Krishna-Godavari Basin (studied locations).

continuous heat flow from the basement, mature up to Early Miocene. In the locations between Eocene shelf edge and Miocene shelf edge, the maturation reaching up to Middle Eocene suggests partial loss of heat at some unconformity levels. Further to the west, in the locations above the Eocene shelf edge, the heat loss at the unconformity gaps (hiatuses) resulted into a further lowering of the maturation level in the geochronologic scale.

Another factor associated with the leverage on account of shelf edge is the rapid subsidence and accumulation of sediments in deeper area of the basin. This has resulted into rapid burial of the deeper basin sediments and accentuated the maturation process in the deeper part. The geothermal gradient of this basin (Text-figs 3-5) is more or less consistent as a whole, however, there are local variations, e.g., in H and I (Text-fig. 5) which have gone to affect the maturation within the reasonable limits of time.

A regular feature of maturation, temperature and TAI relationships is the occurrence of youngest horizon of mature facies in the studied locations, which lies almost between 80°-100°C. It would appear that this temperature range is the effective cooking temperature for the kerogen in the basin.

Source potential—The palynofacies development of Krishna-Godavari Basin is largely sapropelic in the Late Cretaceous-Palaeogene and humic in Neogene. The maturation analysis, as discussed above, in the studied locations indicates that maturation level of 'oil window' reached in Late Palaeocene in A, B, F and E, Middle Eocene in C and D and Early Miocene in G, H and I areas. Viewed in terms of organic matter types and maturation, the sediments within the mature zone in the studied area are considered to possess good source potential to generate mixed type of hydrocarbons.

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