Journal of the Palaeontological Society of India
Volume 64(1), June 30, 2019: 83-96

ISSN 0552-9360

BIOSTRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT OF CENOZOIC SEDIMENTS IN DEEP WATER BLOCK, KRISHNA-GODAVARI BASIN

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ABSTRACT

Multimicrofossil biostratigraphic studies utilizing foraminifera, calcareous nannofossils, spore-pollen and dinoflagellate cysts are carried out on well J from Krishna-Godavari deepwater block to determine age and environment of deposition of sediments and to study their regional variation in other three wells drilled in the same block. The subsurface sediments in well J are predominated by poorly indurated calcareous claystone with minor interlaminations of sandstone and siltstone. Oldest sediments of Early Paleocene age in the well are marked on the basis of the LAD's of dinoflagellate cysts *Phelodinium tricuspe* and *Paleocystodinium australinum* at 5375m and youngest sediments of Late Miocene age at 1958m based on the presence of foraminifer *Globorotaloides variabilis*. Late Paleocene, Middle and Late Eocene, Middle and Late Oligocene and Early Miocene age units are demarcated based on multimicrofossil criteria. Middle to outer shelf conditions of deposition prevailed during Early Paleocene to Middle Oligocene, outer shelf to upper bathyal during Middle Oligocene to Early Miocene and upper bathyal during Middle-Late Miocene, thereby suggesting a gradual deepening of the basin with time.

Biostratigraphic correlation of well J with wells A, B and C drilled in Krishna-Godavari deepwater block, suggests that in the synrift sequence the oldest sediments recorded in well A pertain to Late Hauterivian. Late Cretaceous is characterised by Campanian-Maastrichtian sediments in well C. In wells J and B the Mesozoic sediments are not penetrated. In passive margin sequence, the Miocene sediments have recorded the maximum thickness in well J.

Keywords: Biostratigraphy, Paleoenvironment, Foraminifera, Calcareous nannofossils, dinoflagellate cysts, Krishna-Godavari Basin, India.

INTRODUCTION

The pericratonic Krishna-Godavari Basin was formed as a result of fragmentation/ rifting of eastern Gondwanaland and opening of the Indian Ocean which began in Late Jurassic (Powell *et al*., 1988). The depositional system in the KG Basin ranges from shore face to deep water fans and the hydrocarbon plays are primarily from Cretaceous, Eocene, Miocene and Pliocene ages. The deep water block located off the coast of Godavari Delta in the east coast of India within the shallow to deep water part of the Krishna Godavari basin covers an area of about 7300 sq. km.

GENERALISED STRATIGRAPHY OF KRISHNA-GODAVARI BASIN

The Krishna-Godavari Basin comprises sediments of Permian through Holocene age, both in the onland and offshore regions (Venkatarengan *et al*., 1993). The sedimentary sequence of the basin begins with the Gondwana sediments (Draksharama Argillite, Kommugudem and Mandapeta formations of Permo-Triassic age). The Gondwanas are overlain by Gollapalli/ Nandigama/Kanukollu/Krishna formations of Late Jurassic - Early Cretaceous synrift sediments. A part of Late Triassic and a major part of Jurassic is a hiatus in the basin. The Late Cretaceous sediments are represented by Raghavapuram Shale and Tirupati Sandstone.

The Tertiary sequence starts with Razole Formation (basalts and volcano-clastics) of Paleocene age followed by Palakollu Shale (Late Paleocene), Pasarlapudi Formation (Early Eocene), Bhimanapalli Limestone (Middle Eocene). The Bhimanapalli equivalent in the offshore area is called Vadaparru Shale, which is mainly composed of an argillaceous facies. During Oligo.-Miocene period, Matsyapuri Sandstone and Narsapur Claystone were deposited over Vadaparru Shale. Active delta building during Miocene-Pliocene resulted in deposition of Rajahmundry Sandstone in the onland part and Ravva Formation in the offshore part of the basin. During Pliocene-Pleistocene, the major part of the onland area was covered by alluvium and its equivalent in the offshore Godavari Clay.

The stratigraphy of the Krishna-Godavari Basin (Fig.1) is summarised as follows:

Draksharama Argillite: This formation is composed of shale and sandstone and is of early Permian age. It unconformably overlies the Precambrian basement and underlies the Kommugudem Formation.

Kommugudem Formation: This formation is of Permo-Carboniferous age and characterized by sand and shale with intervening coal beds. Presence of spores and pollen of terrestrial plants and the lithological suites indicate fluvial to lagoonal depositional setting.

Mandapeta Formation: It is composed dominantly of sandstone with minor intercalations of shale/claystone and unconformably overlain by the Gollapalli Sandstone. This formation, deposited under fluvial environment, is assigned a Permo-Triassic age.

Gollapalli Sandstone: This formation comprises of syn-rift sediments deposited under fluvial to marginal marine/lacustrine environment. The lower part of this formation is pebbly sandstone followed by ferruginous claystone, the middle part is sandstone with silts, and the upper part consists of medium to fine-grained sandstone. This formation is Late Jurassic (?) to Early Cretaceous in age.

Raghavapuram Shale: This formation lies above the Gollapalli Sandstone and is underlain by Tirupati Sandstone. It is composed of shale, clay and minor sandstone and deposited

under marginal marine to shallow shelf conditions. It is assigned an Early Cretaceous age and the presence of organic-rich shales in this formation makes it an important source rock in the basin.

Tirupati Sandstone: The lower part of this formation is argillaceous, while the upper part is arenaceous consisting of medium to coarse grained and ferruginous sands. The top of this formation is marked by basaltic traps. The formation was deposited under transitional to marginal marine conditions.

Chintalapalli Shale: It is essentially a shale section with fine-grained sands in the lower part and is considered the offshore equivalent of Tirupati Sandstone. It is of Late Cretaceous age and inferred to be deposited under inner shelf environment.

Razole Formation: Razole traps are encountered extensively both in the outcrop and sub-crop. The formation is mainly composed of basalts with minor limestone and sandstone as inter-trappeans. This formation is assigned a late Maastrichtian to early Danian age.

Vadaparru Shale: This dominantly shale facies overlies Razole Formation in the onland area and Chintalapudi Shale in the offshore. The shale is rich in organic matter and occasionally contains thin beds of sandstones and siltstones. It forms an important source rock and ranges in age from Paleocene to Pliocene.

Bhimanapalli Limestone: This formation consists mainly of hard, fossiliferous limestone with sand and shale alternations. The limestone grades into Vadaparru Shale basin-ward. It is deposited under marginal marine to shallow marine conditions and Middle Eocene in age.

Ravva Formation: This formation is represented by alternate bands of sand and shale with minor siltstone. Age of this formation ranges from Miocene to Pliocene and basinward, it grades into Vadaparru shale. The sands in this formation are hydrocarbon bearing and resulted in several important discoveries.

Godavari Clay: The dominantly clay/claystone sequence overlying Ravva formation is called Godavari Clay and is the youngest stratigraphic unit in the basin. In the deeper part of the basin where Ravva Formation is absent, the entire claystone section is termed as Godavari Clay. Sands within this formation have proved to be hydrocarbon bearing.

The present well (J) is confined to Early Paleocene-Late Miocene sediments in the offshore part of the Krishna-Godavari Basin, encompassing the Vadaparru Formation.

EVOLUTION OF KRISHNA-GODAVARI BASIN

The Krishna-Godavari Basin evolved along the east coast of the Indian peninsula covering both onshore and offshore areas. Along the basin margin, the Gondwana (Chintalapudi sandstone / Mandapeta Sandstone), Early Cretaceous to early part of Late Cretaceous (Raghavapuram Shale), Late Cretaceous (Tirupati Sandstone), Razole Trap and Miocene (Rajahmundry Sandstone) sediments are observed as outcrops. Most of the onland part of the basin is alluvium covered and dominated by two major rivers Krishna and Godavari and their tributaries. The characteristic feature of this basin is the presence of en-echelon system of horsts and grabens filled with thick pile of sediments starting from Gondwanas to Recent.

The basin started as a major intra-cratonic rift within the Gondwanaland during the Permo-Triassic until the Early Jurassic (Rao, 2001) and at present is classified as a pericratonic rift basin (Biswas *et al*., 1993). The early rift Permo-Triassic sediments form the base for the later deposited divergent margin sequences. The basin has a polytectonic history due to the presence of two orthogonal structures- an older NW–SE trending intracratonic Gondwana rift and the younger NNE-SSW oriented KG rift formed during the rifting of the eastern Gondwanaland and subsequent separation of India from the East Antarctica (Gupta, 2006).

These rifting events led to the development of horst and graben structures in the basin. Some of the grabens in the basin contain thick sedimentary sequences ranging in age from late Carboniferous to Recent (Rao, 2001). The pericratonic nature of the basin has brought out growth fault dominated Tertiary sedimentary deposits to the east of the curvilinear fault, popularly known as Matsyapuri-Palakollu fault. Thus, the broad tectonic expression of the basin comprises linear horst-graben systems and growth fault / rollover listric normal faults and block tilting, which are manifestations of a rift basin evolved into a typical passive margin basin.

The Krishna Godavari Basin came into existence following rifting along eastern continental margin of Indian Craton in early Mesozoic. The down to the basement faults which define the series of horst and grabens cascading down towards the ocean are aligned NE-SW along Precambrian Eastern Ghat trend.

The geological history comprises of following stages:

- Rift Stage: The basin got initiated in Permo-Triassic to Early Cretaceous and is characterized by lagoonal / fluvial to occasionally brackish water sediments. The northeastern portion was part of an intra cratonic rift set up till Jurassic that constituted the southeastern extension of NW-SE trending continental rift valley slopping northward.
- Syn Rift Stage: Early subsidence by tectonic fault systems resulted in deposition of early stage synrift sediments. Late Jurassic to Early Cretaceous synrift sediments were deposited as a result of basement subsidence along basement bound fault system. The sequence is represented by sandstone, shale with occasional coal bands and red claystone, deposited under fluvial-marginal setup.
- Drift Stage: A southerly/southeasterly tilt of the basin marks the rift to drift transition which led to widespread marine transgression during Cretaceous and deposition of marine shale sequence. It was followed by the onset of overall regressive phase during Late Cretaceous which is represented by a deltaic sequence comprising Tirupati Sandstone with dominant arenaceous facies. During Maastrichtian-Danian, the basin experienced major volcanic activity known as Razole Volcanism that probably continued over a large periods of time that exposed trap rocks and intertrappen sediments were deposited during periods of quiescence. The volcanic activity possibly covered around 1600 sq. km. area and having span of 5.5 million years.
- Late Drift Stage: The Late Drift Phase is characterized by slippages and slides that led to growth-fault systems. The Tertiary sediments were deposited over the Razole traps due to extensional tectonics in the basin.

SITE LOCATIONS AND SETTINGS

The present well (J) is confined to Early Paleocene-Late Miocene sediments in the offshore part of the Krishna-Godavari Basin, encompassing the Vadaparru Formation.

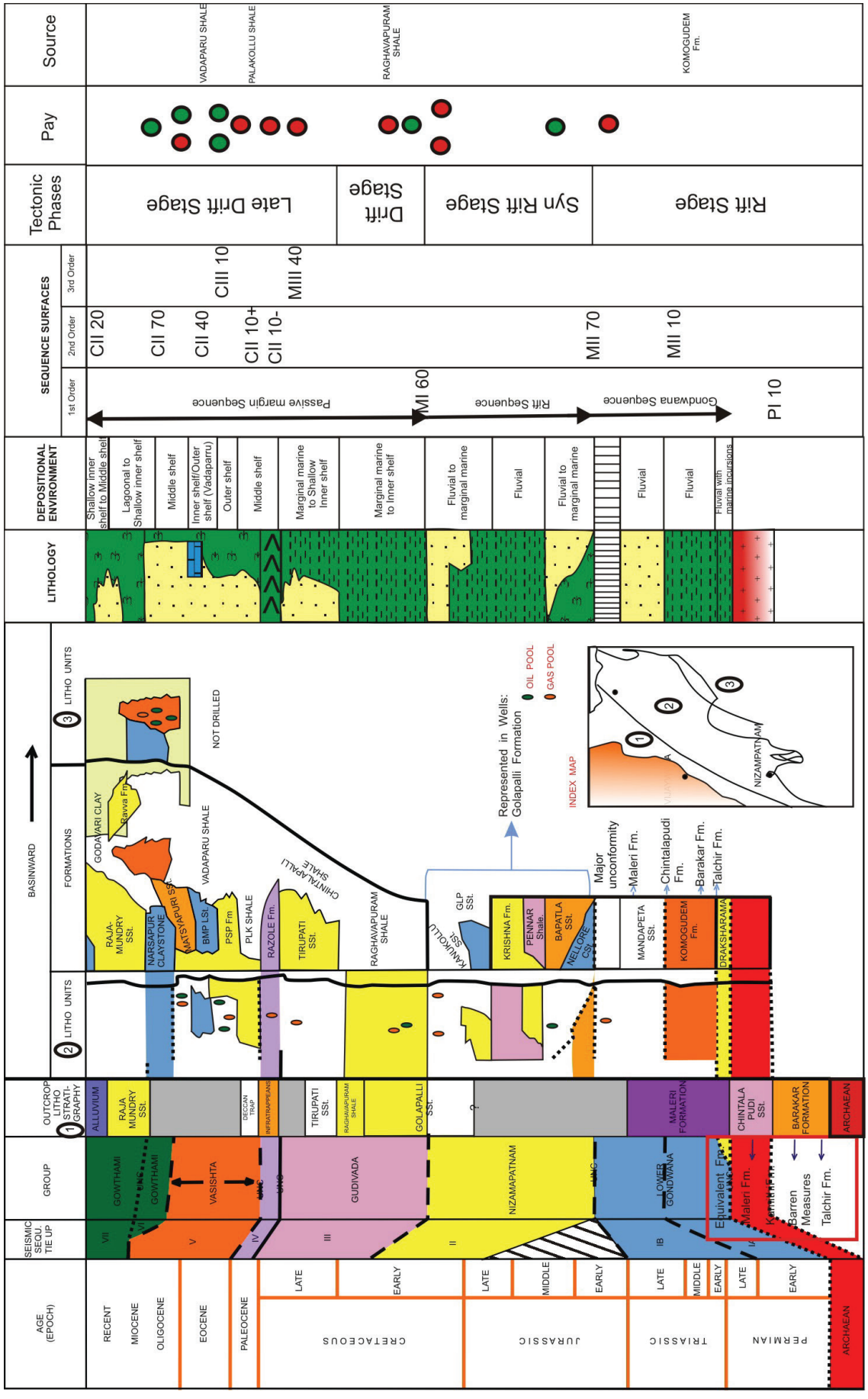


Fig. 1. Generalized Stratigraphy of Krishna-Godavari Basin (modified after Venkatarengan *et al.*, 1993; Prasad, 1999).

The well J was drilled down to more than 5820m in deep water block (Fig.2) of Krishna-Godavari Basin with an objective to explore the hydrocarbon potential of Cretaceous, Paleocene and Eocene sequences in the area. However, biostratigraphic studies suggest that the well was terminated within Paleocene. The well drilled at the water depth of more than 1180m was abandoned as dry. The present work is on biostratigraphic studies utilizing foraminifera, calcareous nannofossils, spore-pollen and dinoflagellates on cutting samples of the well in the interval 1958-5827m for age determination and interpretation of depositional environments to help in hydrocarbon exploration activities in the area. Additionally, biostratigraphic and paleoenvironmental correlations of well J with wells A, B and C drilled in same deep water block (Ali *et al.,* 2008, Raju *et al.,* 2013; Singh *et al.,* 2014; Singh and Sharma, 2014; Singh *et al*., 2015) have been attempted to study spatial and temporal variation in age and paleoenvironment of deposition of sediments in the block.

The well B drilled at a water depth of 1199m is located north east of well J as depicted in figure 2. The well C drilled further north east of well B was drilled under a water depth of 564 m. The well A was drilled further SSW of well J and was drilled under a water depth of 2841m.

MATERIAL AND METHODS

The processing of the samples for multimicrofossil studies viz., foraminiferal, palynofossils and calcareous nannofossils has been carried out using standard processing laboratory techniques (Pandey and Rao, 1991). The relevant literature consulted included Kennett and Srinivasan, 1983 and Bolli *et al*., 1985; for foraminifera; Stover *et al*., 1996; Stover and Williams, 1985; Williams *et al*., 1993; Wilson and Bujak, 1985;. for palynofossils and Martini, 1971; Okada and Bukry, 1980; Perch-Nielsen, 1985 and Young, 1998 for calcareous nannofossils.

Cuttings in the interval 5827m to 1958m were examined at the sample gap of 20 to 50m for foraminiferal, spore-pollen and dinoflagellate cysts and 20 to 100m for calcareous nannofossils studies for age determination and paleoenvironment interpretation. Number of samples studied for foraminiferal, spore-pollen and dinoflagellate cysts and calcareous nannofossils studies are 95, 157 and 58 respectively. Foraminiferal studies of well reveal that the assemblage is represented mainly by smaller benthics and planktics, with good diversity and frequency in the Paleocene to Early Miocene and Late Miocene sections and poor occurrence in the Middle Miocene sections. The calcareous nannofossils record in the well intervals is fair to moderate in the Paleogene section as compared to the Neogene section. Moderate to good assemblage of spore-pollen and dinoflagellate cysts is recorded in the entire studied section.

BIOSTRATIGRAPHIC STUDIES

The distribution of foraminifera, calcareous nannofossils, dinoflagellate cysts and spore-pollen and their interpretations are documented and presented in the figures 3 to 5. The paleoenvironment interpretation of the study area has been made primarily on the foraminiferal data and taking into consideration the other microfossil groups i.e. calcareous nannofossil, spore-pollen and dinoflagellate cysts. Biostratigraphic and paleoenvironmental correlations of well J with wells A, B and C are shown in figures 6 and 7.

Interval: 5827-5375m (Early Paleocene):

*Foraminiferal assemblage***:** Foraminiferal assemblage recorded from the interval comprises *Morozovella conicotruncata, M. uncinata, Globigerina triloculinoides*, *G. velascoensis*, *Planorotalites compressa, P. pussilla pussilla, Planorotalites* sp., *Allomorphina* sp., *Amphicoryna* sp., *Anomalinoides* sp., *Bolivina* sp., *Bulimina pupoides*, *Bulimina* sp., *Cibicides lobatulus*, *Cibicides* sp., *Cibicidoides* sp., *Conorotalites* sp., *Dentalina* sp., *Lagena* sp., *Lenticulina* sp., *Marssonella* sp., *Nonion* sp., *Pararotalia* sp., *Planulina* sp., *Textularia* sp., *Uvigerina* sp., arenaceous forams, miliolids, ostracoda, pteropods etc.

Calcareous nannofossils assemblage: Interval from 5827-5400m consists of *Neococcolithus rosenkrantzi, Toweius eminens, Neochaistozygus concinnus, Ellipsolithus bollii, Campylosphaera eodela, Ericsonia robusta, Ellipsolithus distichus, Cruciplacolithus primus* (large), *Cr. tenuis, Coccolithus foraminis* and *Neococcolithus protenus* indicating a Paleocene age.

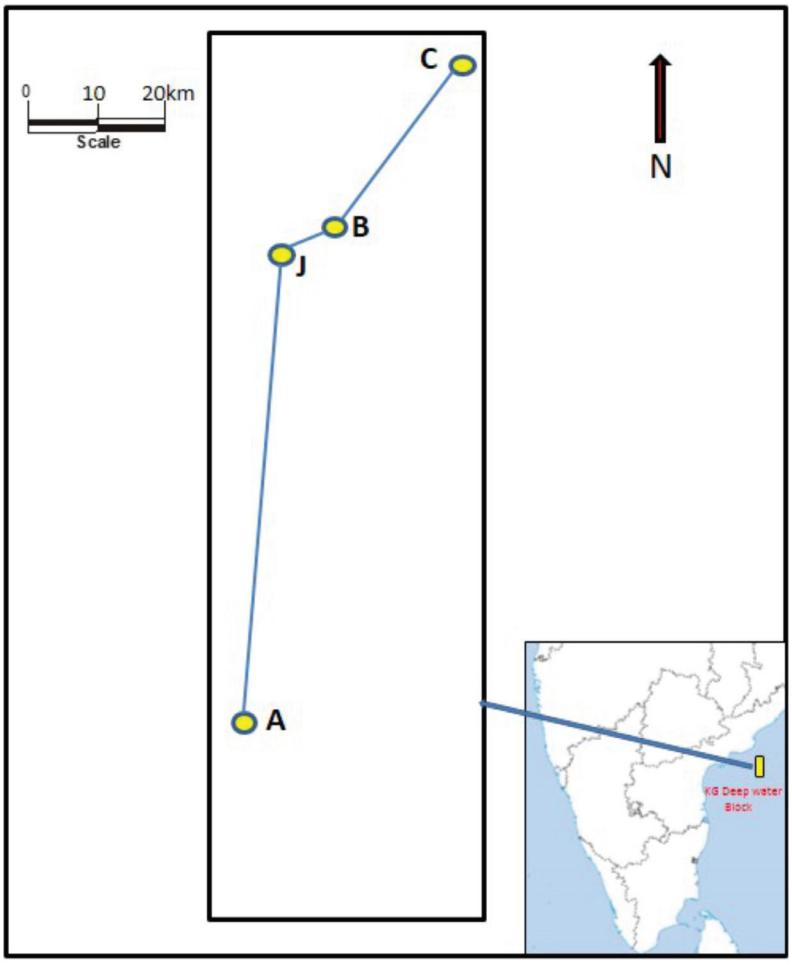


Fig. 2. Location map of studied wells in deep water block, Krishna-Godavari Basin.

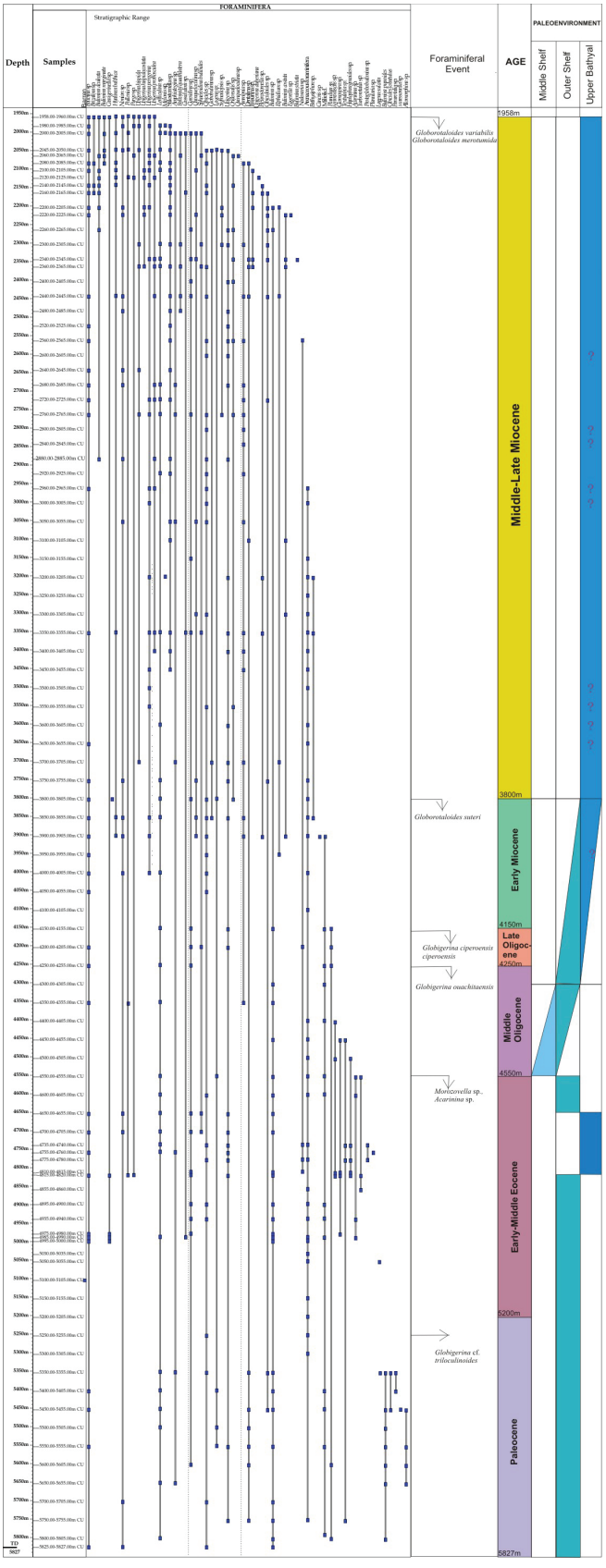


Fig. 3a: Distribution of benthic foraminifera, age and depositional environment in well J, Krishna-Godavari Basin.

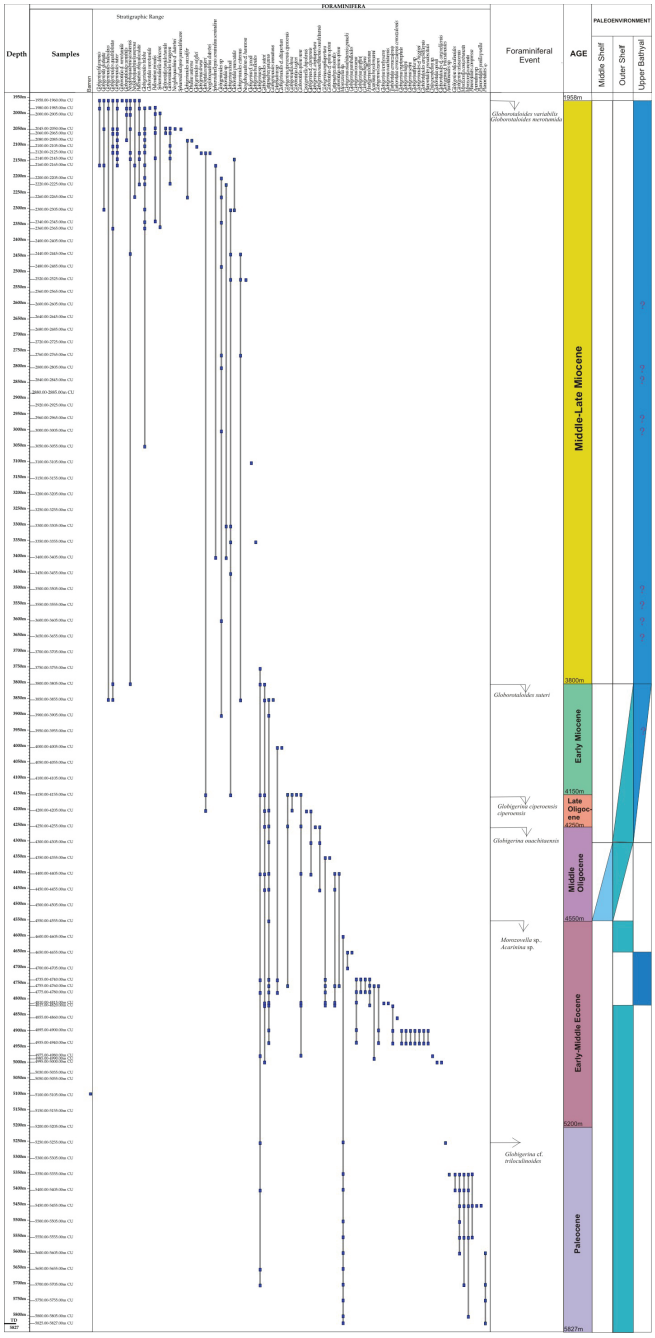


Fig. 3b. Distribution of plankic foraminifera, age and depositional environment in well J, Krishna Godavari Basin.

Spore-pollen and dinoflagellates assemblage: This interval is characterized by the occurrence of *Areoligera senonensis*, *Spiniferites cornutus, Spinidinium ballum, Hafniasphaera septata, Senoniasphaera inornata, Paleoperidium pyrophorum, Tanyosphaeridinium xanthiopyxides, Paleocystodinium australinum, Phelodinium tricuspe, Fibrocysta variabilis.* Associated spore-pollen are *Rhombipollis geniculatus*, *Spinizonocolpites baculatus*, *Proxapertites emendates, Racemonocolpites ramonus, Psittacopollis concentricus, Aquilapollenites pachypolus*, *Proteacidites* sp., *Rutihesperipites trochuensis* and *Mulleripollis bolpurensis.*

Age, gross lithology and paleoenvironment: The LAD of dinoflagellate cysts *Phelodinium tricuspe* and *Paleocystodinium*

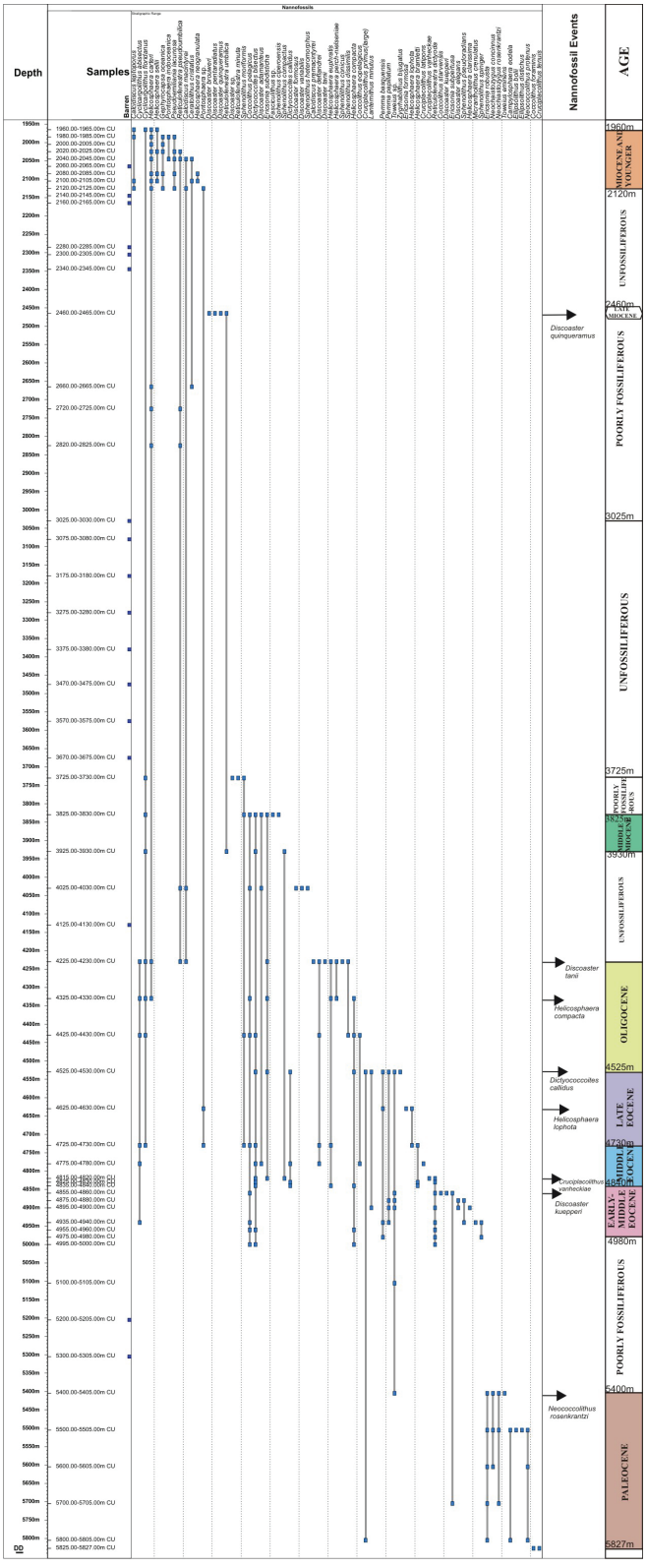


Fig. 4. Distribution of Calcareous Nannofossils and age in well J, Krishna Godavari Basin.

australinum at 5375m with associated spore-pollen suggests Early Paleocene age for this interval. The lithology is mainly grey, moderately indurated claystone. Thick sandstone and siltstone beds are recorded in the intervals 5650-5640m and 5770-5760m. The sediments are interpreted to be deposited under middle shelf conditions.

Interval: 5375-5200m (Late Paleocene):

Foraminiferal assemblage: Foraminiferal assemblage recorded from the interval comprises *Morozovella conicotruncata, Morozovella* sp., *Globigerina triloculinoides*, *G. velascoensis*, *Planorotalites* sp., *Amphicoryna* sp., *Anomalinoides* sp., *Bulimina pupoides*, *Bulimina* sp., *Cibicides* sp., *Cibicidoides* sp., *Conorotalites* sp., *Dentalina* sp., *Lenticulina* sp., *Pararotalia* sp., arenaceous foraminifera, pteropods, etc.

*Calcareous nannofossils assemblage***:** The interval from 5400-5000m is poorly fossiliferous and contains *Toweius* spp.

*Spore-pollen and dinoflagellates assemblage***:** The interval is characterized by the occurrence of *Apectodinium parvum*, *Cladopyxidium saeptum*, *Apectodinium augustum*, *Alissocysta margarata, Palaeoperidinium pyrophorum, Biconidinium longissimum* and *Areoligera senonensis*. Associated spore-pollen are *Dandotiaspora* spp., *Rhombipollis geniculatus*, *Cupanieidites* sp., *Polybrevicolporites cephalus*, *Spinizonocolpites baculatus*, *Proxapertites cursus*, *Longapertites* sp., *Proteacidites* sp. along with fungal spore *Netothyrites vertistriatus.*

Age, gross lithology and paleoenvironment: The LAD of dinoflagellate cyst *Apectodinium augustum* at 5200m and associated spore-pollen suggests Late Paleocene age for the interval**.** The LAD of foraminifera *Globigerina* cf. *triloculinoides* recorded at 5250m also suggests Late Paleocene age. The lithology is monotonous grey coloured claystone. The interlayers of siltstone is absent or very poorly developed. The sediments in the interval are envisaged to be deposited under middle shelf conditions.

Interval: 5200-4550m (Early to Middle Eocene):

*Foraminiferal assemblage***:** Foraminiferal assemblage recorded from the interval comprises *Globigerina eocaena, G. praebulloides*, *Globigerina senni, G. lozanoi, G. carcosellensis, G. cryptomphala, G. hagni, Globigerina ouachitaensis gnaucki, "Globigerinoides" higginsi, Catapsydrax unicavus, Planorotalites pseudoscitula. Globigerinatheka* sp., *Acarinina broedermanni, Globorotaloides suteri, Globorotalia opima nana*, *Catapsydrax unicavus, C. dissimilis*, *Chiloguembelina* sp., *Morozovella* sp., *Turborotalia cerroazulensis, T. griffinae*, *Cassigerinella* sp., *"Hastigerina"* cf. *bolivariana*, *Ammodiscus* sp., *Bolivina* sp., *Bulimina* sp., *Cassidulina* sp., *Cibicides* sp., *Glomospira* sp., *Gyroidina* sp., *Haplophragmoides* sp., *Lagena* sp., *L. sulcata*, *Lenticulina* sp., *Nodosaria* sp., *Protoglobobulimina* sp., *Spaheroidina bulloides, Textularia* sp., *Uvigerina* sp., arenaceous foraminifera, miliolids, etc.

*Calcareous nannofossils assemblage***:** Section from 4840-4735m contains *Dictyococcoites bisecta, D. callidus, Cyclicargolithus abisectus, Coccolithus eopelagicus, Discoaster deflandrei, S. spiniger, H. compacta, H. bramlettei* and *Reticulofenestra dictyoda* indicating Middle Eocene age. The section from 4980-4780m consists of *Pemma basquensis, P. pappillatum, Dictyococcoites callidus, D. bisecta, Reticulofenestra dictyoda, Coccolithus starvensis, Helicosphaera bramletii, H. clarissima, Helicosphaera compacta, Lanternithus minutus, Discoaster kuepperi, Toweius* sp., *Micrantholithus crenulatus, Cruciplacolithus vanheckae, Coccolithus pelagicus, Pontosphaera* sp. indicating an Early-Middle Eocene age.

Spore-pollen and dinoflagellates assemblage: The cutting interval is characterized by sporadic occurrence of

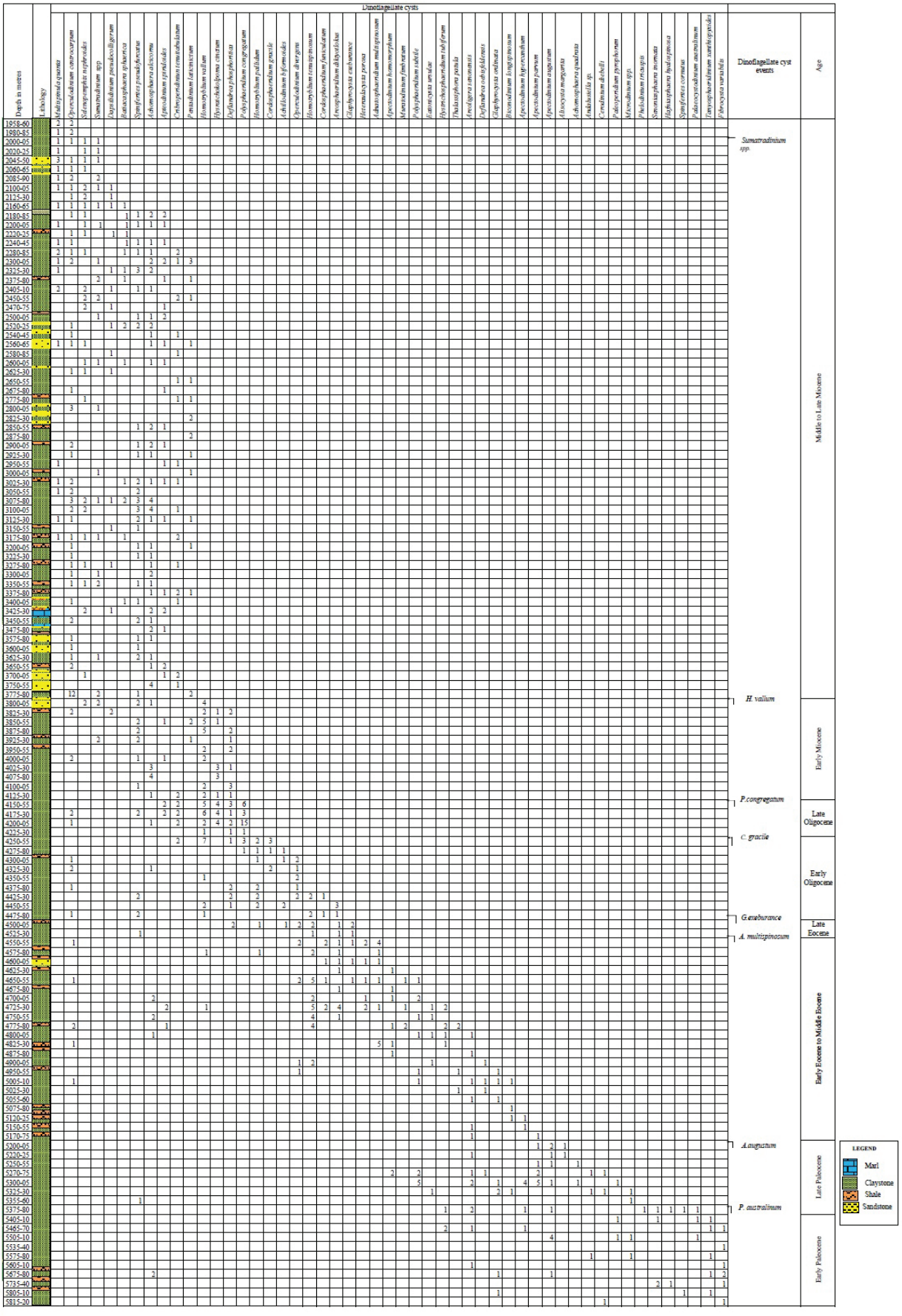


Fig. 5a: Distribution of selected spore-pollen and age in well J, Krishna Godavari Basin.

Heteraulacacysta porosa, Adnatosphaeridium multispinosum, Muratodinium fimbriatum, Apectodinium homomorphum, Hystrichosphaeridium tubiferum, Areoligera senonensis, Hafniasphaera septata, *Thalassiphora patula* and *Deflendrea oebisfeldensis*. Associated spore-pollen are *Spinizonocolpites echinatus, Polygalacidites clarus Marginipollis kutchensis*, *Pseudonothofagidites kutchensis*, *Palmaepollenites ovatus, Longapertites* sp., *Proxapertites cursus, Palmaepollenites eocenicus, Couperipollis kutchensis* etc.

Age, gross lithology and paleoenvironment: The LAD of foaminiferal taxa, *Morozovella* sp. and *Acarinina* sp., along with dinoflagellate cyst *Adnatosphaeridium multispinosum* at 4550m suggests Middle Eocene age. Due to the absence of diagnostic microfossils within the interval the Early and Middle Eocene could not be differentiated and the interval is inferred to be pertaining to Early to Middle Eocene in age. The lithology is monotonous claystone of grey colour. The interlayers of sandstone are observed in the interval 4645-4605m which are dirty white, very poorly indurated and fine to medium grained. There is also associated minor siltstone which is mostly present in the section below. Rest of the section down to 5200m is monotonous claystone as observed in the uppermost part. The sediments in the interval 4650-4550m are interpreted to be deposited under middle shelf, 4820-4650m under outer shelf and 5200-4820m under middle shelf conditions.

Interval: 4550-4500m (Late Eocene):

Foraminiferal assemblage: Arenaceous foraminifera, *Haplophragmoides* sp., *Ammodiscus* sp., *Reophax* sp., etc.

*Calcareous nannofossils assemblage***:** Nannofossil yield in the section consists of *Helicosphaera lophota, H. compacta, H. bramletii, Pemma basquensis, P. pappillatum, Discoaster deflandrei, Zeugrhabdotus bijugatus, Toweius* spp., *Dictyococcoites bisecta, D. callidus* and *Lanternithus minutus.*

*Spore-pollen and dinoflagellates assemblage***:** This interval is characterized by diverse assemblage of dinoflagellate cysts viz. *Homotryblium tenuispinosum, Rhombodinium porosum, Glaphyrocysta exuberans* along with diagnostic spore-pollen assemblage including *Margocolporites* sp., *Couperipollis kutchensis, Polygalacidites clarus, Spinizonocolpites echinatus, Pseudonothofagidites kutchensis*, *Palmaepollenites ovatus, Longapertites* sp., *Polybrevicolporites cephalus* and *P. operculatus.*

Age, gross lithology and paleoenvironment: The LAD of dinoflagellate cyst *Glaphyrocysta exuberans* at 4500m suggests Late Eocene age. Calcareous nannofossil yield in the interval comprising *Helicosphaera lophota* also suggests a Late Eocene age. The lithology is monotonous grey coloured claystone. The interlayers of siltstone are absent or very poorly developed in this section. The sediments are interpreted to be deposited under middle to outer shelf conditions.

Interval: 4500-4250m (Middle Oligocene):

*Foraminiferal assemblage***:** Foraminiferal assemblage recorded from the interval comprises *Globigerina ouachitaensis ouachitaensis, G. ciperoensis ciperoensis, G. praebulloides, G. ampliapertura, Catapsydrax unicavus, C. dissimilis, Globorotaloides suteri, Globorotalia opima opima, G. opima nana, Bolivina* sp., *Bulimina* sp., *Gyroidina* sp., *Planulina* sp., *Lenticulina* sp., *Ammonia* sp., Arenaceous foraminifera, *Reophax* sp., *Ammodiscus* sp., *Glomospira* sp., *Textularia* sp., *Haplophragmoides* sp., miliolids, microgastropods, Ostracoda, etc.

Calcareous nannofossils assemblage: Cuttings in the interval from 4430-4225m contain *Cyclicargolithus abisectus, Sphenolithus conicus, S. dissimilis, S. pseudoradians, Helicosphaera perch-nielseniae, H. euphratis, H. compacta, Ericsonia subdisticha* (reworked), *Cy. floridanus, Discoaster deflandrei* and *D. tanii* assemblage suggesting an Oligocene age.

*Spore-pollen and dinoflagellates assemblage***:** The cutting samples have yielded dinoflagellate cysts viz., *Cordosphaeridium gracile, Senegalinium* sp., *Operculodinium divergens, Homotryblium tenuispinosum, H. pallidum* and *Wetzeliella* sp. Associated spore-pollen are *Psuedonothofagidites* sp., *Marginipollis* sp., *Longapertites vaneedenburgii*, *Palmaepollenites* sp., *Dicolpopollis kalawensis, Schizaeaceaesporites* sp., *Rhoipites* sp. and *Retitricolporites* sp.

Age, gross lithology and paleoenvironment: The LADs of foraminiferal taxa *Globigerina ouachitaensis ouachitaensis* and dinoflagellate cyst *Cordosphaeridium gracile* at 4250m suggests Middle Oligocene top. The lithology is monotonous claystone of grey colour. The interlayers of siltstone are absent or very poorly developed. The sediments in the interval 4300-4250m are envisaged to be deposited under outer shelf to upper bathyal and 4500-4300m under middle to outer shelf conditions.

Interval: 4250-4150m (Late Oligocene):

*Foraminiferal assemblage***:** Foraminiferal assemblage recorded from the interval comprises *Globigerina ciperoensis ciperoensis*, *G. praebulloides, Globorotalia opima nana, G. mayeri, G. kugleri, Globorotaloides suteri, Globigerinella obesa, Catapsydrax unicavus, Cassigerinella chipolensis, Bulimina* sp., *Gyroidina* sp., *Uvigerina* sp., miliolids, *Lenticulina* sp., *Planulina* sp., *Bolivina* sp., *Sphaeroidina bulloides, Nodosaria* sp., etc.

Calcareous nannofossils assemblage: Interval consists of *Cyclicargolithusa bisectus, Ericsonia subdisticha, Helicosphaera perch-nielseniae, H. euphratis, Sphenolithus dissimilis, Calcidiscus premacantyrei, Sphenolithus* cf. *conicus* and *Discoaster deflandrei.* Assemblage suggests a Late Oligocene age.

Spore-pollen and dinoflagellates assemblage: The section is characterized by significant assemblage of dinoflagellate cysts viz. *Impagidinium dispetitum*, *Thalassiphoa pelagica, Polysphaeridium congregatum, Lingulodinium machaerophorum, Hystrichokolpoma cinctum, Homotryblium vallum, Homotryblium plectilum.* The recorded spore-pollen assemblage in this interval includes *Marginipollis kutchensis, Longapertites vaneedenburgii*, *Arecipites* sp., *Dicolpopollis kalewensis, Tricolporites* sp., *Schizaeaceaesporites* sp., *Rhoipites* sp., *Retitetracolporites* sp. and *Polypodiisporites* sp. along with foraminiferal linings.

Age, gross lithology and paleoenvironment: The LADs of foraminifera *Globigerina ciperoensis ciperoensis* and dinoflagellate cysts *Polysphaeridium congregatum* at 4150m demarcates Late Oligocene top. The lithology is dominantly grey to greenish grey, moderately indurated, feebly calcareous claystone with negligible interlayers of siltstone. The sediments are interpreted to be deposited under outer shelf to upper bathyal conditions.

Interval: 4150-3800m (Early Miocene):

*Foraminiferal assemblage***:** Foraminiferal assemblage recorded from the interval comprises *Globorotaloides suteri, Catapsydrax unicavus, Globigerinoides primordius, Gs.* cf. *altiapertura, Gs. quadrilobatus, Ammonia* sp., *Bolivina* sp.,

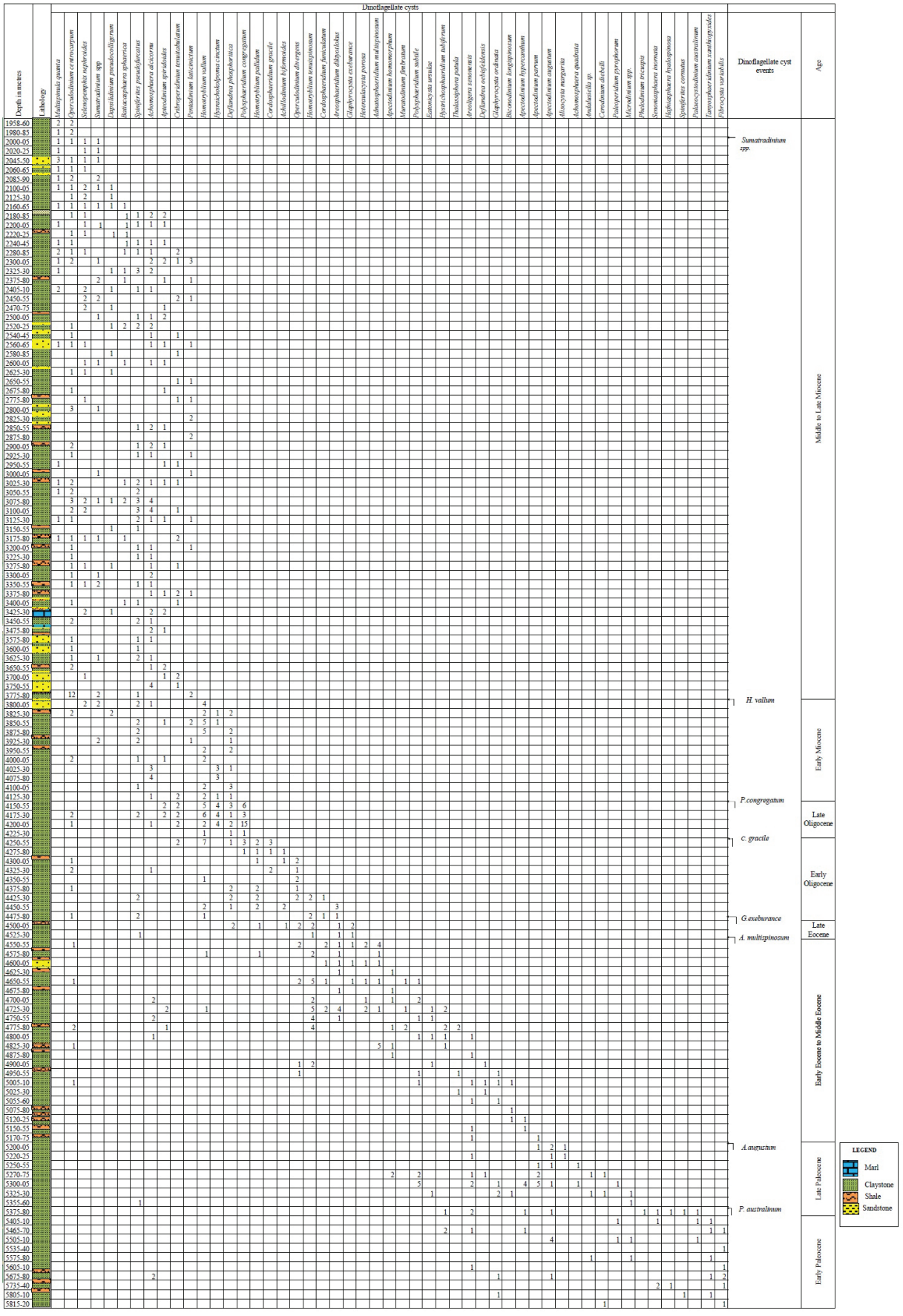


Fig. 5b: Distribution of selected dinoflagellate cyst and age in well J, Krishna Godavari Basin.

Bulimina costata., *Cancris* sp., *Cibicides* sp., *Elphidium* sp., *Globocassidulina* sp., *Globobulimina* sp., *Gyroidina* sp., *Hyalinea balthica*, *Lagena* sp., *Lenticulina* sp., miliolids, *Nonion* sp., *Oridorsalis* sp., *Pleurostomella* sp., *Quinqueloculina* sp., *Uvigerina peregrina, Bathysiphon* sp., *Ammobaculites* sp., *Reophax* sp., arenaceous foraminifera, etc.

Calcareous nannofossils assemblage: Interval from 3930-3825m has yielded *Cy. abisectus, D. bisecta, Ericsonia subdisticha, Sphenolithus ciperoensis, Helicosphaera compacta, Cy. floridanus* along with reworked *H. lophota, Discoastera damanteus* and *Fasciculithus* sp., suggesting Early to Late Oligocene age. Cutting from 4025-30m contains *Sphenolithus heteromorphus, D. formosus, Calcidiscus macintyrei, D. variabilis, Reticulofenestra pseudoumbilica* (large) and reworked *Discoaster adamanteus* and *Dictyococcoites callidus* indicating a Middle Miocene age. Cutting at 4125-30m is devoid of nannofossils.

Spore-pollen and dinoflagellates assemblage: The cutting samples have yielded dinoflagellates viz., *Homotryblium vallum, H. floripes, Evitosphaerula* sp., *Pentadinium laticinctum, Cribroperidinium tenuitabulatum, Heteraulacacysta campanula, Hystrichokolpoma cinctum* and *Cordosphaeridium cantharellum.* Associated spore-pollen are *Longapertites* sp., *Liliacidites reticulates, Striatopollis bellus*, *Verrualetes assamicus, Laevigatosporites* sp., *Verrucosisporites miocenicus, Liliacidites* sp. and *Palmidites* sp.

Age, gross lithology and paleoenvironment: The LADs of foraminifera *Globorotaloides suteri* along with dinoflagellate cysts *Homotryblium vallum* at 3800m demarcates Early Miocene top. The lithology is dominantly claystone which is grey, sticky, poorly indurated and weakly calcareous. Thin beds of siltstone between the interval 3950-3965m are present which are greyish white having dark opaque minerals and are feebly calcareous.The sediments are interpreted to be deposited under outer shelf to upper bathyal conditions.

Interval: 3800-1958m (Middle - Late Miocene):

Foraminiferal assemblage: Foraminiferal assemblage recorded from the interval includes *Globorotaloides variabilis, Gd. hexagona, Globorotalia merotumida, Gr. tumida tumida, Gr. praescitula, Globigerinoides extremus, Gs. ruber, Gs. sacculifer, Gs. triloba, Gs. quadrilobatus, Gs. seigliei, Globigerina druryi, Globorotalia* cf. *mayeri, G. woodi, G. bulloides, G. praebulloides, G. falconensis, Globigerinita glutinata, Neogloboquadrina acostaensis, N. humerosa, Orbulina universa, Pulleniatina primalis, Sphaeroidinellopsis seminula seminula, Ss. paenedehiscens, Ammonia* sp., *Amphistegina* sp., *Bolivina* sp., *Brizalina* sp., *Bolivinita quadrilatera, Dentalina* sp., *Bulimina marginata, B. costata., B. striata, B. aculeata, Cassidulina* sp., *Cibicides* sp., *Cibicidoides* sp., *Dentalina* sp., *Elphidium* sp., *Eggerella* sp., *Fissurina* sp., *Globocassidulina* sp., *Globobulimina* sp., *Gyroidina* sp., *Hoeglundina elegans, Hyalinea balthica*, *Lagena* sp., *Lenticulina* sp., *Melonis* sp., *Nonion* sp., *Oridorsalis* sp., *Pullenia* sp., *Pleurostomella* sp., *Pyrgo* sp., *Quinqueloculina* sp., *Sigmoilopsis* sp., *Sphaeroidinella bulloides, Stilostomella* sp., *Uvigerina hispido-costata, U. peregrina, U. proboscidea, U. auberiana, U. hispida, Bathysiphon* sp., arenaceous foraminifera, echinoid plates and spines, Ostracoda, Radiolaria, etc.

Calcareous nannofossils assemblage: Nannofossil yield in the interval (2140-1958m) consists of *Ceratolithus cristatus, Helicosphaera sellii, H. carteri, H. neogranulata, Cyclococcolithus leptoporus, Pseudoemiliania lacunosa, Gephyrocapsa oceanica, Calcidiscus macintyrei, Pontosphaera indooceanica, Reticulofenestra pseudoumbilica* (medium). Interval from 2340-2140m and 3725-3025m is devoid of nannofossils. Cutting at 3730-3725m contains *Reticulofenestra minuta, Sphenolithus moriformis, Cy. floridanus* and broken *Discoaster* sp. In the absence of age diagnostic nannofossil taxa no definite age could be assigned to the section. However cuttings at 2460-65m contain *Discoaster brouweri, D. quinqueramus, D. pentaradiatus* and *Reticulofenestra umbilica* indicating a Late Miocene age to the interval.

Spore-pollen and dinoflagellates assemblage: The cutting samples have yielded dinoflagellates viz; *Spiniferites splendidus*, *Tuberculodinium vancampoae, Operculodinium centrocarpum*, *Selenopemphix nephroides, Sumatradinium* sp. *Apteodinium spiridoides, Spiniferites pseudofurcatus*, *Achomosphaera alcicornu, Cribroperidinium tenuitabulatum, Pentadinium laticinctum*. Associated spore-pollen are *Deltoidospora* sp., *Graminidites media*, *Couperipollis rarispinosus, Polypodisporites favus, Retitricolporites* sp., *Laevigatosporites* sp., *Polypodiaceaesporites* sp., *Marginipollis concinnus, Polpodiisporites usmensis,, Meliapollis* sp., *Longapertites* sp., *Verrucosisporites miocenicus* and *Crassoretitriletes miocenicus*.

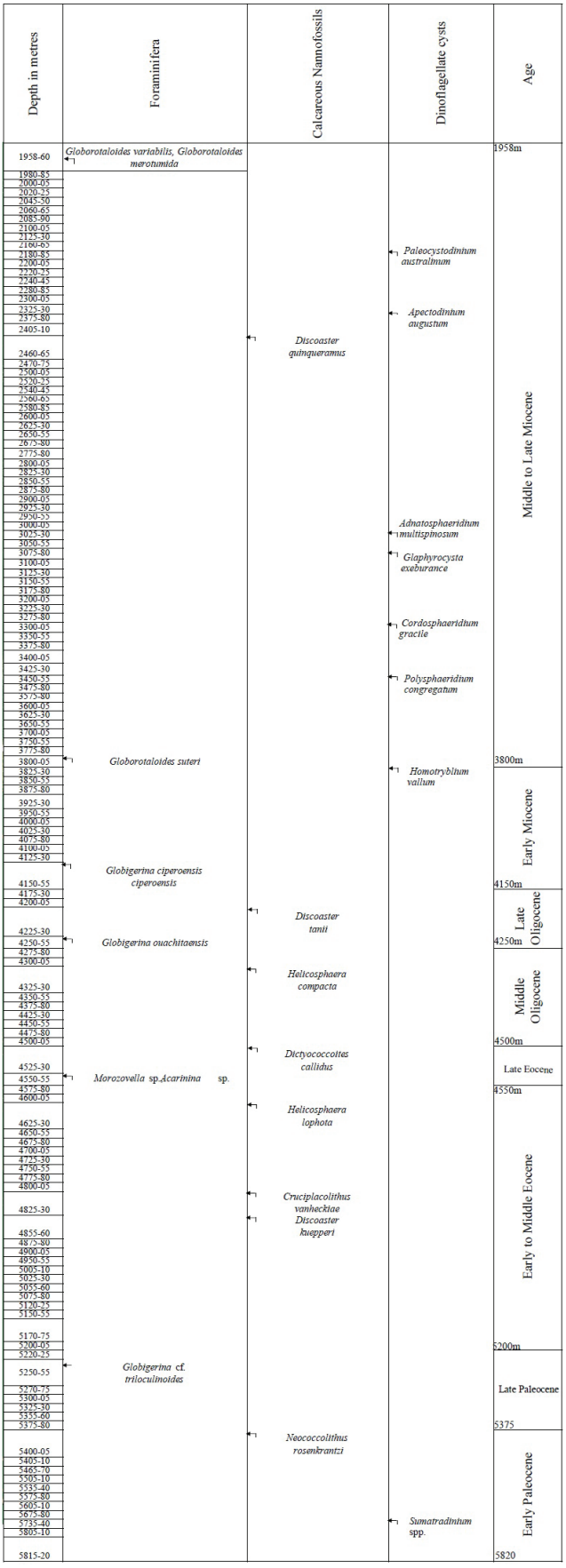
Age, gross lithology and paleoenvironment: The consistent occurrence of foraminifera *Globorotaloides variabilis* and *Globorotalia merotumida* in the youngest intervals (1958-60m, 1980-85m, 2000-05m and 2080-85m) suggests Late Miocene age. Spore-pollen and dinoflagellate cysts yield in this section comprises Late Miocene taxa upto 2020m. Foraminifera having LAD within Middle Miocene i.e., *Globigerina druryi, Globorotalia* cf. *mayeri* are recorded at 2120-25m, and *Gr. praescitula* at 2140-45m and 2300-05m. Due to non-continuous and sporadic occurrence of various Miocene microfossils i.e. foraminifera, dinoflagellate cysts and calcareous nannofosssils in the section, the entire section is dated as undifferentiated Middle-Late Miocene. The dominant lithology is grey to greenish grey, feebly calcareous, moderately hard claystone with the presence of gastropoda and other microfossils along with traces of pyrite (2020m). There are very thin (max. 1m thick) isolated occurrence of loose sandstone interlayers, which are medium to coarse grained and at times pebbly in intervals between 2090-2050m 2120-2115m, 2840-2810m and 3440-3400m. Thin layers of marl have also been developed between 3505-3445m. Between 3800-3610m, there is a change in facies which is characterised by thick, medium to fine grained and poorly sorted sandstone, interlayered with thin shale/ claystone. The sediments are inferred to be deposited under upper bathyal conditions.

INTEGRATION OF DATA AND DISCUSSION

The integration of foraminiferal, calcareous nannofossil, spore-pollen and dinoflagellate cysts data has been carried out to suggest age boundaries based on index microfossils in the studied well section. The study has helped in dividing the section into Early and Late Paleocene, Early-Middle and Late Eocene, Middle and Late Oligocene and Early and Middle-Late Miocene.

Early Paleocene age is marked based on the LAD of dinoflagellate cysts *Phelodinium tricuspe* and *Paleocystodinium australinum* at 5375m with associated spore-pollen. The LAD of

Table. Index fossils (foraminifera, calcareous nannofossils and dinoflagellate cysts recorded in well J-1, Krishna-Godavari Basin).



dinoflagellate cyst *Apectodinium augustum* at 5200m marks the Late Paleocene top**.** The LAD of foraminifera *Globigerina* cf. *triloculinoides* suggesting Late Paleocene age is also recorded at 5250m.

Middle Eocene top is marked based on the LADs of foraminifera *Morozovella* sp. and *Acarinina* sp.*,* along with dinoflagellate cyst *Adnatosphaeridium multispinosum* at 4550m. Early and Middle Eocene could not be differentiated and interval 5200-4550m is inferred to be pertaining to Early to Middle Eocene in age due to the absence of diagnostic microfossils. The interval representing Late Eocene sediments is recognized based on the LAD of dinoflagellate cyst *Glaphyrocysta exuberans* at 4500m. Absence of microfossils restricted to Early Oligocene age points towards the possibility of part absence of Late Eocene-Early Oligocene sediments.

Middle Oligocene top is marked on the basis of LADs of foraminifera *Globigerina ouachitaensis ouachitaensis* and dinoflagellate cysts *Cordosphaeridium gracile* at 4250m. The LADs of foraminifera *Globigerina ciperoensis ciperoensis* and dinoflagellate cysts *Polysphaeridium congregatum* at 4150m demarcates Late Oligocene top.

Early Miocene top is marked on the basis of the LADs of foraminifera *Globorotaloides suteri* and dinoflagellate cysts *Homotryblium vallum* at 3800m. Consistent occurrence of foraminifera *Globorotaloides variabilis* and *Globorotalia merotumida* ranging upto Late Miocene top is recorded in the top most sediments (1958m) of the section. The sediments in the interval 3800 to 1958m are dated as Middle - Late Miocene due to non-continuous and sporadic occurrence of various Middle Miocene microfossils i.e. foraminifera, dinoflagellate cysts and calcareous nannofosssils.

The biostratigraphic data from earlier studied wells A, B and C which lie in the same block have been correlated with the data of well J. In well A, interval 4790 -3868m was dated Early Pliocene, 6000-4790m was dated Early - Middle Miocene, 6305-6000m was dated Late Oligocene, 6400-6305m was dated Early Oligocene, 6520-6400m was dated Middle Eocene, 6540-6520m was dated as Early Eocene, 6540-45m was dated as Campanian-Maastrichtian, 6555-6545m was dated as Albian - Early Cenomanian, 6560-6555m was dated as Albian, 6576-6560m was dated as Late Hauterivian- Early Barremian. In well B, interval 2362.5-2100m (CC#1) was dated as Early Pliocene or younger, 2400-2362.5m-2362.5m (CC#1) was dated as Middle - Late Miocene, 2750-2400m was dated as earliest Middle Miocene, 3445-2750m was dated as Early Miocene, 3625-3445m was dated as Early Miocene and older. In well C, interval from 2300-1602m was dated as Early Pliocene, 3100-2300m was dated as Middle- Late Miocene, 3150-3100m was dated as Early Miocene, 3200-3150m was dated as Late Oligocene, 3300-3200m was dated as Early - Middle Oligocene, 3450-3300m was dated as Late Eocene, 3600-3450m was dated as Middle Eocene, 3900-3600m was dated as Early Eocene, 4300-3900m dated as Late Paleocene, 4500-4300m was dated as Paleocene, 4700-4500m was dated as Campanian-Maastrichtian. Interval from 5103-4700m was unfossiliferous. The biostratigraphic correlation of well J with the earlier studied wells viz. A, B and C was attempted. Well B was terminated within Early Miocene and well J was terminated within Paleocene. Well C and well A encountered Mesozoic sediments. The oldest sediments recorded in well A pertain to Late Hauterivian-Barremian while in well C they pertain to Campanian - Maastrichtian (Fig. 6). Paleocene sediments are absent in well A. Paleogene sediments

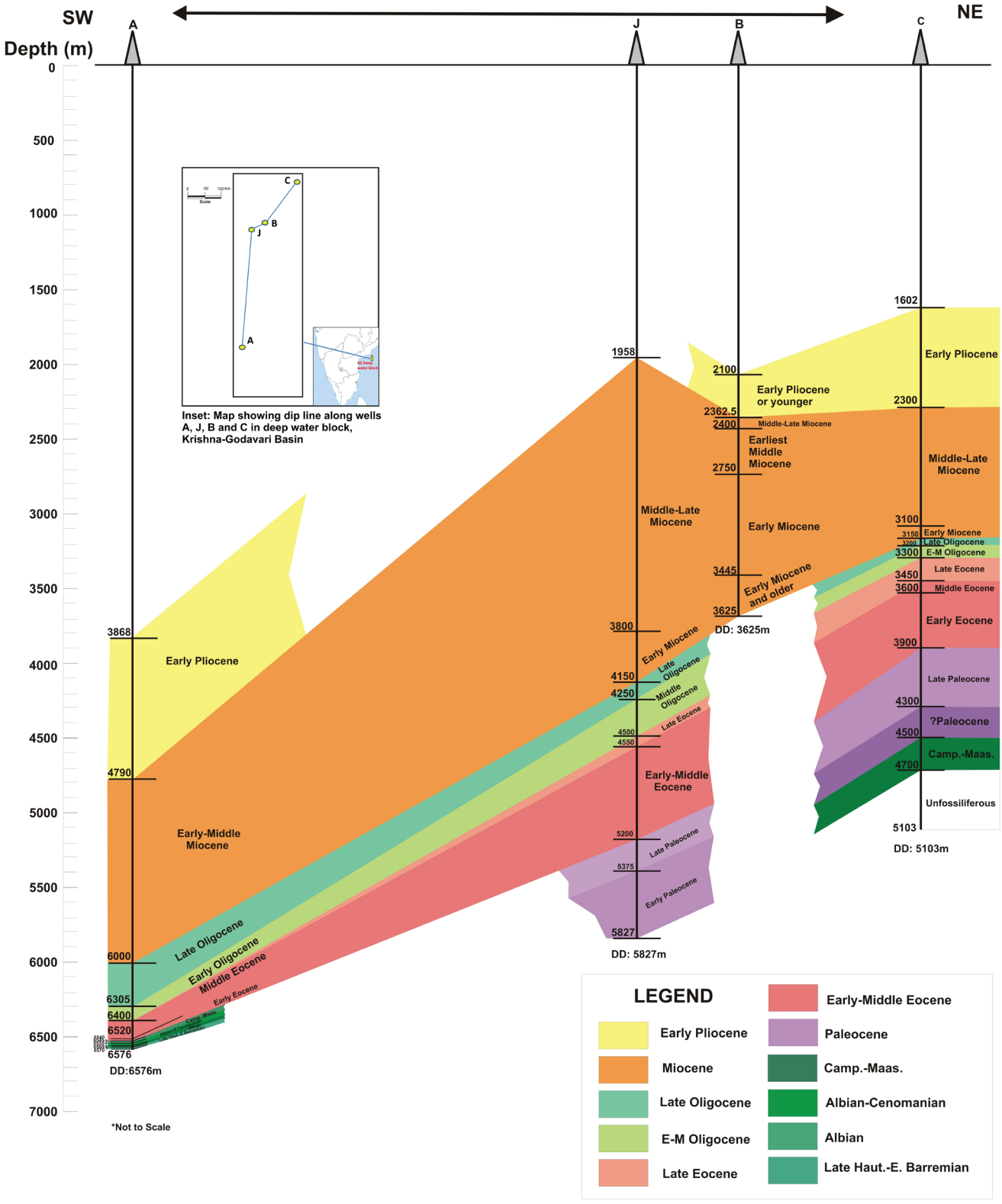


Fig. 6. Biostraticgraphic correlation of wells A, J, B and C in deep water block, Krishna-Godavari Basin.

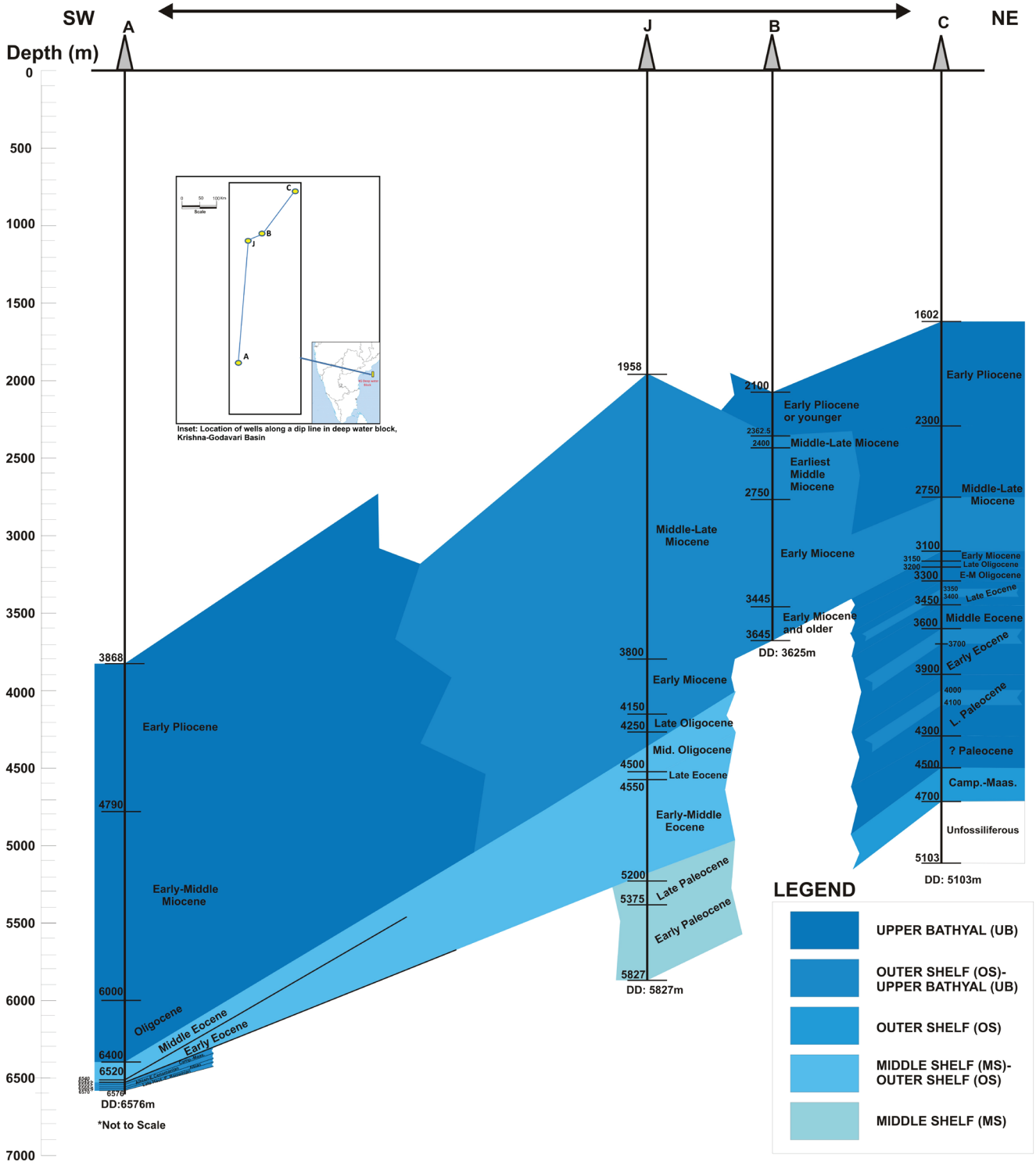


Fig. 7. Paleonenvironmental fluctuations along wells A, J, B and C in deep water blocks, Krishna-Godavari Basin.

are found to be thinning in well A as compared to well J and C. In passive margin sequence, the Miocene sediments have recorded the maximum thickness in well J.

The paleoenvironmental fluctuations with time are schematically depicted in figure 7. Early Cretaceous sediments recorded only in well A were deposited under bathyal conditions. Late Cretaceous sediments encountered in wells A and C were deposited under bathyal and outer shelf regime respectively. Paleocene is deposited in well J under middle shelf conditions while in C fluctuating outer shelf to upper bathyal conditions prevailed. Eocene is deposited under fluctuating middle to outer shelf conditions in wells J and C, while in well A bathyal conditions prevailed. In all the four wells namely, A, J, B and C fluctuating outer shelf to upper bathyal conditions prevailed during Miocene. Upper bathyal conditions prevailed during Early Pliocene in all wells except J, where Early Pliocene was not recorded.

CONCLUSIONS

Integrated multimicrofossil biostratigraphic studies comprising foraminifera, calcareous nannofossils, spore-pollen and dinoflagellate cysts have helped to demarcate the age boundaries and infer paleoenvironment of deposition in well J during Paleocene to Late Miocene.

In well J, deposition during Early Paleocene to Middle Oligocene took place under middle to outer shelf conditions, Middle Oligocene to Early Miocene under outer shelf to upper bathyal conditions and Middle-Late Miocene under upper bathyal conditions, thereby suggesting a gradual deepening of the basin with time.

In the deep water block, the oldest sediments are recorded in well A which pertain to Late Hauterivian - Barremian.

The biostratigraphic correlation of well J with A, B and C suggests that the Paleogene section is thicker in well J as compared to other wells.

During Eocene fluctuating middle to outer shelf conditions prevailed in wells J and C, while in well A deposition took place under bathyal conditions.

ACKNOWLEDGEMENTS

The authors are grateful to Shri A. K. Dwivedi, Director (Exploration) for granting permission to publish the paper. The authors express their gratitude towards Dr. Harilal, ED-HOI, KDMIPE for constant encouragement and facilities. The views expressed in the paper are those of the authors only and not necessarily of the organization they represent. The authors are grateful to Sh. Shekar Srivastava, CGM (Geology) - Head Geology, for encouragement.

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Manuscript received : November 2017

Manuscript accepted : January 2019