PALEOGENE LARGER FORAMINIFERAL BIOSTRATIGRAPHY OF PARTS OF WESTERN INDIAN SHELF

Ph.D. THESIS

by

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ROORKEE-247667 (INDIA)

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A THESIS
submitted in partial fulfilment of the
requirements for the award of the degree
of
Doctor of Philosophy
in
Earth Sciences

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ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "PALEOGENE LARGER FORAMINIFERAL BIOSTRATIGRAPHY OF PARTS OF WESTERN INDIAN SHELF", in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Department of Earth Science of Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period of July, 2008 to July, 2014 under the supervision of Prof. Sunil Bajpai, Director, Birbal Sahni Institute of Paleobotany, Lucknow (currently on lien from Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, 247667, INDIA).

The matter presented in this thesis has not been submitted by me for the award of any other degree of this institute or any other institute.

(Sudhir Shukla)

This is to certify that the above statement made by the part time candidate is correct to the best of my knowledge.

(Sunil Bajpai)
Supervisor

Dated:

The Ph.D viva-voce examination of Mr.Sudhir Shukla, Part-time Research Scholar has been held on……………..

Signature of Supervisor   Chairman,SRC   Signature of External Examiner

Head of the Department/Chairman,ODC

DEDICATION

To

The respected Parents
Whom we all owe our existence and excellence
&
Dear Children
Who fulfill our desire to excel ahead of
our own achievements.

ABSTRACT

The Paleogene of western Indian continental shelf is geographically so extensive that it could be subdivided into several distinct sedimentary basins, each having its own geological history and evolution through time. The western continental shelf extends from the Rajasthan Basin through Kachchh and parts of Saurashtra and Cambay Basin to the western offshore basins, right down to the Kerala - Konkan area, with some remarkable similarities. A major similarity is the Deccan Traps basement (also referred to "technical basement," in hydrocarbon exploration parlance), over which fairly extensive carbonate - shale deposition took place in somewhat varying intensity. The hydrocarbon provinces of these sedimentary basins are distinct, with a few commonalities i.e. deposition of extensive Paleogene carbonate / marl / shale sequence over most of the western Indian continental shelf. These sequences are predominated by larger benthic foraminifera occurring together with the other fossil groups.

In the present study, detailed biostratigraphic work on the taxonomic standardization of selected foraminiferal species with the help of morphometric analysis and foraminiferal biozonation was undertaken on the Paleogene outcrops from two main western Indian sections i.e. Berwali River section (District Kachchh) of the Kachchh Basin and the Tapti River section of the Cambay Basin in the Surat and Bharuch districts; both in the western Indian state of Gujarat. Both these regions provide excellent outcrops of Tertiary formations,

with prolific larger foraminifera, encompassing almost all the epochs of the Tertiary era. Vast outcrops with enormous shelf carbonate facies embedded with both mega and microfossils occur in all the major river or road sections in Kachchh, parts of south Cambay Basin as well as in the neighbouring Jaisalmer Basin of the Rajasthan state in the western India. Besides the outcrops, selected samples from the exploratory wells drilled for the hydrocarbon exploration in Cambay and western offshore basins, have also yielded diagnostic foraminifera useful in proposing larger foraminiferal bio-zonation for western shelf.

In the south-western Kachchh, Paleocene - Eocene outcrops are located in the vicinity of Kakdi - Doriwali river section and road sections on way to Lakhpat/ Narayansarovar. The Berwali river area shows the outcrops of rocks belonging to Middle Eocene, Late Eocene and Oligocene epochs. Further south, Miocene and younger formations successively outcrop in Berwali and other adjoining river sections; dipping and younging towards the present day coast. The thickness of all the outcropping formations greatly increases towards the basinal (Offshore) area. In the south Cambay basin, Paleogene outcrops in Amrawati and Tapti River / road sections; Vastan-Tarkeshwar mines, in Surat – Ankleshwar area are common. The late Eocene carbonates are better exposed here and provide an ample opportunity to collect and study larger foraminifera. The study area was mapped with the help of Brunton compass at 1:50,000 scale, during several field studies undertaken since 1985 onwards. The foraminifera and associated fauna were studied for biostratigraphic determinations. The conclusions drawn from the present work provide insights into geological history of the basins, taxonomic standardization of important species, larger foraminifer zonation applicable to western Indian shelf; stratigraphic range of important species, correlation with the SBZ scheme and Indian equivalents to SBZ scheme. A brief account of paleoecological interpretation and generalized hydrocarbon prospects of the region is also given.

It is important to point out that the morphological as well as biometric (measurable) changes in the tropical Tethyan larger foraminiferal fauna (especially nummulitids) have been recorded and compared with their temperate counterparts in this study and a monograph was published during the year 2009. Elsewhere, similar studies have been mainly conducted in the European basins by Prof. Hans Schaub; Prof. Alphonso Blondeau (on the larger foraminifer *Nummulites* populations of Swiss Alps and Paris basins, respectively); Dr. Andrew Racey and possibly a few more scientists. These studies point to the need to develop locally applicable biostratigraphic zonation on the lines of Shallow Benthic Zonation (Serra Kiel et al., 1995). It has been frequently observed that many forms characterizing Serra Kiel et al. (1995) S.B. Zones do not frequent in Indian material and hence creation of Indian equivalents to the Serra Kiel et al. (1995) scheme was immensely needed. This scheme is a widely acceptable biostratigraphic tool for regional correlations in Indian sedimentary basins and serves as the link between the Mediterranean and Far-Eastern

Tethyan species. The present work supplements, earlier bio-chronostratigraphic investigations carried out by previous workers.

The present thesis is divided into six chapters. The first chapter deals mainly with the location, area of study, previous work, objectives and scope of the work, methodology and the sampling and field related aspects. The second chapter describes geology and tectonic setting, stratigraphy and geological history of the Kachchh and Cambay basins. The third chapter discusses systematic paleontology, as well as microfossil / sample preparation techniques and biostratigraphic data management software utilized in the present thesis. The fourth chapter deals with regional biostratigraphy, systematics, biometric analysis, taxonomic description of species recorded, foraminiferal distribution in the study areas, Tethyan shallow benthic zones, Indian biochronostratigraphic stages and their relationship with the shallow benthic zonation and modified larger foraminiferal biozonation on western Indian shelf. The fifth chapter briefly discusses paleoenvironments of the study areas and generalized hydrocarbon prospects. The sixth chapter comprises the thesis summary and conclusions along with the check lists of foraminifera & proposed biozonation. A list of the publications based on the results presented here is also included at the end of the thesis.

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First of all, I thank Lord Almighty for His kind and unstinted support all through my professional and personal life spanning over thirty three years now, during which, I witnessed a number of ups and downs while sailing through time. I would like to thank Indian Institute of Technology (IIT), Roorkee and my own organization Oil & Natural Gas Corporation Limited (ONGC) for providing me the excellent opportunity to register as part – time research scholar, to complete my Ph.D work and submit the thesis on a subject pursued for long. Working in ONGC provided me much desired knowledge in the varied fields of the hydrocarbon Exploration and Development and my association with the National oil company gave me multifaceted opportunities to learn both the technical as well as managerial domains. This is particularily significant because many of my peers and senior colleagues were of the opinion that continued learning and acquiring higher degrees should be a part of self development, however, with my professional commitments on one hand and my all India movements on the other; this has been made possible now. Getting into business management by acquiring MBA degree and attending to several advanced management modules from the IIMs in India was all charted off in the well known course of life in an Oil company.

At this stage of life when you are a bit lonelier, rather than surrounded by the “friends and seekers,” I can express my thanks to all those people who have directly or indirectly contributed towards my growth and completion of important tasks, the present one also being one of them. I express my heartiest thanks to my research guide Prof. Sunil Bajpai, Director, Birbal Sahni Institute of Paleobotany, Lucknow, U.P., India (Currently on lien from IIT Roorkee), for invaluable guidance, perpetual encouragement and continuous support. I would like to express my sincere thanks towards Head, Department of Earth Sciences, Indian Institute of Technology, Roorkee for facilitating the completion of this research work and submission of thesis. Sincere thanks are also due to Prof. D. K. Mukhopadhyay, Prof. D. C. Srivastava and Prof. V. N. Singh for their kind help at various stages during the course of study.

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(SUDHIR SHUKLA)

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CHAPTER-1: STUDY AREA

1.1 INTRODUCTION

The major outcrop area under study falls in the south-western part of Kachchh, India which is basically a limestone-marl country with vast gently dipping beds and extensive out crops. The low lying hills and domes are characteristic physiographic features in Kachchh mainland which is to a great extent a flat, gently undulating terrain (Wynne, 1869, 1872). In the eastern parts, the Deccan trap forms rather high hillocks because of relatively harder rocks. The weathering effects are also less pronounced in Deccan trap areas, when compared to the Tertiary areas, however at most of the places both the Mesozoic and Tertiary rocks are extremely weathered (Biswas, 1965, 1974). The present geological and micropaleontological studies cover an area roughly between villages Beranda - Vayor to Bernani i.e. Paleogene outcrops in Berwali river section; Kakdi, Doriwali river and road section outcrops near milestone “Narayansarovar 28 kms” in Kachchh Basin. Doriwali River outcrops in the vicinity of Kakdi river (western scarp) section and road section outcrops in the southwestern part of Kachchh demonstrate lower Paleogene formations outcropping with very low dip (Tiwari, 1957). In addition, Tapti river section was also sampled and studied mainly for the Late Eocene foraminifera from the exposures in Surat- Broach areas (Rao, 1969). The late Eocene outcrops near

Amrawati and Tapti river sections in Cambay Basin are partly submerged in river water during rainy season.

In Kachchh, the study area has revealed the Tertiary system represented by Paleocene, Eocene and Oligocene formations. The younger sequences were not mapped / studied because of falling out of the scope of the present work. In Surat-Broach area, the Middle- Late Eocene facies are developed within the Amrawati and Tapti river sections and are richly fossiliferous at certain levels. In both the areas, the rock types are dominated by carbonate sediments, which are richly fossiliferous; however, the clastics are poorly fossiliferous. The larger benthic foraminifera are most significant among the total faunal yield from these samples (Vredenburg, 1906). The other important groups of fossils besides foraminifera include mollusks, bryozoans, corals, nannoplankton, pollen and spores, and other vertebrate and invertebrate groups. The present study directed towards selected larger foraminifera and their biometric analysis has led to the establishment of taxonomic standardization of species through biometric parameters besides providing biozonation, paleoecological interpretation, stratigraphic ranges, occurrences, correlation and allied aspects. With these objectives, the sampling and further studies were carried out by the researcher in Oil & Natural Gas Commission Laboratories at KDMIPE, Dehradun. Both the Kachchh and Cambay basins constitute part of the vast western Indian continental shelf (Fig.1.1), which has witnessed widespread carbonate deposition during the post rift –passive margin phase. The search of hydrocarbon and other economic minerals also categorized and classified major sedimentary basins in India presented in the Fig. 1.2.

FIG 1.1 LOCATION MAP WITH SATELLITE IMAGES OF WESTERN INDIAN SHELF, KACHCHH AND CAMBAY BASIN (STUDY AREAS)

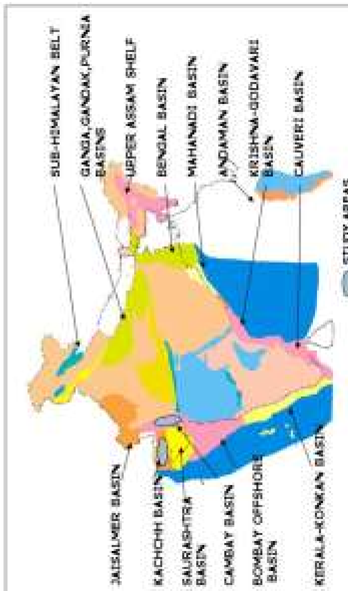


FIG 1.2 MAJOR SEDIMENTARY BASINS OF INDIA

1.1.1 THE GUJARAT STATE

Gujarat is one of the relatively prosperous states in western part of the country and has about 196,077 km² area along with a coastline of 1,600 km. The state has population in excess of 50 million with capital in Gandhinagar near to Ahmadabad. Gujarat's coastal cities served as ports and trading centers since historical times and Gujarat played an important role in the economic development of India. The state has the fastest growing economy, is also one of the most industrialized states of India, and has a per capita GDP almost twice that of the national average. Gujarat is the main producer of tobacco, cotton, and groundnuts in India. Other major food crops produced are rice, wheat, jowar, bajra, maize, Tur, and gram.

1.1.2 KACHCHH

Kachchh has its administrative centre at Bhuj which is well connected by rail, road and air from other parts of the country. With large international seaports in close vicinity the majority of roads are in very good condition and motorable throughout the year. Physiographically, the Kachchh mainland is bounded on western side by the Arabian Sea; on eastern side by the little Rann of Kachchh; on northern side by the great Rann and the islands – Pachcham, Khadir, Chari, Bila and Chorar; and on the southern side by the gulf of Kachchh. The sedimentary basin of Kachchh extends from western part of Banaskantha to Kachchh districts in north Gujarat between meridians 68^0 E to 71^0 30 E and continues in the offshore areas. Kachchh is also the largest district in Gujarat (Fig. 1.3). The Great Rann of Kachchh lies to the north and the Little Rann of Kachchh to the south. In the west its shores are lapped by the Arabian Sea and tidal marshes and creeks here from part of the Indus delta. Being industrial hub and fast developing, even after the large earthquake during the year 2000; the scenario changes rapidly every year coupled with new developments in and around Kachchh. With high quality limestone, lignite and other economic minerals occurring in plenty, the cement, power, transport and ceramics industries have strong foothold in and around the region. The extensive mining even threatens the existence of beautiful outcrops and hill sections in future. Mule tracks and smaller nonmetallic roads are also motorable in most of the field work season. An abundance of tradition, color, and enchantment adds to the remoteness and intriguing history in the Kachchh experience. Common languages spoken in the region include Gujarati, Hindi, and local dialects.

FIG. 1.3 LOCATION MAP: KACHCHH

FIG.1.4 (A and B) SATELITE IMAGES OF SW-KACHCHH SHOWING GEO - MORPHOLOGICAL FEATURES. NOTE THE SEMICIRCULAR PATTERN OF THE SUCCESSIVELY YOUNGER FORMATIONS OUTCROPPING IN THE AREA. THE TEXTURAL DIFFERENCE IS ALSO CORROBORATING TO DIFFERENT LITHOLOGIES OF SUCCESSIVE FORMATIONS.

1.1.3 HOW TO REACH

Indian (Western) railways, private sector and Indian airlines run their regular train, bus and air service to Bhuj, Kachchh. The region being on western most side of the Indian union and incorporating a part of international border is classed as “Restricted Area” as per the Union Government notification. Bhuj can be reached by road or by air from Ahmadabad, Mumbai and several other places in western India. State transport buses are available from Ahmadabad and all big cities of Gujarat. *Tourism-of-India.com* provides complete information on tourism in Kachchh. Kandla a major seaport of the country with its single point-mooring facilities happens to be the free trade zone (SEZ) of India. Kachchh becomes a sort of island during the monsoon months, when the Gulf of Kachchh is separated from the Kathiawar Peninsula (in south) by inundating sea. To the north also, it gets separated from the Sindh region of Pakistan by the flodded Great Rann of Kachchh.

1.1.4 HISTORY & TOURISM

Bhuj, the district headquarters of Kachchh was founded in the year 1548 AD. It was set up when Khengarij I of the Rao dynasty of Kutch shifted his capital from the town of Anjar. Due to its close proximity to the sea, a lot of cultural interaction took place and the Orient and the Occident architecture developed. The town of Bhuj is located low, basically as an amphitheatre of hills dominated by the Bhuja Hill. Kachchh museum and Aiana Mahal are famous tourist's attractions. Bhuj reverberates with thousands of colors, festivity and music during the Kachchh fair. The artistic creativity of the Bhuga people can be seen by their use of vegetable colors to create wonderful designs on the walls, and decorating mirrors and beads. The last day of the fair: Shivaratri festival, at Dhang shows locals dressed in colorful, traditional costumes and competitions such as camel, horse and bullock races and wrestling are organized. The people in Kachchh are traditional, simple, hard working and very good at handicrafts and fine art works. The region produces some of Gujarat's most exquisite crafts like embroidery, tie die fabrics, enameled silverware and other handicrafts. (www.gujarat.nic.in).

1.1.5 CLIMATE

Being in the arid area of the country, the climate of the Kachchh region is extremly hot during summer and very cold during winter. Summer is rather severe in the entire state of Gujarat. The amount of rainfall is very less and during the rainy season the area experiences very scanty rainfall. The best time to visit Kachchh would be between November and March. Arid to semiarid present day environments in Kachchh result in undulatory topography, at places, exhibiting younger stages of weathering of the rocks (Fig. 1.4). Continuous Tertiary formations bedding out in river and major road sections and isolated outcrops are common in the entire area. The rivers in study area are generally dry and seasonal. Some important rivers to name are Berwali, Kakdi, Rakhadi, Khari, Doriwali etc. Flash floods during the rainy season are quite common in the area.

1.1.6 FAUNA AND FLORA

The fauna and flora is not too encouraging in Kachchh, however the area has the distinction in being the first and only marine wild life sanctuary in India i.e. Gulf of Kachchh; in being the sanctuary of wild asses in India; and also for its, famous flamingos or the fire birds. There is also a large bird population, particularly of the large flamingos. The other fauna includes camels – single and double humped; cattle; snakes; Titar; Peacocks, Deers; and small nocturnal creatures. The vegetation in Kachchh is sparse with xerophytes and Mesophytes predominating over any other type of natural vegetation.

1.1.7 LIGNITE AND OTHER MINERALS

Lignite is popularly known as 'Brown Gold' all over the world. Gujarat is rich in high grade Lignite and to explore this GMDC and TAKRAF of Germany have made a joint venture. Large reserves of Lignite, about 200 million tones of lignite have been identified at different locations in Kachchh and geological investigations are on to locate more lignite. Panandhro, the largest of these reserves, has been developed as major mining center of Lignite which is used as a fuel in a large number of process boilers in the state as well as to produce power. It is very alarming that a great amount of Tertiary limestone in the SW-Kachchh is being excavated, mined and utilized for Cement manufacture in the area by large Cement companies i.e. M/S Jaypee Cement; M/S. ABG Cements and others. The rapid industrialization in Kachchh has taken toll on some of the best outcrops and river sections in the area. Recent visits in the area were quite demoralizing as far as the field geology in the area is concerned.

1.2 PREVIOUS WORK:

Pioneering contributions on the Tertiaries of Kachchh include those by Tiwari (1952, 1957); Tiwari and Bhargava (1960); Bhatia (1982, 1985); Biswas (1965, 1993), Singh (1967) and others. Biswas (1965) carried out systematic mapping of Tertiary sediments of Kachchh along with detailed biostratigraphic studies by the palaeontologists of ONGC. This work was largely unpublished and is available in the form of internal (Company) reports. Biswas et. al. (1968) and Biswas & Deshpande (1981) also carried out studies on the basement of the Mesozoic sediments and prepared the geological / tectonic map of the Kachchh basin. Nuttal et al (1925) worked on the Oligocene *Nummulites* of Kachchh, which is supposedly one of the first records of Tertiary larger foraminifera. Subsequently, micropaleontological work was done by Tiwari (1952-70), Sengupta (1959), Mohan et al (1970), Raju (1970), Samanta (1981) Samanta and Lahiri (1985) and others. Mathur (1966) studied the spores and pollens from the Madh series sediments and assigned Paleocene age to the sediments. Bhatt (1968) reported a number of planktic foraminifera such as *Globigerina meckennai, G. yeguaensis, G.rex, Globigerina sp, Globanomalina wilcoxensis* from the *A. granulosa* – *N. atacicus* Zone from the same area. Tandon (1971) recorded planktic foraminifera of definite Paleocene age from the lower part of the Kakdi stage near Nareda.

Sengupta (1964) described three biozones in the middle Eocene of Lakhpat area (in ascending order) on the basis of larger foraminifera:

Zone I: *N.perforatus- N.acutus* Zone

Zone II: *Discocyclina dispansa, D.sowerbyi* and *N. (A.) exponens* Zone

Zone III*: N. beaumonti, Alveolina elliptica, Dictyoconoides cookie, Nummulites bagelensis* and *Discocyclina* sp.

Mohan (1970) recognized planktic biozones in Berwali river section and proposed four foraminiferal zones (in ascending order) for the Babia stage:

1) *Hantkenina aragonensis* Zone

2) *Globigerinoides kugleri-Globigerina frontosa* Assemblage Zone

3) *Porticulasphere mexicane* Zone

4) *Catapsydrax unicavus-Truncorotaloides rohri* Assemblage Zone

Raju (1970) proposed following zones (in ascending order) for the Eocene and Oligocene sequences in the south-western part of the Kachchh Basin:

1) Poorly fossiliferous Zone

2) *N. perforatus- Truncorotaloides topilensis* Assemblage Zone

3) *Orbulinoides beckmannni* Zone

4) *Truncorotaloides rohri* Zone

5) *Nummulites fitcheli – N. intermedius* Assemblage Zone

6) *N. fitcheli - Lepidocyclina (Eulepidina)* sp. Assemblage Zone

7) *Miogypsina (Miogypsinoides) complanata /M. (M.)* sp. cf. *M. bermudezi* Assemblage Zone

Detailed biostratigraphic studies in onland area / wells and offshore wells were continued by the palaeontologists of ONGC and other researchers during 1980s through present day. Recent works in the relevant fields include Shukla (1986, 1990, and 2008) and summations by Raju and Misra (ed. 2011). Jauhri (1991, 1993) studied smaller benthic foraminifera from the middle Eocene of Kachchh. Matsumaru (1974) has carried out exhaustive studies on the Tertiary Larger Foraminifera from the Ogasawara Islands, Japan. Pignatti et. al. (1998) studied Paleogene shallow benthic forms of the Tethys and compiled the Paleogene larger foraminifera reference list. Drobne (2003) extensively studied larger foraminifera at the Paleocene / Eocene boundary on the Adriatic Carbonate and along with co-workers also worked on the microfauna and nannoplankton below the Paleocene / Eocene transition in hemi-pelagic sediments at the southern slope of Mt. Nanos in NW part of the Paleogene Adriatic carbonate platform, Slovenia (2012). Gupta (1993, 1997) and co-workers (2013) have extensively worked on the species diversity of Miocene deep-sea benthic foraminifera and water mass stratification in the north-eastern Indian Ocean and Paleoceanographic and paleoclimatic history of the Somali Basin. The orbitoids and other foraminifera of the upper Oligocene from SW France were studied by Cahuzag and Poignant (1987). Dogra (2004) reported the palynological assemblage from the Anjar intertrappeans, Kachchh and discussed their age implications.

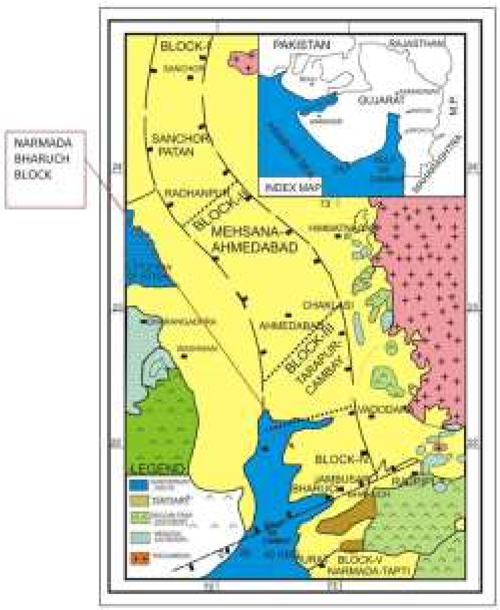


FIG. 1.5 LOCATION MAP: CAMBAY BASIN

In the Cambay Basin (Fig. 1.5), Dutta et al (1969) reported *Nummulites thalicus* from the base of Cambay Shale Formation and dated it as Paleocene in age. Planktic foraminifera such as *Globorotalia pseudobulloides, Globorotalia inconstans* and *Globorotalia* sp. cf. *G. trinidadensis* were also reported from this section. Further, *N. burdigalensis* Zone was also marked in the upper part of the Cambay Shale by Pandey and Dwarikanath (1975) and several other workers of ONGC (unpublished reports). Bhandari (1991) reported non-marine Ostracoda from the Cambay Shale Formation. Several other workers have reported marine and terrestrial vertebrates and mammals (dated Ca 53.5Ma) from the Cambay

Shale Formation, exposed in the Narmada block near Vastan quarries (e.g. Bajpai et. al. 2005, 2008 and 2009). *N. globulus* Zone marking the top of Paleocene (Zone P-6A) is also reported from the Cambay shale of the Vastan area.

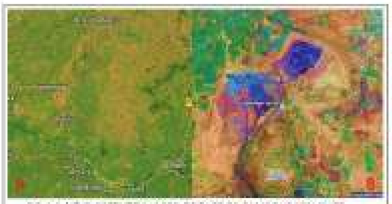


FIG 1.6 A & B: SATELLITE IMAGES OF PART OF CAMBAY BASIN (LATE EOCENE STUDY AREAS); NOTE THE FLAT TOPOGRAPHY AND HIGHLY INHABITED AREAS (A); LIGNITE MINING ACTIVITY IN THE VICINITY OF VASTAN AND MANGROL (B). THE OPENCAST MINING PITS PROVIDE AMPLE SCOPE FOR THE STUDY OF SUBSURFACE SEDIMENTS

FIG 1.7 SATELLITE IMAGE OF OPENCAST MINING PITS NEAR TADKESHWAR (LATE EOCENE CARBONATE STUDY AREA); NOTE THE FLAT TOPOGRAPHY AND HIGHLY INHABITED AREA; LATE EOCENE OUTCROPS MAY BE ASSIGNED TO THE DADHAR FORMATION OF THE CAMBAY BASIN SUBSURFACE.

The Paleocene and Eocene outcrops of the Vastan area (Fig. 1.6) and nearby Tadkeshwar mines (outcrops of the middle and late Eocene) were revisited by the author during 2012 and carbonate facies equivalent to Ankleshwar Formation (Also referred to Dadar Limestone in the subsurface) of the south Cambay Basin has shown prolific larger benthic foraminifera of the Late Eocene age (Fig. 1.7). The faunal assemblage is similar to the outcrop sections in Dinod, Amrawati and Tapi river sections. Several exploratory wells drilled in the area have also shown the presence of similar assemblages in the core and cutting samples attributed to the Paleocene and Eocene formations.

Larger foraminifera and their palaeoecology from late Oligocene-early Miocene sections of Southwestern Kachchh was also discussed by Kumar and Saraswati (1994). They have reported a highly diversified fossil assemblage comprising of foraminifera, gastropoda, pelecypods, echinoids, bryozoa, corals, ostracoda, algae and plant fossils from the mixed carbonate-siliciclastic deposit of Late Oligocene-Early Miocene sequence, from the southwestern part between Waior ($23^0$25'5"N :$68^0$41'37"E) and Aida ($23^0$24'30"N : $68^0$48'10"E). Eighteen species were recorded which belong to *Archaias, Heterostegina, Lepidocyclina, Miogypsina, Operculina, Planolinderina, Sorites* and *Spiroclypeus*. Their internal features and microstructures are illustrated by scanning electron micrographs. For palaeoecological interpretation, the depositional environment is inferred by sedimentary facies analysis. It is found to range from back-reef lagoon to shallow subtidal, intertidal, beach-ridge, swamp and tidal channels. The environmental parameters and biotic interactions are investigated by carbonate microfacies and stable isotopic analysis. The temperature of the ambient sea-water where larger foraminifera grew varied between 17^0C and 27^0C. With this palaeoecological understanding from Kachchh, a model is suggested to explain the major extinction in Middle Miocene and further re-appearance of some taxa in Late Pliocene on the western shelf of India. Excessive nutrition, leading to phytoplankton bloom and diminished light is postulated as the cause of extinction in this region. Some of the genera re-appeared in Late Pliocene when the environment became oligotrophic.

1.3 OBJECTIVE AND SCOPE OF WORK

The following major objectives were pursued during the present investigation:

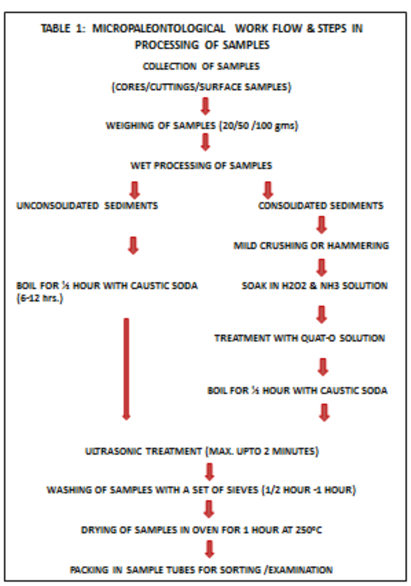
- Recovery, description and study of Paleogene larger benthic foraminifers from south-western Kachchh and south Cambay Basins of Gujarat, western India.
- Taxonomic standardization of important species based on the qualitative and morphometric characters; documentation of stratigraphic ranges and correlation with the SBZ scheme of Serra Kiel et al. (1995).
- Establishing Paleogene larger foraminiferal biostratigraphy for the western Indian shelf on the lines of Shallow Benthic Zonation of Serra Kiel et. al. (1995).
- Proposing Indian equivalents to SBZ scheme to serve as the link between the Mediterranean and Far-Eastern Tethyan species
- Interpreting generalized paleoecological conditions and hydrocarbon prospect of the region.

In south-western Kachchh, Paleogene shallow water carbonate / shale outcrops are extensive and the thickness of outcropping formations increases towards the basinal (Offshore) area. Similar outcrops in Amrawati/Tapti river sections and mining areas near Vastan in south Cambay Basin comprise predominantly Eocene and younger larger foraminiferal facies, which is the key subject of present research investigation. Comprehensive Paleogene larger foraminiferal biostratigraphy on western Indian shelf needs to be established, firstly as the local reference. Such a scheme will be widely acceptable to establish local biostratigraphic zonation and help regional correlations in various Indian sedimentary basins. To overcome the problem of endemism in many larger foraminifera species, proposed biozonation would also serve as the link between the Mediterranean and Far-Eastern Tethyan species.

The morphological / biometric (measurable) changes observed in the tropical, Tethyan larger foraminiferal fauna as compared to their temperate counter parts necessitated detailed study of tropical Indian fauna in our own local stratigraphic context and in order to develop locally applicable biostratigraphic zonation on the lines of Shallow benthic zonation (Serra Kiel et al., 1995). The present work is likely to supplement earlier stratigraphic and chronological investigations carried out by previous workers in the area.

1.4 METHODOLOGY

Although significant geological and paleontological work has been carried out over the study areas by various scientists, it was found that a comprehensive study based on morphometric analysis was lacking and a biostratigraphic scheme on the lines of Shallow Benthic Zonation was desired for sequences rich in the Tethyan Paleogene larger foraminifera. In view of the need to carry out detailed biostratigraphic work incorporating the taxonomic standardization of selected foraminiferal species, a record of foraminiferal species mainly from Kachchh and Cambay basin areas is prepared in the present work. Collection of the samples, wet processing, separation, sorting, identification of isolated microfossils and selected photographic illustrations is completed. Micropaleontological work flow and processing methodology is presented in Table-1. Processing and sample preparation techniques required the use of certain hazardous materials and equipment and are carried out in ONGC laboratories. The interpretation of results and foraminiferal biostratigraphy and paleoecology is also completed. Exhaustive study over Indian nummulitids and other larger foraminifer fauna was carried out earlier by Shukla (2009) and documented as a monograph under the *Paleontographica Indica* (No.9) published in the year 2008 by the KDM Institute of Petroleum Exploration, Dehradun, India.



During the present work, several field trips were undertaken in the outcrop areas of both study areas. Efforts were made to cover the entire Paleogene larger foraminifera occurring in all the epochs and for this purpose, the late Eocene sections in the Cambay basin were also taken into account. The late Eocene sections in the Kachchh onland are eroded away and hardly 50 cms. or 1.0 m section can be traced in the Berwali river area (Biswas, 1986; Shukla, 2008). However, towards the entire offshore / basinal part, the late Eocene sections are commonly recorded.

1.5 SAMPLING AND FIELD STUDIES

The study areas in Kachchh and Surat-Bharuch were visited by the author several times during the years 1985 to 2013. Geological mapping and systematic collection of rock samples were undertaken from the Paleogene outcrops in the study area. Bulk samples (approx 2-5 kg) were collected for laboratory studies. The Berwali river sections were geologicaly mapped with the help of a Clinometer / Brunton Compass and measuring tape. One of the biggest advantage in Kachchh river sections is that one can trace the very low angle dipping beds along their bedding (dip) direction, which also coincides with the downstream direction in most of the SW-Kachchh. The field mapping and outcrop sampling was basically restricted to the Matanomadh Formation, Naredi Formation, Harudi Formation, Fulra Limestone Formation and Maniyara-fort

Formation upto the village Rambada (Figs. 1.8 to 1.35), south of which mostly the Mio-Pliocene formations are outcropping.

FIG. 1.8 DECCAN TRAP OUTCROPS IN THE VICINITY OF DORIWALI RIVER SECTION, EAST OF CULVERT, SW –KACHCHH ; ALSO VISIBLE ARE MARINE LATE PALEOCENE–EARLY EOCENE SECTIONS IN THE BACKGROUND; FIELD VISIT (JAN-2013)

FIG. 1.9 PANORAMIC VIEW OF DECCAN TRAP AND MARINE LATE PALEOCENE-EARLY EOCENE OUTCROPS IN THE VICINITY OF DORIWALI RIVER SECTION, WEST OF CULVERT, SW KACHCHH ; FIELD VISIT (JAN-2013)

FIG. 1.10 NAREDI FORMATION (MARINE EARLY EOCENE) OUTCROPS IN THE VICINITY OF KAKDI RIVER SECTION, WEST OF ROAD TO NARAYAN SAROVAR, SW –KACHCHH; ASSILINA GRANULOSA LIMESTONE IS VISIBLE IN THE UPPER SECTION AS DISCRETE BANDS; FIELD VISIT (JAN-2013); AUTHOR IN THE FOREGROUND

FIG. 1.11 SIDERITIC PARTINGS BETWEEN HARUDI SHALE AND FULRA LIMESTONE (MIDDLE EOCENE) IN BERWALI RIVER SECTION, SW –KACHCHH ; HARUDI SHALE HAVE N. OBTUSUS BAND IN THE LOWER PART; FIELD VISIT (JAN-2013)

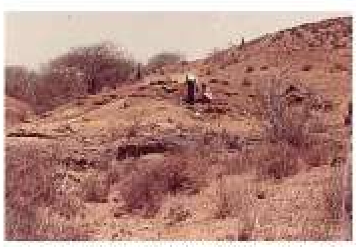


FIG. 1.12 FIELD PHOTOGRAPH SHOWING DECCAN TRAP OUTCROPS IN THE FOREGROUND & OVERLYING SHALE OF NAREDI FORMATION, EAST OF ROAD SECTION NEAR CULVERT CLOSE TO VILLAGE NAREDI

FIG. 1.13 FIELD PHOTOGRAPH SHOWING SIDERITIC PARTING BETWEEN KAKDIAN STAGE (NAREDI FORMATION) AND BABIAN STAGE (FULRA LIMESTONE) NORTH OF VILLAGE HARUDI

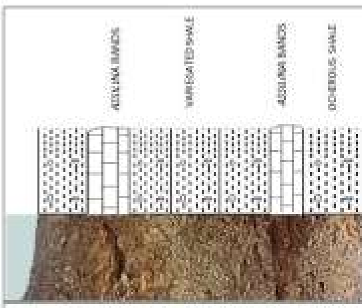


FIG. 1.13 FIELD PHOTOGRAPH SHOWING EARLY EOCENE OUTCROPS OF NAREDI FORMATION, WEST OF ROAD SECTION NEAR CULVERT, CLOSE TO VILLAGE NAREDI

FIG. 1.14 EARLY EOCENE OUTCROPS (KAKDIAN STAGE) NEAR DORIWALI / KAKDI RIVER SECTIONS ; KACHCHH

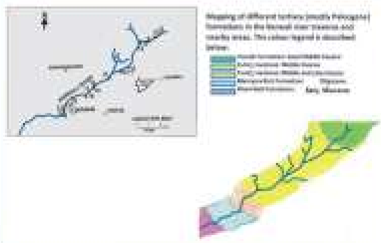


FIG. 1.16 SAMPLE LOCATIONS IN BERWALI RIVER SECTION AND NEARBY AREAS

FIG 1.17. OUTCROPS OF FULRA LIMESTONE NEAR LOCATION-18, BERWALI RIVER SECTION, KACHCHH

FIG. 1.18 CONTACT OF HARUDI SHALE WITH FULRA LIMESTONE NEAR VILLAGE HARUDI, IN BERWALI RIVER SECTION, SW-KACHCHH

FIG. 1.19 FULRA LIMESTONE (BABIAN STAGE-MARINE MIDDLE EOCENE) OUTCROPS IN BERWALI RIVER SECTION, SW –KACHCHH ; CONCHOIDAL WEATHERING AND BIOTURBATION IS VISIBLE IN THE LARGER FORAMINIFERAL LIMESTONE ; FIELD VISIT (JAN-2013)

FIG 1.20 FIELD PHOTOGRAPH SHOWING LARGER FORAMINIFERS STUDIED IN THE MIDDLE EOCENE FULRA LIMESTONE , BABIAN STAGE, LOCATIONS 10-12, BERWALI RIVER SECTION, SW-KACHCHH

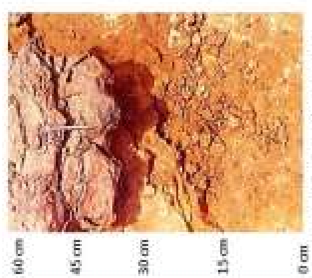


FIG. 1.21 FIELD PHOTOGRAPH SHOWING CLOSEUP OF SIDERITIC PARTINGS OVER-LYING OCHRE SHALE OF KARDAN STAGE, SOUTH-WEST OF RIVER SECTION NEAR VILLAGE NARED

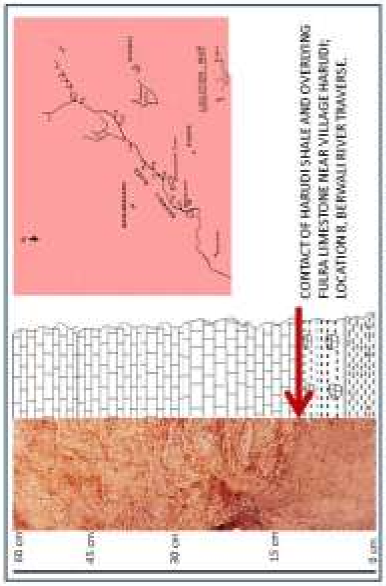


FIG. 1.22 FIELD PHOTOGRAPH OF HARUDI FORMATION – FULRA LIMESTONE CONTACT

FIG. 1.25 FULRA LIMESTONE (MARINE MIDDLE EOCENE) OUTCROPS IN BERWALI RIVER SECTION, SW –KACHCHH; CONCHOIDAL WEATHERING AND BIOTURBATION VISIBLE IN THE LARGER FORAMINIFERAL LIMESTONE; FIELD VISIT (JAN-2013)

FIG. 1.26 LIGHT YELLOW, BUFF FULRA LIMESTONE (MIDDLE EOCENE) OVERLAIN BY HARD DARKER CORALLINE LIMESTONE OF EARLY OLIGOCENE AGE (TUNA FORMATION) NEAR BERWANI VILLAGE, BERWALI RIVER SECTION, SW –KACHCHH; FIELD VISIT (JAN-2013)

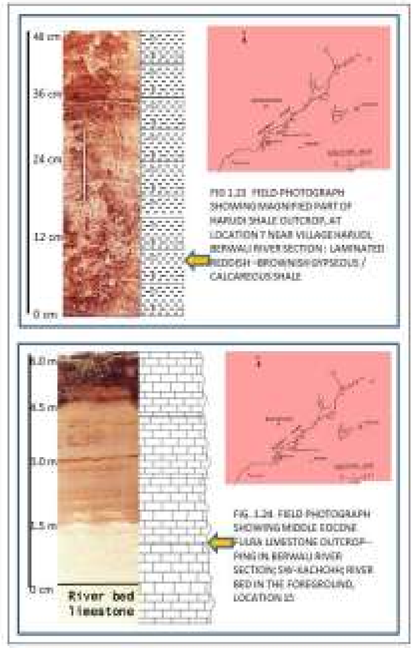


FIG 1.23 FIELD PHOTOGRAPH SHOWING MAGNIFIED PART OF HARUDI SHALE OUTCROP, AT LOCATION 7 NEAR VILLAGE HARUDI, BERWALI RIVER SECTION : LAMINATED REDDISH –BROWNISH GYPSEOUS / CALCAREOUS SHALE

FIG. 1.24 FIELD PHOTOGRAPH SHOWING MIDDLE EOCENE FULRA LIMESTONE OUTCROP-PING IN BERWALI RIVER SECTION; SW-KACHCHH; RIVER BED IN THE FOREGROUND, LOCATION 15

The Paleocene-Early Eocene outcrops are best developed in the Kakdi / Doriwali river sections (Figs. 1.8 and 1.9), on both sides of the culvert (Road to Narayan Sarovar). The eastern side of the culvert even has the outcrops of Deccan Trap and continental Matanomadh Formation (Fig. 1.10). The overlying coal, sideritic band and shale are thin and strongly weathered; however, at places these are about two meters thick and could also be traced in down dip direction towards the major part of the Kakdi river section (Fig. 1.11 and 1.12). The western side has fairly high cliff with outcrops of Naredi Formation which was sampled from the bottom to the top and has provided very fine zones characterized by index larger foraminifera. The interpreted lithology and details about the field location and specific characters of the Naredi Formation, Harudi Formation, Fulra Limestone Formation and Maniyara Fort Formation exposed in the Berwali river and vicinity are also presented in the Figs. 1.14 to 1.35. For the purpose of brevity, those details are not being repeated here. Systematic geological mapping and collection of field samples was also undertaken from the Paleogene (Early Eocene and late Eocene) outcrops in the south Cambay Basin, specially the Amrawati / Tapi river sections (Late Eocene) , Tarkeshwar mines (Late Eocene) and Vastan Lignite Mines (Early Eocene). The details about the lithology and samples are presented in Figs. 1.36 to 1.41. Selected Paleogene well sections yielding good larger foraminifera from the western shelf wells are presented in Fig. 1.42. The locality index and their coordinates are presented in the Annexure-1.

1.6 REPOSITORY OF THE MATERIAL

The entire collection and the species described in this dissertation are housed in the Paleontology Division, KDMIPE, ONGC, Dehradun. The type material has been catalogued as IPE/X01/04/nnnn denoting the name of the Institute, sample series, cabinate and the serial number of the specimen. The abbreviations and their full expanded meaning are referred in the annexure.

FIG. 1.27 LIGHT YELLOW, BUFF COLOURED FULRA LIMESTONE (MARINE MIDDLE EOCENE) IN BERWALI RIVER SECTION, SW –KACHCHH ; VERY LOW DIP TOWARDS SW DIRECTION HELP TRACK BEDS ALONG THE RIVER COURSE OVER LONG DISTANCE; FIELD VISIT (JAN-2013)

FIG. 1.28 LIGHT YELLOW, BUFF COLOURED FULRA LIMESTONE (MARINE MIDDLE EOCENE) IN BERWALI RIVER SECTION, SW –KACHCHH ;ALVEOLINA BANDS SEEN IN MARLY SECTIONS; FIELD VISIT (JAN-2013)

FIG. 1.29 RIVER BED SHOWING CONFORMABLE CONTACT OF HARUDI (OLDER) AND FULRA LIMESTONE (MARINE MIDDLE EOCENE) IN BERWALI RIVER SECTION, SW –KACHCHH ; STUDENT STANDING ACROSS LOCAL NORMAL FAULT POSSIBLY FROM RECENT TECTONIC ACTIVITY; FIELD VISIT (JAN-2013)

FIG. 1.30 FULRA LIMESTONE (MARINE MIDDLE EOCENE) OUTCROPS IN BERWALI RIVER SECTION, SW –KACHCHH ; LARGER FORAMINIFERAL LIMESTONE POINTED BY MR.GOURAV , STUDENT OF KACHCHH UNIVERSITY; FIELD VISIT (JAN-2013)

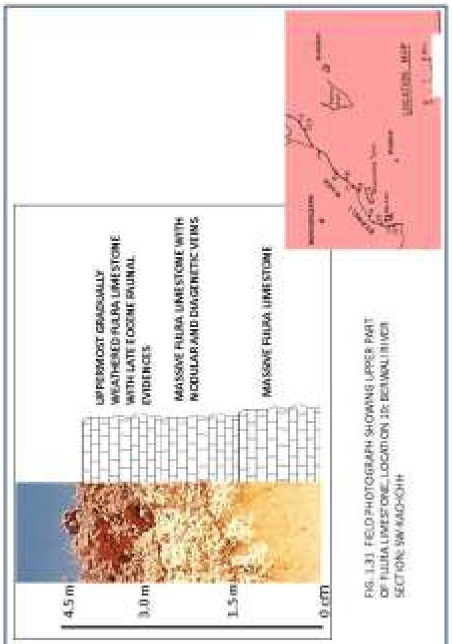


FIG. 1.31: FIELD PHOTOGRAPH SHOWING UPPER PART OF FULRA LIMESTONE, LOCATION 15: BERWALI RIVER SECTION: SW-KACHCHH

FIG. 1.32 FULRA LIMESTONE OUTCROPPING NEAR LOCATION 16, BERWALI RIVER SECTION, SW-KACHCHH

FIG. 1.33 FULRA LIMESTONE OUTCROPPING NEAR VILLAGE BERNANI & RAMVADA

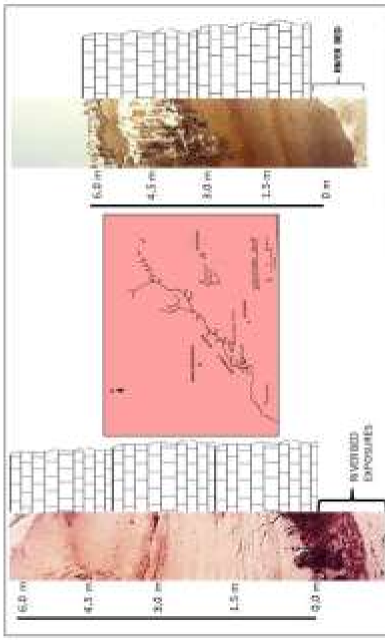


FIG. 1.34 FIELD PHOTOGRAPH SHOWING FULRA LIMESTONE OUTCROPS AT LOCATION 16, IN THE BERWALI RIVER SECTION, SW-KACHCHH

FIG. 1.35 FIELD PHOTOGRAPH SHOWING LIGHT BUFF / YELLOWISH CORAL- ALGAL OLIGOCENE LIMESTONE OUTCROPS IN THE VICINITY OF VILLAGE BERWALI-RAMVADA, LOCATION 23, BERWALI RIVER SECTION

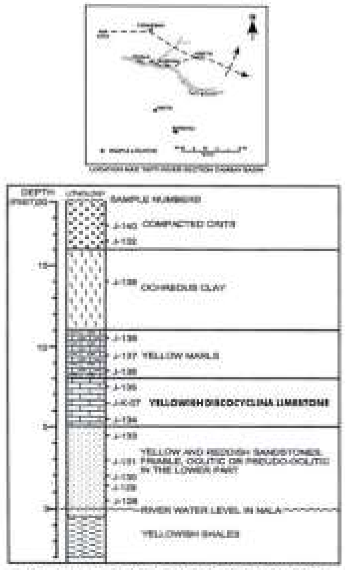


FIG. 1.36 LATE EOCENE OUTCROP SECTION (NEAR BODHAN/ TARKESHWAR) IN CAMBAY BASIN

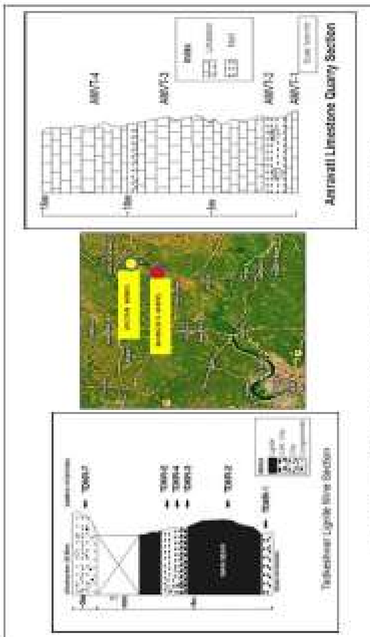


FIG 1.37 OUTCROP SECTIONS IN AMRAWATI, MANGROL- TARKESHWAR AREA, CAMBAY BASIN

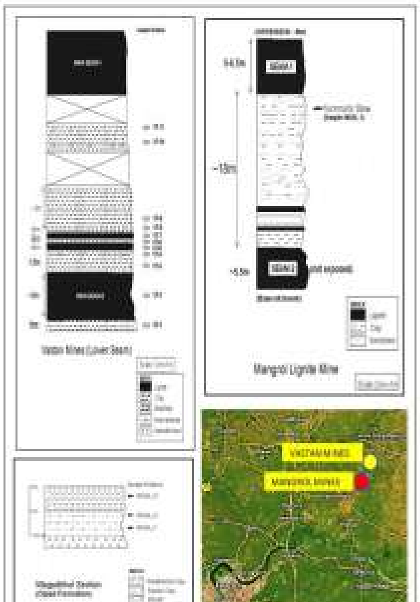


FIG 1.38 OUTCROP SECTIONS IN VASTAN, MANGROL-TADKESHWAR AREA, CAMBAY BASIN

FIG. 1.39 OUTCROPS OF DADHAR LIMESTONE (LATE EOCENE) IN MANGROL-TADKESHWAR AREA, CAMBAY BASIN

FIG. 1.40 QUARRY OF DADHAR LIMESTONE (LATE EOCENE) IN MANGROL-TADKESHWAR AREA, CAMBAY BASIN

FIG.1.41 VASTAN LIGNITE MINES: UPPER PART WITH *N. GLOBULUS* BANDS (EARLY EOCENE)

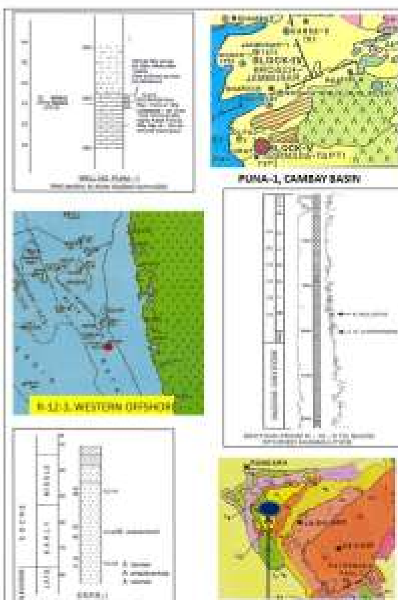


FIG. 1.42 SELECTED PALEOGENE WELL SECTIONS ON WESTERN SHELF

CHAPTER 2: GEOLOGY AND TECTONIC SETTING

2.1 GEOLOGICAL HISTORY OF KACHCHH BASIN

2.1.1 INTRODUCTION

Kachchh Basin is one of the pericratonic basins bordered by Nagar-Parker Hills in the North, Radhanpur-Barmer uplifts in the East and Kathiawar uplift towards South. Six major uplifts recorded by various workers in the basin include Kachchh mainland, Wagad and the four island belt hills (Grant, 1857). These uplifts are surrounded by residual depressions of Great and Little Rann of Kachchh and bounded by sharp, monoclinal faults which developed asymmetric anticlines in the subsurface cross sections (Biswas, 1982, 1993). The zone of marginal folding along the marginal faults was also described as *flexure zones*. All the marginal or master faults are characterized by up-thrust faults with a vertical sense of movement (Prucha et al., 1965). Numerous secondary and cross faults (high angle normal faults) of low magnitude occur along the zones of maximum tension. Beloussov (1962) first used the term: *Residual depression*s which are structural lows forming the Great and little Rann of Kachchh. The coastal plain of the mainland is widest and exposes maximum thickness of the low dipping tertiary sediments. Median high separates the higher eastern part of the basement from the gradually deepening western part and is a prominent structural feature. Several igneous intrusions in different fault blocks give rise to the number of domes and are localized in nature. This also proves genetic relationship between the tectonics and the igneous activity. The main east-west structural lineaments of Kachchh basin can also be traced through the sub-surface of the Cambay Basin. The structures of the Kachchh basin are also related to the adjacent montane zone rather than to the Peninsular India. Four prominent plains of erosion resulting in the development of the paleosols developed during Paleocene, post Paleocene, post Miocene and early Quaternary ages. The regional tectonic element of western shelf basins is presented in Fig. 2.1, after Biswas (1993). The basement faulting along the Precambrian trends define the regional structural pattern in the basin. The Tertiary structural style evolved after the main diastrophic cycle in the main cretaceous times and resulted in synchronous major orogenic cycles and the formation of discontinuous folding patterns.

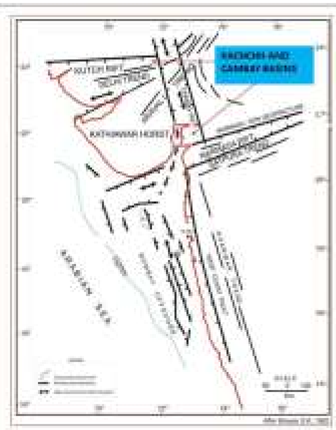


FIG 2.1 REGIONAL TECTONIC ELEMENTS OF WESTERN SHELF BASINS

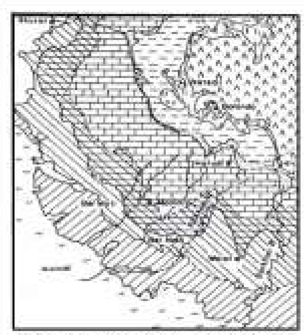
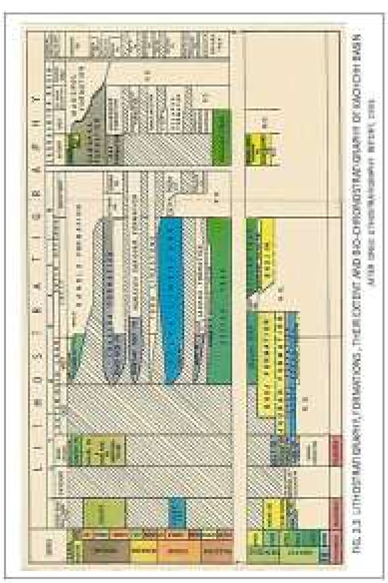
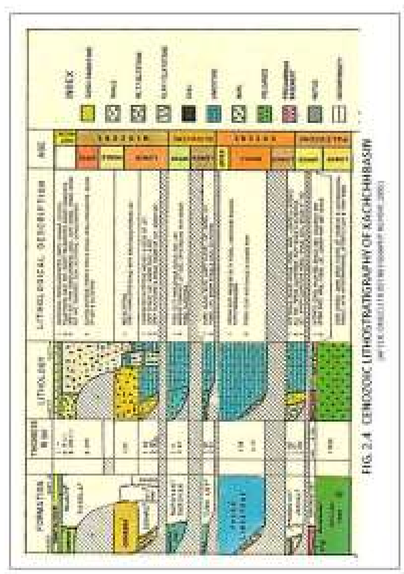


FIG. 2.2 GEOLOGICAL MAP OF SOUTH-WESTERN KACHCHH (AFTER BISWAS & RAJU, 1973)

2.1.2 STRATIGRAPHY

The geological map of the south-western Kachchh (Biswas and Raju, 1973) is presented in Fig. 2.2 and the generalized stratigraphy of the Kachchh Basin is followed after the ONGC summarization on the *lithostratigraphy of Indian Petroliferous Basins: Kachchh basin (1993),* shown in Fig. 2.3. Lithological and faunal characters of Paleogene and basal Neogene formations in the basin were studied by several academicians as well as industrial workers. The Cenozoic Lithostratigraphy of the Katchchh Basin is also followed after the above referred report (1993), describing each formations in greater details (Fig. 2.4). Biswas and Raju (1973); Pandey and Dave (1993) also summarised the lithological and faunal characters of studied formations, which are briefly described below:





Deccan Trap: Alternating volcanic flows of amygdaloidal basalt with intertrapeans. Vast extent both in onland and offshore parts of the basin, referable to uppermost Cretaceous- lower Paleocene in age and sub aerial to subaquous in environment

Matanomadh Formation: Brightly colored clastic / volcanic material, clay, red laterite, bauxite, bentonitic clays, ferruginous clays-tuffaceous sandstone and occasional lignite. The upper contact is marked by lignite bands in disconformable nature. Pollen/spores indicate Palaeocene age with sediments deposited during vaning phase of volcanism under fluvial / lacustrine environment.

Naredi Formation : Consists of three members:

1. Gypseous shale: Grey, brown, glauconitic sandstone and splintery shales with thin layers of gypsum with sideritic concretions with *Nautilus.*
2. *Assilina* limestone: Dirty white limestone and greyish marl with *Assilina spp.*
3. Ferruginous claystone: Grey and brown claystone with layers of gypsum and red ferruginous laminae. Also locally developed black shale facies, pyretic shales and lignite beds.

Naredi formation overlies the Deccan Trap or over a well marked disconformity between this formation and Matanomadh Formation. The upper contact with Harudi Formation is marked by red ferruginous partings and erosional surface. Extensivly worked for the fauna and flora, some of the characteristic foraminifera include *Nummulites globulus indica, N. burdigalensis*, *Assilina granulosa* suggesting Late Paleocene to Early Eocene age and deposited under nonmarine to shallow inner shelf conditions.

Harudi Formation: Consists of splintery shale / yellow limonitic partings with occasional concretionary / oolitic fossiliferous limestone bands in the lower part and calcareous claystone and siltstone with occasional layers of gypsum and carbonaceous shale in the upper part. Coquina beds also occur near the base. Lower contact is disconformable and marked with laterite bed of Naredi formation; upper contact is conformable and marked with overlying massive foraminiferal limestone containing *Discocyclina* (Sengupta, 1959a & b). About three feet thick, extensive, ferruginous, gypseous clayey marlite with *Nummulites obtusus* is also a characteristic marker bed within the formation. The foraminifera include *Truncorotaloides topilensis, Orbulinoides beckmanni, Turborotalia frontosa, Nummulites obtusus* and *N. acutus* (Mohan and Soodan, 1970). Other fossils are *Brarrudosphaera biglowi, Discoaster barbadiensis, Bolies, Xomcus, Porocidaris* and *Cidaris* suggesting Lutetian to lower Bartonian age and littoral to lagoonal (lower part) and inner to middle shelf environment (Singh, 1980a & b) .

Fulra Limestone Formation: Massive, yellowish limestone overlying Harudi Formation, disconformable (cut and fill structures and bioturbation) with overlying

Maniyar Fort formation in the study area. In the Kachchh offshore, Fulra limestone is unconformably overlain by Tuna limestone and the boundary between these is marked by last occurrence of *Pellatispira.* Fulra limestone has maximum thickness (about 60m) outcropping in the Berwali river section which is the main study area. In the offshore subsurface more than 400m thickness of Fulra limestone is common in several exploratory wells. Highly fossiliferous, the formation consists of several species of foraminifera, calc nannofosssils, invertibrates and possibly vertibrates besides other groups of microfossils (Samanta; 1970, 1981). Two biozones: *Orbulinoides beckmanni* zone in the lower part and *Truncorotaloides rohri* zone in the upper part were initially enacted for planktic foraminifers (Tandon, 1976). The larger foraminifera zonation is published by the author (Shukla, 1990) and presented in the thesis. The suggested age is Middle Eocene and sediments were deposited under stable shelf, low energy, conducive, 'foraminiferal banks' probably under inner- middle-shelf environment.

Maniyara Fort Formation: The formation comprises yellowish siltstone and calcareous gypseous claystone, coral limestone, glauconitic argillaceous sandstone, and hard grey to yellowish foraminiferal limestone with silty marl bands. The formation is Oligocene to basal Miocene in age. Four members are observed in the study area (Berwali river section):

1. **Basal Member**: About 4 m, alternating beds of foraminiferal, glauconitic, and brownish to yellowish siltstone and occasional calcareous gypseous claystone. Glauconite concentrations observed at the lower disconformity.

2. The overlying **Lumpy Clay Member** is about 5m thick; cement colur to brownish calcareous lumpy claystone, occasionally containing thin limestone and marl beds.

3. The **Coral Limestone Member** is about 10m thick and consists of dirty white nodular limestone, alternating with calcareous claystone. The upper part grades to grey to dirty white massive limestone with abundant corals forming bioherms.

4. The **Bermoti Member** is about 10m thick and best developed in Berwali and Khari rivers. The lower part consists of brown, friable, glauconitic argillaceous sandstone with pseudoolites. The upper part is thinly bedded, very hard grey to yellowish foraminiferal limestone full of *Spiroclypes ranjani.*

2.1.3 TECTONIC HISTORY AND STRUCTURE

Kachchh Basin witnessed first east-ward, marine transgression over the Precambrian platform during Bathonian times. This was the time, when Africa and India began to separate, and in between a narrow Salt Range sea existed (Krishnan, 1968). Sedimentation in Kachchh Basin continued till the Oxfordian time, when the basin became tectonically active. Apparently, the *Median High* was formed along the hinge line, during this time. The marine sedimentation was completed by the end of Late Jurassic and the deltaic deposition followed during the early Cretaceous (Valanginian - Santonian). During late Cretaceous, the deltaic system was active and sedimentation continued till the regional uplift and erosion near the close of Cretaceous (Biswas and Deshpande, 1970). Most of the present day structures came into existence during this time. The Mesozoic sedimentation in the basin was vast and got terminated by the Upper Cretaceous regional uplift, however, the igneous activity (Deccan trap) continued till the basal part of Paleocene and was followed by peneplanation and lateritization resulting in the deposition of trap-wash and volcanic debris as Madh sediments (Biswas, 1982, 1993). Deccan trap lava flow was the most prominent eruptive activity till the lower Paleocene times. The Tertiary sedimentation in the Kachchh has prominent marine transgressions and intermittent regressions and huge thicknesses of carbonate platform sediments and shale of various ages were deposited. Several unconformities of varying magnitudes vis-à-vis recognizable MFS and MRS are also reported during the tertiary period. The Cenozoic Sequence Stratigraphy of the Kachchh Basin is based after the recent ONGC compilations on the basinal Sequence Stratigraphy working pamphlets (2008). The first tertiary marine transgression was in Ypresian, followed by another one during the Lutetian and Rupelian (Early Oligocene). Further major transgressions with intermittent regressions occurred during Chatian and Aquitanian continuing into the Burdigalian stages (Biswas and Raju; 1973). A major regression coupled with the uplift and erosion was observed Post Burdigalian. Further on, Pliocene to the present day period is primarily the period of deltaic sedimentation under major regressive phase with intermittent marine transgressions. One of the significant features of the tertiary sedimentation is the deposition of marine and paralic rocks over vast areas and with very low (2-3 degrees), gentle dip towards the west and south-west direction. Thickness of tertiary sediments greatly increases in the basinal part (offshore part of the basin) of the subsurface. In terms of sequence stratigraphy, basin during Mesozoic and Early Cretaceous was under rift phase and from Late Cretaceous to Quaternary under the passive margin phase (Fig. 2.5).

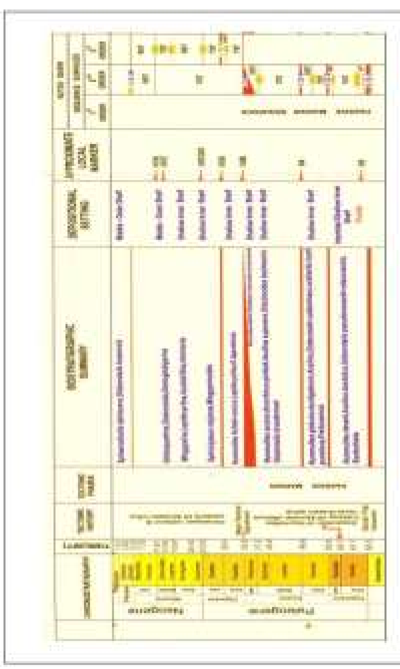


FIG. 2.5 CENOZOIC SEQUENCE STRATIGRAPHY OF KACHCHH BASIN, WESTERN INDIAN SHELF

FIG. 2.6 LOCATION MAP OF CAMBAY BASIN

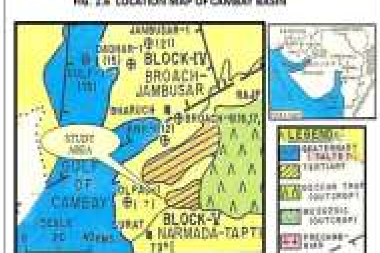


FIG. 2.7 GEOLOGICAL MAP OF PART OF CAMBAY BASIN

2.2 GEOLOGICAL HISTORY OF CAMBAY BASIN

2.2.1 INTRODUCTION

Cambay Basin is a linear NNW- SSE trending, narrow and elongated, intra-cratonic tertiary rift basin filled with more than 7 km of sedimentary rocks overlying the Deccan Trap (referred to technical basement also). Cambay basin is bounded by major eastern and western margin faults and divisible into four tectonic blocks (Fig. 2.6). Several north-south trending normal faults and east–west trending transfer faults characterized the tectonic elements in different blocks. Four tectonic blocks having well defined structural setting recognized in Cambay basin, respectively from south to north are:

- Narmada Block,
- Jambusar - Broach Block,
- Cambay-Tarapur Block,
- Ahmedabad- Mehsana – Patan Block.

Geological map of a part of the southern Cambay basin (Fig. 2.7) shows exposed Deccan Trap formation and areas of the tertiary outcrops.

2.2.2 STRATIGRAPHY

The generalized stratigraphy of the Cambay Basin is followed after the ONGC summarization on the *Lithostratigraphy of Indian Petroliferous Basins: Cambay Basin, (1993)* and presented in Fig. 2.8. Lithological and faunal characters of Paleogene and basal Neogene formations were mostly studied in subsurface (Exploratory wells) by several workers from ONGC (Rao, 1969; and Sudhakar and Basu, 1973) and this information is mostly in the form of unpublished project reports whereas partly published data is also available in the public domain (Fig. 2.9). Pandey and Dave (1993) summarised the lithological and faunal characters of formations covering the Paleogene and basal Neogene which are briefly described below:

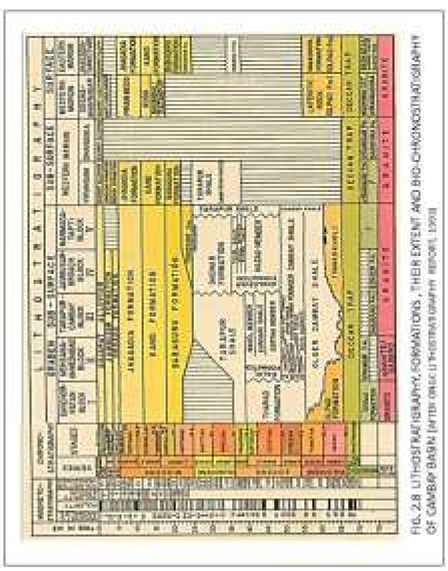


FIG. 2.8 LITHOSTRATIGRAPHY, FORMATIONS, THEIR EXTENT AND BIO-CHRONOSTRATIGRAPHY OF CAMBAY BASIN (AFTER ONGC LITHOSTRATIGRAPHY REPORT, 1993)

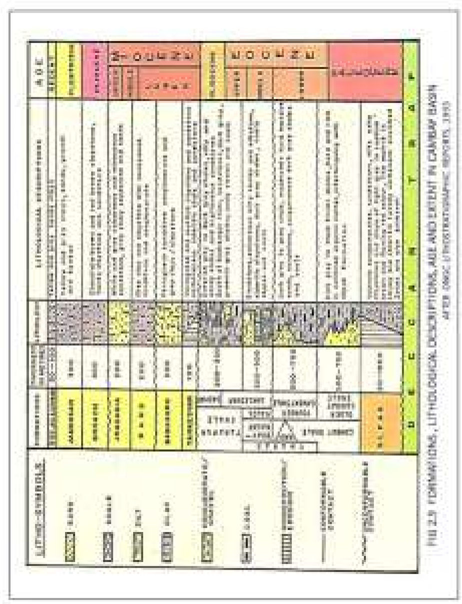


FIG 2.9 FORMATIONS, LITHOLOGICAL DESCRIPTIONS, AGE AND EXTENT IN CAMBAY BASIN AFTER ONGC LITHOSTRATIGRAPHIC REPORTS, 1993

Deccan Trap: Vesicular and non-vesicular dark grey to greenish grey, melanocretic basalts associated with andesite, trachyte etc. Deccan trap is the product of effusive volcanic activity and dated as ranging from upper Cretaceous to Lower Paleocene age. More than 14 lava flows are recognized totaling the entire pack thickness to about 1500m or more and the trap layers are separated by fresh water / lacustrine intertrapean beds. The intertrapeans beds are made of variegated shales, chocolate brown with greenish grey specks and pockets pf calcite. No micro fauna is reported from the intertrapean beds. Deccan trap forms the technical basement in different sedimentary basins on the western Indian shelf, more so ever for the purpose of oil exploration in the area.

Olpad Formation: Volcanic conglomerate, sandstone, silt, shale, claystone, and clays exclusively derived from basalts. Sudhakar and Basu (1973) divided Olpad formation into two lithounits: Grey and mottled claystone and Trap conglomerate-Sandstone. Pandey et al., (1993) divided Olpad Formation into three lithounits; the upper sandstone lithounit, middle claystone lithounit, and the lower Trap lithounit. Olpad Formation is unconformable with underlying Deccan Trap and intertonguing with overlying Cambay shale. Olpad Formation is poorly fossiliferous and the fauna (after Pandey et al., 1993) recorded are thin walled fresh water Gastropods, bivalves shells and chitinous plates. Palynofossils are also recorded and the formation was deposited under fresh water to slightly brackish water coastal environment. Paleocene to Lower Eocene age has been assigned based on palynofossils and indirect stratigraphic methods (Pandey et al., 1993).

Cambay Shale: Dark grey to black, fissile, frequently laminated and bituminous shale with occasional bands of sands and siltstones. Cambay Shale is poorly fossiliferous. Important foraminifera recorded from upper part of the Cambay Shale include: *Nummulites burdigalensis, Operculinoides sp.,* and rare occurrences of *Assilina granulosa* and *Assilina sp.* cf. *A. spira* and ostracodes *i.e. Alocopocythere longilinea, A. abstracta, Gyrocythere grandilavis, Butonia boldi, Paracypris sp.,* and *Neocyprideis suratensis, Phylcetenophora meridionalis* and *Acanthocythereis vastanensis* suggesting Lower Eocene age. The younger Cambay Shale is rich in nonmarine ostracodes. They include *Canada cambayensis*, *Cythereidella gujaratensis*, *Cythereidella govindanii*, *Theriosynoeum*? *Danielopoli*, *Frambocythere colinii*, and *Metacypris bhatiai*. Kumar (1993) reported *Globorotalia* sp., *Chiloguembelina* sp., and arenaceous foraminifera from the upper part of the formation. Cambay Shale was deposited in fluctuating brackish to shallow inner neritic conditions.

Ankleshwar Formation: Alternating sequence of shale, sandstone and claystone. Unconformably underlain by Cambay shale and conformably overlain by Dadhar Formation. Sudhakar & Basu (1973) reported *Nummulites* sp*., Discocyclina* sp*., Trucorotaloides* and *Chiloguembelina* sp*., Nummulites acutus, N. striatus, N. maculatus, N. beaumonti* and *Pseudohastigerina micra,* with *Haplophragmoides, Trochammina* sp. Some ostracodes are *Proxapertites cursus, Polycolpites flavatus, Ploycolpites granulatus, Palmaepollenites ovatus, Dicolpopollis* sp*., Psilodiporites hammeni, Glaphyrocysta exuberans.* Shallow open marine environment and Middle to Upper Eocene age is suggested for the formation with sandstone beds representing delta front sands.

Dadhar Formation: Sandstone with finely bedded shale alterations, unconformable with overlying Tarkesvar Formation. In Narmada block, the formation consists of time transgressive Upper Eocene-Lower Oligocene Limestone towards the onland part which grades to finer clastics in the basinal parts. Fauna includes *Baculogypsinoides tetraedra, N. beaumonti*, *Nummulites fabianii, Pellatispira* sp*., Discocyclina* sp*., N. retiatus, Operculina* sp*., Rotalia* sp*.,* and Gastropods, suggesting shallow marine neritic paleoenvironment.

Tarkesvar Formation: Variegated / mottled claystone, minor argillaceous sandstone and occasional thin coal beds. The formation is unconformable with underlying Dadhar / Tarapur Formation and conformable with overlying Babaguru Formation. Poorly fossiliferous; with rare occurrence of *Quinqueloculina* sp., *Ammonia* sp., arenaceous foraminifera, gastropods and ostracodes suggesting basin wide regression and sub aerial exposure. Suggested age is Upper Oligocene and Lower Miocene (Sudhakar & Basu, 1993); Lower Miocene (Pandey et al., 1993).

2.2.3 TECTONIC HISTORY AND STRUCTURE

The Cambay Basin located in the western Indian state of Gujarat was initiated as narrow elongated intracratonic rift basin trending NNW-SSE. The Tertiary rift graben has accommodated more than 7 km of sediments over the Deccan trap and the basin is bounded by regional level eastern and western marginal faults. Different tectonic blocks are identified in the basin and have their own tectonic settings. The rifting was initiated close to the end Cretaceous and is associated with Deccan Trap eruptions. The basin evolution involved the following three stages:

- Syn rift (Extensional, Paleocene- early Eocene),
- Post rift stage I (Thermal subsidence , Middle Eocene- Early Miocene),
- Post rift stage II (Structural inversion, Middle Miocene-Recent): has led to formation of various structural traps. Major hydrocarbon migration and accumulation occurred in this phase.

The sequence stratigraphy of the Cambay Basin (Fig. 2.10) is followed after the recent ONGC compilations on all the basinal Sequence Stratigraphy working sheets / pamphlets (2008). The Cretaceous and Tertiary Passive margin sequences are separated by intervening Rift phase ranging from Danian-Thanetian and several 1st order, 2nd order and 3rd order parasequences are identified in the Cenozoic period.

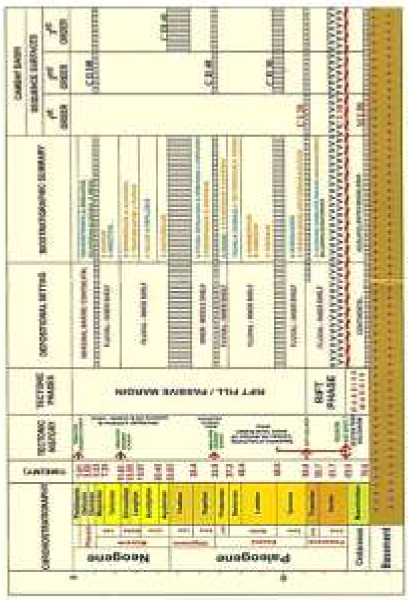


FIG. 2.10 SEQUENCE STRATIGRAPHY OF CAMBAY BASIN, WESTERN INDIAN SHELF
MODIFIED AFTER ONGC-SEQUENCE STRATIGRAPHY HANDOUT,2008

CHAPTER 3: SYSTEMATIC PALEONTOLOGY

3.1 FORAMINIFERA

Amongst the major fossil groups in hydrocarbon exploration, the foraminifera have a known geological range from the earliest Cambrian to the present day but are more prominent during late Carboniferous and Permian and then after Early Cretaceous. The earliest forms which appear in the fossil record (the allogromiinae) have organic test walls or are simple agglutinated tubes.

3.1.1. CLASSIFICATION

Foraminifera are unicellular organisms having a single or many chambered test (calcium carbonate or agglutinated) with pores (foramen) of secondary origin. Their systematic position is as follows:

Phylum: Protozoa

Subphylum: Sarcomastigophora

Superclass: Sarcodina

Class: Rhizopoda

Order: Foraminiferida

Only about 1200 valid genera were recognized and 1267 genera included as synonyms, by Loeblich and Tappan (1964). After commencement of the Deep Sea Drilling Project (DSDP) in 1968, additional 1150 genera were included mainly by scanning electron microscopy and other new techniques.

3.2 MICROPALEONTOLOGICAL PROCESSING TECHNIQUES USED IN THE PRESENT INVESTIGATION

Micropaleontological Techniques involve collection of the samples, wet processing, separation, sorting, identification of isolated microfossils, thin section identification and photographic illustrations. Further on the interpretation of results and assigning biostratigraphy and paleoecology follows. In this part we will be concentrating on the processing techniques. All preparation techniques require the use of certain hazardous materials and equipment and should only be carried out in properly equipped laboratories, wearing the correct safety clothing and under the supervision of qualified staff.

3.2.1 SAMPLE COLLECTION

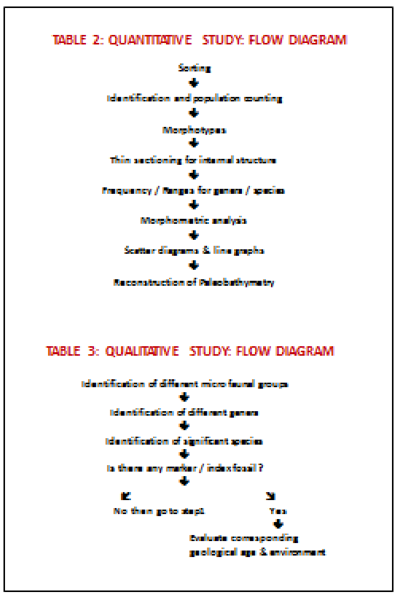
Samples for micropaleontological analysis are basically two types: either from outcrops, or from wells (Subsurface). The well samples may belong to cuttings, conventional cores or side wall cores. The sedimentary rocks are generally fossiliferous and may have microfossils. Besides loose sediments from littoral zones may also be sampled for abundant recent skeletal materials. The lithology /composition and degree of digenesis of sedimentary rocks also determines the selection of samples from exposed sequences. Thin clay-bands, calcareous sediments are usually preferred lithologies, as most of the skeletal material is calcareous in nature; Calcareous shales, limestone and dolomites yield good foraminifers and ostracods. Coarser arenaceous sediments are generally found devoid of foraminifer microfossils. Glauconitic sandstones; and carbonaceous shales may contain conodonts, pollen and spores and pyritized microfossils. When the material is to be collected at predetermined stratigraphic levels, these are called spot sampling. Channel sampling is employed across low dipping outcrops when a large stratigraphic sequence is to be sampled at a constant vertical intervals. Well / bore hole samples are collected for subsurface data, in hydrocarbon exploration.

3.2.2 SAMPLE PREPARATION / WET PROCESSING (WASHING)

The rock samples for micropaleontological investigations are either big chunks like field and core samples or small well cuttings. In former case, the material is to be first broken down by hammer (preferably nylon in case of softer rocks) to 0.5 to 1 cm size before soaking. Planktic and smaller benthic foraminifera are prepared by disintigrating the sediment sample in a glass beaker or porcelain vessel. Water and washing soda or 6% hydrogen peroxide is added for disintigration and then the material is gently heated and allowed to simmer.

Dilute acetic acid may be used, if required, since the acid penetrates through the pre-existing or impact created micro-cracks in the rocks and dissolves matrix making the rock loose and porous. Additives and cleaning agents may be added before the material is washed through a 200/260 mesh sieve until the liquid coming through the sieve is clean (i.e. the clay fraction has been removed). The sample is then dried and packed with proper records, labels and descriptions.

The flow chart of the processing technique is depicted in table 2:



Most of the recent and sub recent samples are **unconsolidated** and loose, especially samples from sea bed. This type of sample is easy to washing. Each sample is accurately weighted and disintegrated in sodium carbonate solution. Then the sample is gently boiled so that disaggregating takes place without any damage to tests of foraminifera and other microfossil. The different size fractions are subsequently dried in an oven at a constant temperature of

100°C. These dried fractions are packed and labelled for micro faunal sorting (Table 1). The processing of **consolidated sediment** is summarized as under:

♣ 10 or 20 gm of material is water soaked and then put into 10 to 20 ml of Hydrogen peroxide and concentrated Ammonia solution of 15 volumes and put in a oven for 8 to 12 hrs.

♣ Then this sample is placed in a bowl of 500ml capacity and water filled upto half of its height. After this work 20 gm " Washing Soda " is put into the solution and its boiled for 20 to 25 minutes.

♣ Washing soda or caustic soda solution is decanted and material is put in a beaker and washes that solution with the help of 63 micron sieve, then the residue sediment covered under water to give ultrasonic treatment. The beaker is placed into the ultrasonic machine for half minute to two minutes.

♣ The ultrasound treated material is washed usually over a 200 mesh sieve but at times even finer sieves are deployed.

♣ It is assessed during washing, if all the clay has been fully removed. In case the clay is seen in the sample steps are repeated.

♣ After ensuring that the sample is well washed of clay grade particles it is dried in an oven at 100-250°C. After drying the sample, processed sample is ready for the next stage that is the sorting of microfossil.

3.2.3 RAPID WASHING AT DRILLSITES

Paleontologist at drill sites may use rapid washing to process and study samples to help in biosteering and age determinations to identify important horizons of hydrocarbon occurrence or high pressure zones. Rapid washing involves 30 minutes boiling of 20-30 gm cutting sample or granulated samples in a strong detergent powder in the ratio of one heaped table spoon in 250 ml water. After boiling, the mixture is cooled and placed in a slow electric mixer to disintegrate. This mixture is subsequently washed over a 200 mesh sieve with water to remove mud and clay. The residue is dried in porcelain crucible under high voltage table lamp or oven and packed for sorting.

3.3 SEPARATION OF MICROFOSSILS UNDER MICROSCOPE

The disintegrated sample residue has different grades of rock particles and released fossils whose ratio (fossils to rock particles) varies differently. It is mandatory to extract fossils from the mixture of unwanted rock particles separated. The basic principle of sorting is to extract fossils from the mixture and separate them for detailed micropalaeontological study. For this small sieve sets, sorting tray and other equipments are required. The sorting tray is a flat girded metal tray on which the disintegrated rock matter spread as a thin coating. Processed sample is put to sieving with the help of different mesh sieves such as 30, 60 and 100 mesh sieves and taken into a triangular copper tray, fraction after fraction, for spreading on sorting tray. With light jerking movements washed residue is spread as thin film on the sorting tray. The tray is now moved under the binocular microscope left to right, line after line. The fossils are picked up by water soaked fine sable hair brush and placed in the assemblage or round punch slides. Big specimens may be picked up by forceps and collected in glass tubes. Common equipments used for this work include:

- Fine sable hair brush for picking up fossils from sediment mixture.
- Triangular copper tray and rectangular sorting plate with square segments.
- Faunal slides (Assemblage slide and Round Punch slides).
- Sieves of different meshes (e.g. 30, 60, 80,100,160 etc) arranged in successive manner having least mesh sieve on top and highest mesh sieve at bottom.
- Needle for picking up very tiny fossils
- Binocular microscope.

Water, malachite green / methelene blue dyes, alcohol, glycerene etc. are also required. The residue after picking fossils are put back into the sampling tubes and stored. Assemblage and index slides are prepared. Care must be taken to clean all sieves and materials used between the preparations of each sample to prevent contamination. The methods of separation of the different groups of microfossils not only depend upon the type and composition of the group but also the type, composition and compactness of material sampled. The quantitative and qualitative analysis steps are summarised in Tables 2 and 3.

Thin sections

Hard, Indurated rocks and larger foraminifera are also studied after making rock thin sections, oriented sections and stained for clarity of internal structure. Most suitable stains are methyline blue or malachite green.

3.4 BIOSTRATIGRAPHIC DATA MANAGEMENT SOFTWARE USED IN THE PRESENT INVESTIGATION: STRATABUGS

StrataBugs is one of the latest amongst biostratigraphic data management software used by major E & P companies and research organizations across the globe. In context with the continuous technological upgradation of the infrastructure facilities at KDMIPE, Paleontology Laboratory procured StrataBugs (version 1.8) during 2006, which is state of the art PC based software operating on UNIX and PC platforms in interactive windows environment. The ability to link with other UNIX and corporate computer systems makes StrataBugs an ideal choice for organizations with various computing infrastructure in place. At the heart of StrataBugs, there is a relational database (taxonomic database) which helps protect the integrity of the biostratigraphic data and provides a sound basis for other applications too. This database is supplied with a dictionary of taxon names which is easily augmented by the user. Biostratigraphic data can also be exchanged with subsidiary databases and charts can also be imported into desktop publishing packages (Fig. 3.1).

FIG. 3.1 STRATABUGS FEATURES

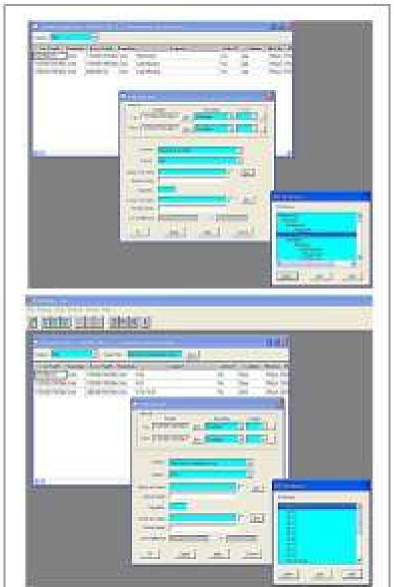


FIG. 3.2 STRATABUGS FEATURES: IGDs

Editing taxon names, linking synonyms, merging and grouping taxa are all facilitated. Bio-chronostratigraphic events can be generated automatically from the database or can be user defined in an integral graphic correlation module or saved for export to other programs. These can be displayed graphically against other well data and used for correlation. Fossil occurrence data may be entered using a membrane keyboard fitted with overlay menus which are verified against the inbuilt taxonomic database. User can also enter interpreted geological data such as ages, biozones, lithostratigraphy, paleoenvironments and sequences (Fig. 3.2). Data can be displayed against graphic lithologies and wireline log traces on the screen and in hardcopies. StrataBugs holds data about each well including Well Name and unique Code, Operator, Field, Country, Quadrant, Block / Sub block, Latitude and Longitude, TD, RTE, Sea Bed and Sea Level, Spud and Completion dates. There is a facility for entering outcrop data measured above or below a reference datum as the samples are recorded by depth / elevation (feet or meters) and types (cuttings, sidewall cores, cores, outcrop).

StrataBugs stores interpreted geological data (IGD) which can be displayed alongside biostratigraphic data and digital log data in user defined scale. Such data types include Biozones, Lithostratigraphy, Chronostratigraphy, Sequences and Paleoenvironments. Boundaries between units may be depth labeled and recorded with different degrees of confidence or as unconformities or faults, and used for inter well correlation. Autocorrelation facility may also be used for multi-well biostratigraphic correlation. Amongst the numerous features it has, biostratigraphic data entry via concept keyboard, strong inbuilt faunal data base, biostratigraphic distribution and events on charts, interpretations, lithology and wireline logs, multi well autocorrelation, chronostratigraphic distribution and events on charts are very interesting and being used in the lab. The software is also helping biostratigraphers to create / update their own digital databases for every fossil group and basin / project and store it for future work.

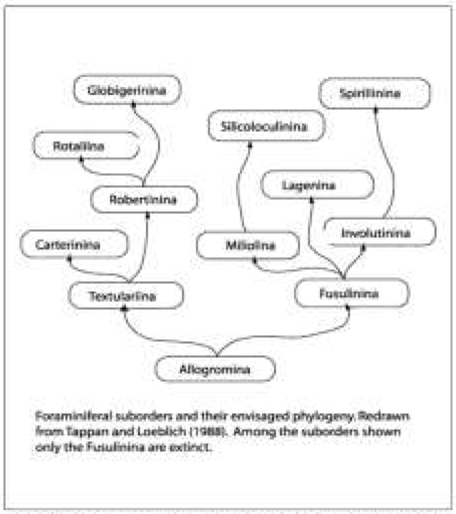
CHAPTER 4: BIOSTRATIGRAPHY

4.1 SYSTEMATICS

Study of the larger benthic foraminifera is the focus of present investigation. The larger benthic foraminifera are common in the Paleogene shallow shelf carbonate facies prevalent over the entire western Indian shelf, subdivided into various geographical entities and basins, from the hydrocarbon exploration point of view.

4.1.1 TAXONOMIC POSITION

Loeblich and Tappan (1964) summarized different classifications of foraminifera proposed by various authors and presented a widely acceptable classification which is followed below. In foraminiferal classification, wall compositions and ultrastructure compositions are more fundamental rather than number and arrangement of chambers. Genetically controlled test composition, mineralogy, ultrastructure and methods of test formation are main characters to define the suborders. Loeblich and Tappan (1988) proposed 3620 generic taxa of *Foraminiferida* of which 2455 genera are recognized and described in new treatise whereas 960 are regarded as synonyms. 208 genera are unrecognizable and 16 are not included in any category, excepting for their names and reference. Within the order *Foraminiferida,* there are suborders viz- *Allogromina, Textulariina, Fusulinina, Involutinina, Lagenina, Robertinina, Globigerinina, Rotaliina* and *Carterinina* (Fig. 4.1) and a number of super-families (about 74), 296 families and 302 sub-families.



Foraminiferal suborders and their envisaged phylogeny. Redrawn from Tappan and Loeblich (1988). Among the suborders shown only the Fusulinina are extinct.

FIG. 4.1 FORAMINIFERAL SUBORDERS AND PHYLOGENY

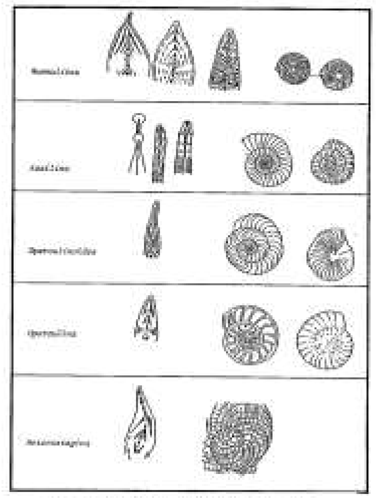


FIG 4.2 ORIENTED SECTIONS AND INTERNAL STRUCTURES OF NUMMULITIDS

4.1.2 BIOMETRIC ANALYSIS

Larger benthic foraminifera need to be studied for their external and internal features (oriented or split sections) for taxonomic / biometric determinations, age, paleoecological assignments and correlation (Fig. 4.2). Freed specimens of each morphotypes are quite useful and all morphologically identical specimens of both the asexual stage i.e. microspheric generation and the sexual stage i.e. megalospheric or macrospheric generation need separately analysed. Following biometric parameters (Figs. 4.3 and 4.4) are useful for the biometric analysis of Indian nummulitids:

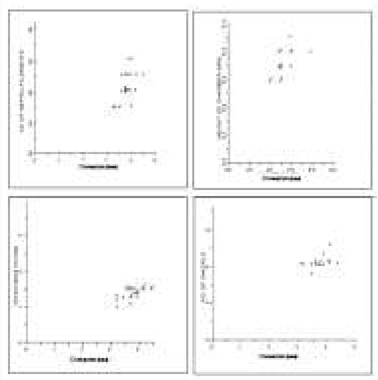


FIG. 4.3 SELECTED BIOMETRIC PARAMETERS

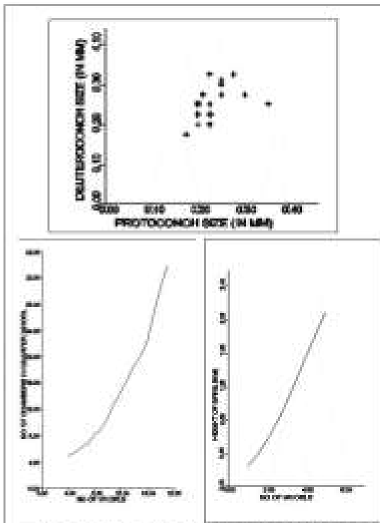


FIG. 4.4 SELECTED BIOMETRIC PARAMETERS

1. **Diameter / thickness**-gives information about the size of test, maximum values are taken into account.

2. **Number of septal filaments / diameter** – on each specimen a count of septal filaments can be made over test surface under the microscope, either by putting water or glycerin or by etching the surface. Septal filament count can be done for compete test or for a quarter portion.

3. **Number of whorls / diameter**- in an oriented section passing through the center of test, all the whorls become visible. A count of these whorls along the growing spire could be easily done, however, while counting the

number of whorls proloculus and deuteroconch are not included in the present study.

4. **Height / width of chamber** – in a growing spire chamber height and width could be measured in 3rd – 4th whorl in the case of megalospheric equatorial section; and 5th – 6th whorl in case of microspheric equatorial section.

5. **Proloculus / Deuteroconch size-** gives information regarding the size of nucleoconch and the inter-relationship of these two initial chambers. Maximum diameters for these chambers, over an equatorial section, are incorporated in the present study.

6. **Number of chambers per quarter whorl / number of whorls** gives information regarding rate of increase of chambers in successive whorls. The values incorporated in the present study include half chambers also.

7. **Height of spire / number of whorls-** also referred to "spiral diagram" or "Spiradiagram" or "winding curve" by many European authors. This parameter gives valuable information regarding the rate of opening of spire and type of coiling. The height or spire is the sum total of individual heights of successive whorls.

4.1.3 TAXONOMIC DESCRIPTION OF IMPORTANT SPECIES

A. CLASSIFICATION

Phylum-–*Sarcomastigophora*

Sub-phylum—*Sarcodina*,

Superclass—*Rhizopoda*

Order—*Foraminiferida,* Eichwald, 1830

Suborder- *Rotaliina,* Delage & Herouard, 1896

Superfamily- *Rotaliacea,* Ehrenberg, 1839

Family- *Nummulitidae*, de Blainville, 1825

Subfamily- *Nummulitinae*, de Blainville, 1825

GENUS- *ASSILINA* D'ORBIGNY, 1839

1. *Assilina daviesi* Cizancourt
2. *Assilina exponens* Sowerby
3. *Assilina granulosa* d'Archiac
4. *Assilina placentula* (Deshayes)
5. *Assilina spinosa* Davies

GENUS – *NUMMULITES* LAMARCK, 1801

1. *Nummulites acutus* Sowerby
2. *Nummulites beaumonti* d' Archiac & Haime
3. *Nummulites burdigalensis* de la Harpe
4. *Nummulites douvillei* Vredenburg
5. *Nummulites fabianii* (Prever) forma *fabianii*
6. *Nummulites fichteli* Michelotti, forma *clypeus* Nuttall
7. *Nummulites fichteli* Michelotti, forma *fichteli*
8. *Nummulites globulus* Leymerie
9. *Nummulites obtusus Sowerby*
10. *Nummulites pinfoldi* Davies
11. *Nummulites vascus* Joly and Leymerie

GENUS – *OPERCULINA* d'ORBIGNY, 1826

1. *Operculina pellatispiroides* Colom

GENUS: *PELLATISPIRA* BOUSSAC, 1906

1. *Pellatispira inflata* Umbgrove

2. *Pellatispira madaraszi* (Hantken)

Order—*Foraminiferida,* Eichwald, 1830

Suborder- *Rotaliina,* Delage & Herouard, 1896

Superfamily- *Orbitoidacea*, Schwager, 1876

Family- *Discocyclinidae,* Galloway, 1928

GENUS- *DISCOCYCLINA* GUMBEL,1870

1. *Discocyclina dispansa* (Sowerby)
2. *Discocyclina omphalus* (Fritsch)
3. *Discocyclina sowerbyi* Nuttall
4. *Discocyclina undulata* Nuttall

GENUS- *ACKTINOCYCLINA* GUMBEL, 1870

1. *Acktinocyclina alticostata* Nuttall

Order—*Foraminiferida,* Eichwald, 1830

Suborder- *Rotaliina,* Delage & Herouard, 1896

Superfamily- *Rotaliacea,* Ehrenberg, 1839

Family- *Rotaliidae,* Ehrenberg, 1839

Subfamily- *Rotaliinae,* Ehrenberg, 1839

GENUS- *DICTYOCONOIDES* NUTTALL, 1925

1. *Dictyoconoides cooki* (Carter)

GENUS- *LOCKHARTIA* DAVIES, 1932

1. *Lockhartia alveolata* Silvestri

Order—*Foraminiferida,* Eichwald, 1830

Suborder- *Textulariina,* Delage & Herouard, 1896

Superfamily- *Lituolacea,* de Blainville 1825

Family- *Orbitolinidae,* Martin, 1890

GENUS- *DICTYOCONUS* BLANCKENHORN, 1900

1. *Dictyoconus indicus* Davies

Order—*Foraminiferida,* Eichwald, 1830

Suborder- *Rotaliina,* Delage & Herouard, 1896

Superfamily- *Orbitoidacea,* Schwager, 1876

Family- *Planorbulinidae,* Schwager, 1877

GENUS- *EOANNULARIA* COLE & BERMUDEZ, 1944

1. *Eoannularia eocenica Cole* and *Bermudez*

GENUS- *LINDERINA* SCHLUMBERGER, 1893

1. *Linderina buranensis* Nuttall

B. DESCRIPTION

Assilina

***Assilina daviesi* Cizancourt**

Plate 1, Figs.1-5; Table 5

Assilina daviesi, Cizancout, M. de, 1938, p.23

Form-A (Megalospheric): Test evolute, discoidal; equatorial periphery circular; axial outline more or less "wasp" shaped, with distinctly depressed poles, rounded margins; D/T ratio 2.40-3.40; Septal filaments 26-30 in final whorl, curved; pustules small, moderate, present over depressed poles, absent toward periphery. Equatorial section shows 3½ - 4½ whorls; spiral growth moderate, consistent; chambers high; intercameral septa straight, slightly inclined; nucleoconch moderate to large, isolepidine type.

Recorded range: Early Eocene

Occurrence: India- Rajasthan, Western Offshore, Himalayan foothills, Bengal Basin, Krishna-Godavari basin. Also from Pakistan.

***Assilina exponens* Sowerby**

Plate 1, Figs.6-10; Table 5

Nummulites exponens, Sowerby, J. de C., 1840, p.719; pl.41, figs.14 a-e

Form-B (Microspheric): Test evolute, discoidal, flat, with gentle depression at poles, big; equatorial plane often undulatory; D/T 9.33-18.00; spire visible over surface excepting at poles; septal filaments 80-120 in final whorls primarily depending on size of test, radial, straight; no granulation, smooth surface. Equatorial section shows 14-19 whorls; loose coiling; whorl lamina fairly thick;

spiral growth rapid, height of successive whorls increases continuously excepting for outermost whorls; chambers high; intercameral septa upright, straight.

Recorded range: Middle Eocene

Occurrence: India; Kutch, Western offshore. Also USSR, Italy, Switzerland, Germany, many western European basins, Pakistan, Iran.

Remarks: *A. mamillata (d'Archiac*, 1847) is regarded as form-A of *A. exponens* (Sowerby).

Assilina granulosa **d'Archiac**

Plate 2, Figs.1-10; Table 5

Nummulites granulosa d'Archiac, 1847, p.1010

Form-B (Microspheric): Test discoidal, evolute, flat, large, slightly depressed at polar region; marginal cord thick and externally gives swollen appearance along the whorls; D/T ratio 8.54-17.7; septal filaments difficult to count on dried surface. However, 48-64 in outermost whorls, straight; pustules around polar region; fade out over later whorls giving relatively smooth outlook to peripheral portion. Equatorial sections with 7-10 whorls, spire divisible into three portions, first whorls tightly coiled, 4^{th} – 9^{th} whorls show rapid increase in the height of spire and outermost whorl tight, only middle portion shows distinct thickening of whorl lamina; intercameral septa double layered, thin, straight (in inner whorls), slightly inclined (in outer whorls); chambers higher than wide.

Form-A (Megalospheric): Test discoidal, D/T ratio 4.72-8.35; septal filaments 28-36 in outer whorl, slightly curved; smooth or pustular test. Equatorial sections show 4-6 whorls; fairly tight coiling; intercameral septa thin, straight, upright or slightly curved in the outer whorls, chambers higher than wide. Axial section shows tight coiling; alar triangular, high; no pillars. Anisolepidine nucleoconch; both chambers subround, however, deuteroconch generally bigger.

Recorded range: Early Eocene

Occurrence- India; Kachchh, Western offshore, Rajasthan, Himalayan foothills. Also from Pakistan, France, Germany, Switzerland, Algeria, Turkey.

Assilina placentula **(Deshayes)**

Plate 2, Figs.11-15; Table 5

Nummulites placentula, Deshayes, G.P., 1838, pp.37-69

Form-B (Microspheric): Test discoidal, flat, evolute; prominently pustulose; obtuse margins, slightly depressed at poles; D/T ratio 5.65; septal filaments straight, 26 in outermost whorl. Equatorial section shows about 8 whorls; spiral growth rapid after 2-3 whorls; intercameral septa thin, upright, slightly inclined; chambers higher than wide.

Form-A (Megalospheric): Test resemble microspheric ones but more prominently pustulose, D/T ratio 4.88-8.90; septal filaments 24-34, heavily beaded with pustules joining to form radial ridges; ornamentation very significant, two types – first, strong, round pustules occur along spire to form distinct circular patterns in the central portion (polar region); second, pustules join together to form radial ridges corresponding to septal filaments; over peripheral portion; more prominently ornamented than microspheric specimen. Equatorial section shows about 4½ - 6 whorls; slightly tight coiling; spiral growth rapid, chambers high intercameral septa straight, upright; nucleoconch small to moderate size.

Recorded range: Paleocene- Early Eocene.

Occurrence: India, Kachchh, Rajasthan, Western offshore. Also from Pakistan.

Assilina spinosa **Davies**

Plate 3, Figs.1-7; Table 5

Assilina spinosa Davies, 1937; In: Davies, L.M. & Pinfold, E.S., 1937, vol.24, pp.31.

Form-A (Megalospheric): Test discoidal, evolute, slightly thick and highly pustulose, D/T ratio 2.90-6.35; septal filaments 28-40, test highly ornamented, strong, spine-like (Protruding) pustules, forming a circular pattern over the successive whorls. Equatorial section shows 5½ whorls, spire growth fast, spiral height increasing in the successive whorls, whorl lamina is moderately thick, chambers generally higher than wide and intercameral septa thin, sometimes slender and inclined. Nucleoconch isolepidine, generally proloculus better round than "Kidney" shape deuteroconch. Alar area resembles "dome" shape, usually conical margins of alar curved, pillars frequent all over test resulting in "spinose" outline, marginal cord thin.

Recorded range: Late Paleocene – Early Eocene

Occurrence: India, Kachchh, Rajasthan, Himalayan foothills, Western Offshore, Krishna-Godavari basin, Meghalaya shelf. Also from western European basins, Pakistan.

Nummulites

***Nummulites acutus* Sowerby**

Plate 4, Figs. 1-6; Table 6

Nummulites acuta, Sowerby, J. de C., 1840, p.327-329

Form-B (Microspheric): Test lenticular, discoidal, flattened; axial margins angular; equatorial plane undulatory; D/T ratio 2.58-5.60; septal filaments 40-64, highly curved or meanderine; small, round pustules all over the test, located between the septal filaments. Equatorial section shows 7-15 whorls; coiling tight initially; whorl lamina moderately thick in central (middle) part of spire; with tight coiling and slow growth; outer part with loose coiling and fast growth; intercameral septa thin, inclined and chambers rectangular, generally slightly wider than high.In axial section alar prolongations visible; marginal cord distinct; whorl lamina moderately thick, uniform; pillars present all over the test, concentrated at poles.Nucleoconch very small, microspheric.

Form-A (Megalospheric): Test lenticular, symmetrical i.e. unlike *N. bagelensis;* pustulose; D/T ratio 1.42-2.00; septal filaments 22-32, strongly curved, faint; test highly ornamented with pustules-larger on poles surrounded by gradually smaller ones towards periphery; pustules present over and adjacent to septal filaments in rather ill-defined patterns. Equatorial section has 3 - 4 ½ whorls; whorl lamina thin; coiling loose; spire growth rapid, intercameral septa thin, inclined, and curved. Nucleoconch anisolepidine type, fairly big, chambers wider than high.

Recorded range: Middle – Late Eocene.

Occurrence: India, Kutch, Western Offshore, Bengal Basin, Krishna-Godavari Basin, Meghalaya.

***Nummulites beaumonti* d' Archiac & Haime**

Plate 4, Figs.7-9; Table 6

Nummulites beaumonti d' Archiac & Haime, J. 1853, p.133

Form-A (Megalospheric): Test lenticular, globose; smooth; axial margins obtuse and fairly rounded; D/T ratio 1.75-2.26; septal filaments 28-44, straight, slightly curved; ornamentation insignificant, concentration of pillars over polar region. Equatorial section shows 7 ½ whorls; spire does not increase much in height in successive whorls; intercameral septa straight, slightly inclined, chambers high; nucleoconch of two chambers; proloculus slightly bigger than deuteroconch; alar prolongations long in axial section; pillars deep, concentrated over polar region.

Recorded range: Middle-Late Eocene

Occurrence : India, Cambay basin, Kachchh, Western Offshore, Krishna-Godavari basin. Also from many west European basins, Pakistan.

***Nummulites burdigalensis* de la Harpe**

Plate 5, Figs.1-7; Table 6

Nummulites burdigalensis, de la Harpe, ed. Rozlozsnik, 1926, p.71

Form-B (Microspheric): Test lenticular; axial margins sharp and angular; D/T ratio 1.77-3.68; septal filaments 32-48, slightly curved, undulatory, more clearly visible over the peripheral part, prominently raised; test highly ornamented, pustules frequent over a large part. Equatorial section shows about 6-8 whorls; slightly loose coiling; intercameral septa strong, thick (up to 3-4 whorls) straight or slightly curved (beyond 3-4 whorls); spiral growth fast; at increasing pace in successive whorls; marginal cord wide, prominent in axial section; alar and alar prolongations long, narrow, frequently traversed by pillars. Nucleoconch very small, microspheric, anisolepidine type.

Form-A (Megalospheric): Test lenticular; D/T ratio 1.45-2.91; septal filaments 22-35, curved, strong ornamentation of pustules over entire polar region, equatorial section shows 3-5 whorls; spiral growth regular, at constant pace right from 2nd whorl; marginal cord fairly wide; nucleoconch chambers subround; intercameral septa stout, upright slightly curved, chambers narrow, higher than wide in initial whorls, reversed beyond third whorl. In axial section alar prolongations long, pillars dense, deep, distinctly visible over polar area.

Recorded range: Early Eocene

Occurrence: India, Kachchh, Rajasthan, Western offshore, Krishna-Godavari Basin, Bengal Basin, Himalayan foothills, Meghalaya shelf. Also from Pakistan, West European basins.

***Nummulites douvillei* Vredenburg**

Plate 5, Figs.8-13; Table 6

Nummulites douvillei, Vredenburg, E., 1906, pp.79.

Form-B (Microspheric): Text lenticular, flattened, discoidal, large; axial margins highly angular; D/T ratio more than 6.33; septal filaments about 40, thin; highly meanderine but non anastomosing type; highly pustulose surface, pustules occur over or adjacent to septal filaments, small as well as large pustules uniformly distributed all over test; polar boss absent. Equatorial section with 8 ¼ whorls; loose coiling; whorl lamina uniformly thick; spiral growth rapid; height of successive whorls increases gradually; chambers much higher than wide; intercameral septa upright, stout, curved towards base.

Form-A (Megalospheric): Test lenticular, small; D/T ratio 2.75-4.00; septal filaments 26-32; highly curved; pustulose surface, bigger pustules concentrated at poles and along spiral line. Equatorial section shows 2-2 ½ whorls; coiling regular; whorl lamina uniformly thick; spiral height not increasing much, intercameral septa upright, double, straight, slightly inclined; chambers high; nucleoconch large, isolepidine type.

Recorded range: Middle Eocene

Occurrence: India, Kutch, Western Offshore. Also from Pakistan.

***Nummulites fabianii* (Prever)**

Plate 6, Figs.1-5; Table 7

Bruguieria fabianii, Prever, 1905, p. 1805-1825

Form-A (Megalospheric): Test lenticular; smooth, no pustules; axial margins angular; D/T ratio 1.90-3.80; septal filaments reticulate, primary reticulation of rectangular shape; subsequently polygonal shapes prominent; equatorial section shows 8 whorls; regular coiling spiral height very slowly increases in successive whorls, whorl lamina thin in inner 3-4 whorls, moderately thick in outer whorls; intercameral septa short, straight inclined at an angle of about 70^0-80^0; chambers wide. In axial section high alar; long, narrow alar prolongations; and small, deep, segregated pillars seen; nucleoconch fairly large size; isolepidine type.

Recorded range: Late Eocene

Occurrence: India, Kachchh offshore, Cambay basin, Western offshore. Also from west European basins.

***Nummulites fichteli* Michelotti, forma *clypeus* Nuttall**

Plate 7, Figs.1-3, 5, 8, 12; Table 7

Nummulites fichteli Michellotti, G. 1841, p.296.

Form-B (Microspheric): Test lenticular, flattened; D/T ratio 4.10-7.24; septal filaments reticulate, strongly anastomosing type; polar area thick, often an ill-defined Polar plug may be present. Equatorial section with 23-38 whorls; whorl lamina thin; spire growth regular after 5-6 whorls; initially the first part (6-8 inner whorls) shows gradual increase in the height of spire; intercameral septa almost straight and upright, whorl lamina thin; second part (8^{th} to 18^{th}-19^{th} whorls) shows almost constant, regular growth, less increase in the height of whorls and wider chambers; and the outer portion (5-10 outermost whorls) shows gradually decreasing height of spire; slender, inclined septa at about 50^0 to 60^0 angle, often badly preserved and different to count. Axial marginal cord small;

occasional pillars in outer whorls; alar prolongations short; while alar area in between middle to outer whorls slightly wide. Chambers are wider than high, rectangular, with H/W ratio 0.64-0.85.

Form-A (Megalospheric): Test lenticular, with polar plug, axial margins angular; D/T ratio 1.75-3.65; septal filaments with high grade reticulation. Equatorial section shows 2-7 whorls; tight coiling; spire growth regular and successive whorls do not increase much in height; whorl lamina thin; intercameral septa very thin, slender and curved; chambers wider than high; nucleoconch large. Axial section shows high and narrow alar area; prominent marginal cord; large anisolepidine nucleoconch.

Recorded range: Early Oligocene

Occurrence: India, Kachchh, several basins; world over many basins

Nummulites fichteli* Michelotti, forma *fichteli

Plate 7, figs.4, 6, 7, 9, 10 and 11; Table 7

Nummulites fichteli, Michelloti, G. 1841, p.296

Form-B (Microspheric): Test lenticular, flattened, generally with uneven sides due to undulatory equatorial plane; well rounded axial margins; D/T ratio 5.70-6.27; septal filaments reticulate, highly anastomosing and form the surface ornamentation of test; no polar plug (mammilla) or pustules. Equatorial section shows about 16-38 whorls; tight coiling; thick whorl lamina; spire divisible into three parts- inner, middle, and outer; inner part consists of about 6-8 whorls showing very tight coiling and less increase in the height of successive whorls; middle part, from 8^{th} – 9^{th} whorl to about 26^{th} – 28^{th} whorl, characterize rapid growth of spire and successive whorls show an increase in their height specially in the beginning, however, latter whorls in this part do not grow much and here the spire consists of 28^{th} to 38^{th} whorls and again shows tight coiling, and a gradual decrease in the height as the spire grows; chambers wider than high, often in middle part of spire; intercameral septa thin, slender and highly inclined (at about 45^0 – 50^0 angle in the inner part, poorly preserved in outermost whorls. Axial section shows 21-26 whorls: tight coiling; whorl lamina thin; marginal cord slightly thick; outer whorls alar area high and wide and alar prolongations short and indistinct.

Form-A (Megalospheric): Test lenticular, well rounded, obtuse axial margins; D/T ratio 2.80-5.31; septal filaments reticulate, anastomosing, often the reticulation pattern more complex over polar area, however, sometimes in smaller tests peripheral portion exhibits slightly primitive reticulation comprising of rectangular shapes; no pustules or polar boss, reticulation of septal filaments forms distinct ornamentation. Equatorial section shows about 5-7 whorls; fairly tight coiling, thin whorl lamina; intercameral septa strong, moderately thick, inclined at about 45^0-50^0 angle; chambers wider than high, in outer whorls chamber width could well be 2 to 2 ½ times of the height. Regular opening of spire, axial section shows prominent marginal cord; large anisolepidine, nucleoconch and wide alar area wide, alar prolongations long; pillars scattered all over the test.

Recorded range: Early Oligocene

Occurrence: Widely occurring, India, Kachchh, Western Offshore basins, Cambay basin, Krishna-Godavari basin. A prominent index marker for early Oligocene age in several basins, world over.

Nummulites globulus **Leymerie**

Plate 8, figs.1-3; Table 6

Nummulites globulus, Leymerie, A., 1846, pp.5-41

Form-B (Microspheric): Test lenticular, poles prominent; sharp angular margins; D/T ratio 1.87-2.76; septal filaments 36-48, highly curved, raised; pillars deep, sunken type, concentrated in polar region, join together to form polar plug. Equatorial section shows 5-8 whorls; spiral opening fast in first 3-4 whorls, after that almost constant; intercameral septa stout, double, upright, also inclined at about 80^0-85^0; whorl lamina uniformly thick, marginal cord indistinct; chambers high. Nucleoconch is very small, microspheric.

Form-A (Megalospheric): Test similar to microspheric forms; but smaller and more globular, lenticular-globose, poles prominent; angular axial margins; D/T ratio 1.73-2.26; septal filaments 27-40, raised; ornamented with distinct polar plug or closely placed mass. Equatorial sections with 3 ½ - 6 whorls; whorl lamina thick; spiral growth uniform, regular, successive whorls at almost constant height; intercameral septa stout, upright, often slightly inclined at about 80^0 angle; chambers high. Axial section with slightly loose coiling; and wide alar

Recorded range: Paleocene-Early Eocene

Occurrence: India, Kachchh, Western offshore, Rajasthan, Krishna-Godavari basin, Bengal basin. Also from Pakistan, East Indies west European basins.

Nummulites obtusus Sowerby

Plate 6, Figs.7-10;

Nummulites obtusa, Sowerby, J. de C., 1840, pp.327-329

Form-B (Microspheric): Test lenticular, globose, oval or asymmetrical; axial margins obtuse, rounded; diameter 6.25-17.00mm; thickness 2.50-8.00mm; D/T ratio 1.56-2.62; septal filaments show considerable variation; radial, slightly curved or undulatory in smaller test; highly curved, wavy, meanderine or anastomosing in bigger test; "trabeculae" associated with septa form very fine network of septal structure. Equatorial section shows 15-36 whorls, tight coiling; whorl lamina thin; spiral opening variable:divisible into three parts- (a) Inner (up to $4^{th}/5^{th}$ whorl) with low height of spire, thick, straight intercameral septa; (b) Middle ($5^{th}/6^{th}$ to $10^{th}/18^{th}$ whorls depending on the size of specimens) with successively increasing height of spire; (c) Outer (beyond $10^{th}/18^{th}$ whorls) with greatly reduced height of spire; marginal cord prominently visible in axial section. Nucleoconch very small, microspheric.

Recorded range – Middle Eocene.

Occurrence - India, Kachchh, Western Offshore, Bengal basin.

***Nummulites pinfoldi* Davies**

Plate 8; Figs.4-6, Table 6

Nummulites pinfoldi, Davies*,* L.M., 1940, p.209

Form-A (Megalospheric): Test lenticular: poles prominent; axial outline hexagonal with flat poles; D/T ratio 1.44-1.94; septal filaments 36-52, raised, straight or slightly curved; one single, large, flat polar plug at each poles.Equatorial section shows 4-7 whorls; fairly tight coiling; whorl lamina thick; nucleoconch isolepidine; chambers generally higher than wide; intercameral septal straight, stout; in axial section height of alar area increases in successive whorls.

Recorded range: Middle Eocene

Occurrence: India, Kachchh, Western Offshore, Bengal basin, Krishna-Godavari basin. Also from Pakistan.

***Nummulites vascus* Joly and Leymerie**

Plate 8, Figs.7-9; Table 6

Nummulites vasca nobis, Joly and Leymerie, 1848, p.38, 67.

Form-A (Megalospheric): Test lenticular, poles prominent, axial margins obtuse; D/T ratio1.5-1.72; 12-19 raised septal filaments, slightly curved towards periphery. Equatorial section shows 3 - 4½ whorls; slightly tight coiling; thick whorl lamina, intercameral septa stout, thick, inclined; rapid spiral growth. Axial section shows 4 - 4½ whorls; tight coiling; small marginal cord and short alar prolongations. Isolepidine, subround nucleoconch.

Recorded range: Early Oligocene; also recorded in Oligocene.

Occurrence; India, Kachchh, Western Offshore, Cambay basin, east coast basins.

Pellatispira

Pellatispira inflata **Umbgrove**

Plate 9, Figs.1-3

Pellatispira inflata Umbgrove, J.H.F., 1928, pp.63, figs. 42-49; 50-56.

Test lenticular; globose, inflated; very thick; evolute; pustules very prominent, canal system openings giving pitted look to the test; Observed D/T values (mm) are 2.33/1.33; 1.40/1.00; 2.66/1.66; and 2.40/1.33. Equatorial section shows 2-3 whorls; whorl lamina very thick; frequently traversed by radial and intercameral canal system; chambers domal; intercameral septa slender curved or inclined.

Recorded range: Late Eocene

Occurrence: Rajasthan, Cambay basin, Kachchh offshore; KG and east coast basins

Pellatispira madaraszi **(Hantken)**

Plate 9, Figs.4-6

Nummulites madaraszi, Hanken, M.V., 1875, pp.1-93, Table. 1-16

Test discoidal; flat; evolute in outer whorls; loosely coiled; pustulose and perforated; observed D/T values (mm) are 2.20/0.80; 2.40/0.93; 2.33/0.93; 2.46/1.00 and 1.86/0.80;

equatorial section shows 2-3 whorls, thick, perforated whorl lamina with complex canal system, spire rapidly opening after ontogenetic stage; chambers domal; proloculus slightly smaller than deuteroconch.

Recorded range: Late Eocene

Occurrence: Cambay basin, western offshore, K.G .basin, Bengal-Shilong shelf.

Discocyclina

***Discocyclina dispansa* (Sowerby)**

Plate 10, Figs.1-3;

Lycophris dispansus Sowerby, 1840, p. 327, pl. 24, figs.16, 16a-b.

Form-A (Megalospheric): Test medium to large size; umbonate; flattened, uniform granulation, prominent over umbo, medium to large size granules present. Observed D/T values (mm) are 6.80/2.66; 7.86/3.00; 6.66/2.66; 5.33/2.66 and 4.66/2.33. Single equatorial layer with rectangular chambers arranged in somewhat concentric spiral rings surrounding the initial chambers. Chambers alternate in successive spirals; nucleoconch bilocular, eulepidine and surrounded by periembryonic chambers; axial section thick at poles; lateral chambers elongated, numerous, frequently traversed by long pillars.

Recorded range: Middle – late Eocene

Occurrence: India, Kachchh, Western Offshore, Bengal basin, Krishna-Godavari basin. Also from Pakistan.

***Discocyclina omphalus* (Fritsch)**

Plate 10, Figs. 7-9

Discocyclina omphala, Fritsch, K. von; 1878, pp.139-146, pl.18, figs.13.

Form-A (Megalospheric): Test lenticular, medium to large size, sometimes saddle shaped; inflated in center to form distinct, umbonal area which has a pronounced depression in the center; granulated exterior; almost equal size granules present all over test; observed D/T values (mm) are 3.33/1.00; 2.80/0.93; 1.93/0.93; 1.93/0.93; 3.20+/0.80 and 3.33+/0.80. Equatorial section with eulepidine nucleoconch, medium size; chambers small, square to rectangular, alternating and thick walled arranged in concentric spirals; no elongation of chambers seen. Axial section shows marked gentle depression over umbonal area, thin median layer and equally distributed pillars.

Recorded range: Middle-late Eocene

Occurrence: India, Kachchh, Western Offshore, Bengal basin, Krishna-Godavari basin. Also from Pakistan.

***Discocyclina sowerbyi* Nuttall**

Plate 10, Figs. 4-6.

Discocyclina sowerbyi Nuttall, W.L.F., 1926, pp.149-150, pl.8, figs.1-3

Form-A (Megalospheric): Test medium to large size; lenticular, saddle shaped or flat and thin; mostly flanges of test are not complete; great variation in size and shapes observed; umbonal area generally thick, granulation profuse, small almost equal size granules occur over whole test; observed D/T values (mm) for a few specimens are 7.33/2.33; 2.80+/1.80; 2.13+/1.66; 8.33+/2.66; 3.86+/1.80 and 5.46+/1.80; Equatorial section with large size eulepidine nucleoconch, smaller proloculus completely enclosed by large size deuteroconch; median layer single, equatorial chambers rectangular, elongated, arranged in concentric spirals. Axial section shows very thin median layer and very large nucleoconch.

Recorded range: Middle – late Eocene

Occurrence: India, Kachchh, Western Offshore, Bengal basin, Krishna-Godavari basin. Also from Pakistan.

Discocyclina undulata **Nuttall**

Plate 11, Figs. 1-3

Discocyclina undulata, Nuttall, W.L.F., 1926, pp.115-164, pp.7, figs. 8-9, pl.8, fig.5.

Form-A (Megalospheric): Test medium to large size; umbonate; undulatory or sometimes saddle shaped; with very wide, thin lateral flange and central inflated umbo, small size granules distributed all over test; observed D/T values (mm) are 7.33/2.00; 8.00+/2.00; 4.53+/1.66; 2.80+/1.66; 2.86+/1.66; 8.00+/2.00; 4.53+/1.66; 2.80+/1.66; 2.86+/1.66; 8.00+/2.00; 4.53+/1.66; 2.80+/1.66; 2.86+/1.66. Large size bilocular nucleoconch with smaller protoconch completely enclosed by very large deuteroconch; periembryonic chambers present in ring shape arrangement, further surrounded by concentric rings of equatorial chambers which are elongated, rectangular, alternating and rather thin walled; pillars deeply seated, lateral chambers bigger.

Recorded range: Middle Eocene

Occurrence: Kachchh, Western offshore.

Other larger foraminifera

***Operculina pellatispiroides* Colom**

Plate 8, Figs. 10-11; Table 7

Operculina pellatispiroides, Colom, G., 1954, p.182.

Form-A (Megalospheric): Test discoidal, low flaring, involute during early stage, after that evolute, flattened; margins gently rounded; D/T ratio 3.42-5.38; septal filaments curved, raised pustulose, 16-22 in final whorls; pustules associated with septal filaments, often join together to form ridges, arranged in circular patterns. Equatorial section shows 2½ - 4 whorls; inner whorls with slightly tight coiling, beyond 2^{nd} whorl loose coiling; spiral height considerably increases; whorl lamina slightly thick; chambers high; intercameral septa gently curved, inclined; nucleoconch small.

Recorded range: Lower Eocene, Upper Ypresian and lower Lutetian.

Occurrence; India, Kachchh; several other basins; Also from SE Spain.

Remarks; *O. pellatispiroides* resembles *O. jiwani* reported from Paleocene-Eocene of Pakistan, however, *O. pellastispira* is characterized by more flaring of whorls as compared to *O. jiwani*.

Eoannularia eocenica Cole **and** ***Bermudez***

Plate 11, Figs.6-7

Eoannularia eocenica; Cole and Bermudez, 1944, pp.342, figs. 562, 1-4.

Form-A (Megalospheric): Test discoidal; flat or concavo-convex; sometimes umbonate; smooth, without significant ornamentation; no granulation; calcareous; coarsely perforated; D/T values (mm) are 1.93/0.46; 1.53/0.33; 1.46/0.33; 1.46/0.33 and 1.60/0.33. Equatorial section shows biloculine embryonic apparatus; proloculus small, round, partly enclosed by deuteroconch; whorls many, indistinctly arranged as annular rings in a single layer; chambers rectangular and alternating in position; however in inner annulus often these are with arched walls.

Recorded range: Middle Eocene

Occurrence: Kachchh, western offshore basins

Linderina buranensis **Nuttall**

Plate 11, Figs. 9-10

Linderina buranensis, Nuttall, W.L.F. in Silvestri, 1939, pl.4, fig.5.

External: Test discoidal; calcareous; perforated; central portion thickened; biconvex; equatorial periphery crenulated or lobulate; surface smooth, small granules; observed D/T values (mm) are 1.53/0.66; 1.13/0.60; 1.46/0.66; 1.33/0.60; 1.40/0.66; 1.40/0.60; 1.13/0.53 and 1.13/0.53. Equatorial section shows small, bilocular embryonic apparatus surrounded by concentric rings of arched arcute or ogival chambers; equatorial layer single; lateral chambers not visible; chambers on equatorial plane alternate with each other in successive rings (annuli).

Recorded range: Eocene

Occurrence: Kachchh, western offshore basins

***Lockhartia alveolata* Silvestri**

Plate 9, Figs. 7-9, Table 5

Lockhartia alveolata, Silvestri, 1942, pp.49-89, pl.11, fig.4.

Test conical to lenticular; calcareous, smooth to prominently pustulose spiral side; trochospiral coiling with wide umbilicus filled up by the calcite plates; coarsely perforated, with interio-marginal slit-like apertures; vertical section shows single trochospiral layer with bilocular embryonic apparatus; 3-4 whorls and arcute chambers; observed H/W values (mm) are 0.93/1.60; 0.46/0.80; 1.16/1.46. *L. hunti* Ovey regarded as the junior synonym of *L. alveolata* Silvestri.

Recorded range: Eocene

Occurrence: Kachchh, Rajasthan, Western offshore basins, Cambay Basin, Krishna-Godavari Basin, Bengal Basin, some parts of Himalayan foothills

***Dictyoconoides cooki* (Carter)**

Plate 6, Fig. 6

Conulites cooki, Carter, H.J., 1861, p.457, pl.15, figs.7a-7g.

Test large, spiral side conical; umbilical side flattened, single wide, conical, spiral "inverted cup" filled up with numerous vertical pillars, similar to *Lockhartia;* excepting for large size and multi-spiral character of the *Dictyoconoides*; observed H/W values(mm) are 8.40/2.66; 4.66/2.33; and 3.73/2.26. Trochospiral initially, with nucleoconch at the apex of cone; apertures multiple, opening into umbilical cavity; in vertical section spiral chambers with outward growth and curved walls with intercalary whorls.

Recorded range: Middle Eocene

Occurrence: Kachchh, Rajasthan, Western Offshore, Krishna Godavari Basin, Himalayan foothill areas (Subathu)

***Dictyoconus indicus* Davies**

Plate 11, Figs.8, 11

Dictyoconus indicus, Davies, L.M., 1930, p.497, pl.1, figs. 10-13, pl.2, figs.7-11, 13, 16

Test conical, fairly big size, with high cones and pointed apex, initial coiling trochospiral; embryonic apparatus situated in apex portion; vertical section shows marginal zone with one line of chambers and vertical / horizontal partitions or plates within the chambers, central area filled up with labyrinthic shape plates and interseptal pillars; observed H/W values (mm) are 1.66/1.40; 1.53/1.40; 1.73/1.20 and 1.73/1.00.

Recorded range: Early to Middle Eocene

Indian occurrence and observed range: Kachchh, Western offshore, Rajasthan, Bengal basin

***Acktinocyclina alticostata* Nuttall**

Plate 11, Figs.4 - 5

Acktinocyclina alticostata, Nuttall, W.L.F., 1926, pp.115-164, pl.1-8.

Form-A (Megalospheric): Test discoidal, stellate; inflated umbo, granulated; radial rays 8-16, of which 6-8 are major; unlike *Asterocyclina*, radiating portions connected with flanges; single layer of primary chambers arranged in roughly annular (ring shape) rows radiating away from the centre; nucleoconch nephrolepidine or eulepidine, a number of periembryonic chambers; Axial section shows single primary layer, elevated rays formed due to increase in the number of lateral chambers; pillars small, deep and concentrated over umbonal area.

Recorded range: Middle Eocene-Late Eocene

Occurrence: Kachchh, Cambay Basin, Western offshore basins.

4.2 FORAMINIFERAL DISTRIBUTION IN THE STUDY AREA

4.2.1 PALEOCENE

The continental / fluvial Matanomadh Formation is characterized by occurrence of plant fossils and pollen / spores belonging to Paleocene age. The overlying Naredi Formation (late Paleocene-Early Eocene) is truly marine in nature (especially in the upper part) where several minor cycles of sea level fluctuations could be observed. *Nummulites globulus indicus, Nummulites burdigalensis, Nummulites* sp., shell fragments, *Assilina spinosa* and *Assilina granulosa* are the major foraminiferal constituents present here (Fig. 4.5).

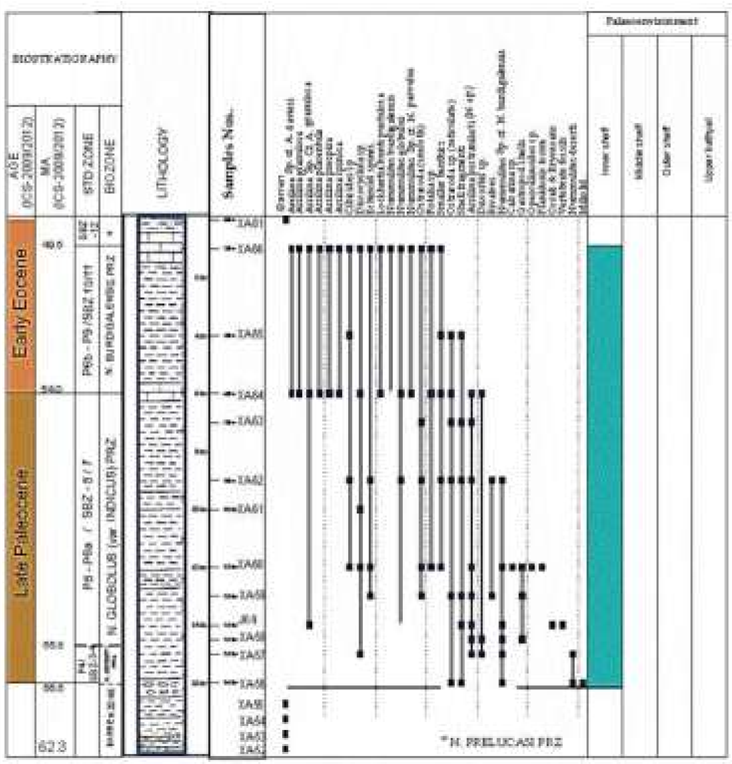


FIG. 4.5 PALEOCENE - EARLY EOCENE IN BERWALI RIVER SECTION

4.2.2 EOCENE

In the Kakdian stage section, near Doriwali River and road mark, *Nummulites deserti* along with several species of *Assilina* such as *Assilina spira, Assilina daviesi, Assilina nili, Assilina placentula* are reported by Shukla (2008). Other associated foraminifera include *Discocyclina* sp., *Operculinoides* sp., *Calcarina* sp., *Cibicides* sp., *Discorbis* sp*., Lockhartia hunti pustulosa* and other invertebrate / vertebrate fossil remains (Fig. 4.5). Equivalent facies in the offshore, in many exploratory wells, have reported occurrence of *Ranikothaline Nummulites, Lockhartia sp, M. miscella*, and *P. pseudomenardii* and *G. subbotinae* suggestive of middle shelf environment. In the Narmada Block, two prominent exposures of Cambay shale in Vastan area are characterized by early Eocene index forms such as *Nummulites burdigalensis, Operculinoides* sp., *N. globulus* and rare occurrence of *Assilina granulosa* and *Assilina spira.* The associated non-marine Ostracods in the Cambay shale include *Allocopocythere longilinea, Alocopocythere abstracta, Gyrocythere grandilavis, Buntonia boldi, Paracypris* sp., *Acanthocytheris vastanensis* etc. occur in the lower part. In the upper part of Cambay shale several ostracoda species such as *Canada cambayensis, Cythereidella gujaratensis* etc. along with the *Globorotalia* sp., *Chilogumbelina* sp. and arenaceous foraminifera are present.

The basal part of overlying Harudi Formation is characterized by a prominent *Nummulites obtusus* band (about 2.5m thick). Associated foraminiferal species include *Nummulites acutus, Assilina prespira, Assilina* sp. along with *Truncorotaloides topilensis, Orbulinoides beckmanni, Turborotalia frontosa* and certain *Discoasters* (Calcareous Nannofossils) and Invertebrate forms.

The Fulra limestone was also referred as the "*Nummulitic*" by Wynne (1872) and is very richly fossiliferous both in the onland and the offshore areas. The maximum thickness of fulra limestone is exposed in the Berwali river section (Fig. 4.6) and the associated foraminifera include *Orbulinoides beckmanni* (Zone in the lower part) and *Truncorotaloides rohri* (Zone in the upper part). A variety of larger foraminifera including many species of *Nummulites, Discocyclina, Fasciolites* and imperforate foraminifera are present. The upper most 1.5m band of limestone in the vicinity of village Bermoti also has few *Nummulites fabiani* and rare forms of *Pellatispira assymmetrica* which is perhaps the oldest *Pellatispira* on the western Indian shelf. The late Eocene in the southwestern Kutch has been regressive facies and its development is better in the offshore wells where it is referred to Tuna formation.

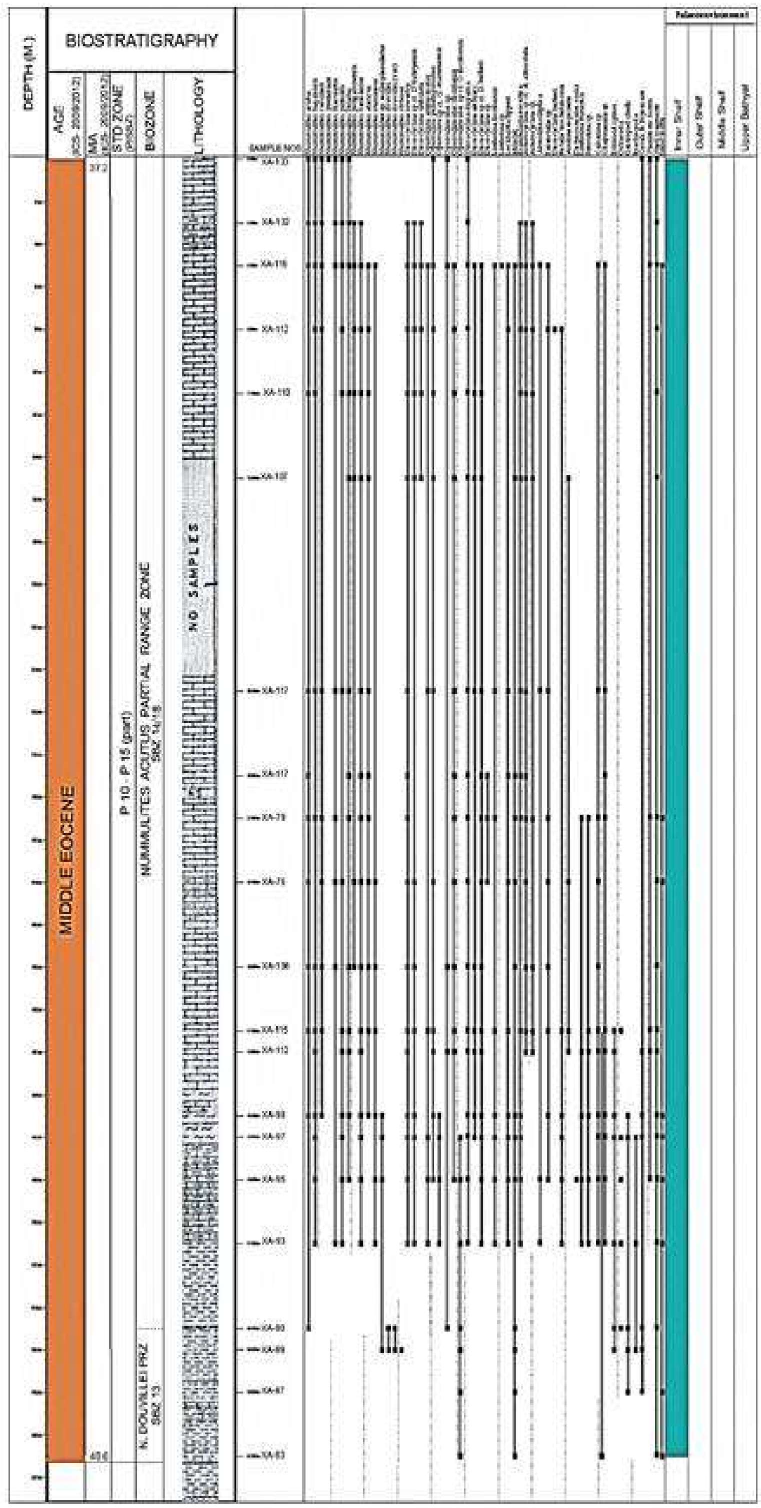


FIG. 4.6 MIDDLE EOCENE IN BERWALI RIVER SECTION, KACHCHH

The exposures belonging to the Tarapur / Dadhar formation of the Middle Eocene to basal Early Oligocene age are from Tapi River and Tarkeshwar areas (Fig. 4.7 and 4.8). The limestone / marl / shale sequences are richly fossiliferous with both invertebrate and vertebrate fossils. Important larger foraminifera from these sediments comprises *Nummulites acutus, N. maculates, N. fabiani, N. beaumonti, N. stamineus, N. uranensis, Discocyclina dispansa, Discocyclina sp., Asterocyclina sp, Dictyoconoides cooki, Chilogumbelina martini* along with planktic foraminifera such as *Globigerina eocaena, G. yuguaensis, G. linaparta, Turborotalia cerroazulensis* and *Globigerina* spp. The Dadhar limestone exposed in the vicinity of Vastan lignite mine area also *comprises Baculogypsinoides tetraedra, Pellatispira madaraszi, Pellatispira inflata, Pellatispira sp*,(late Eocene) and *N. fichteli, N. retiatus, Operculina sp., Rotalia sp.* and Gastropods (from Early Oligocene).

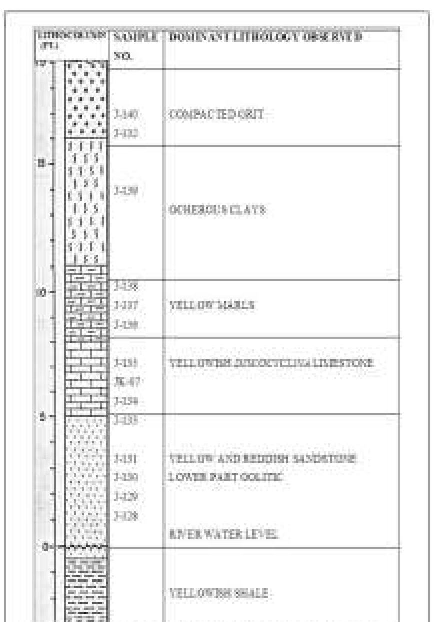


FIG. 4.7 LATE EOCENE LITHOUNITS IN SOUTH CAMBAY BASIN

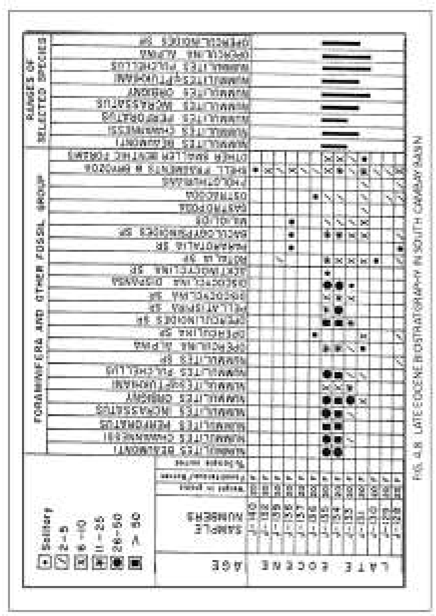


FIG. 4.8 LATE EOCENE BIOSTRATIGRAPHY IN SOUTH CAMBAY BASIN

4.2.3 OLIGOCENE

The Maniyara Fort Formation exposed south of village Bernani, in the Berwali River, has the lowest member characterized by the first occurrence of *Nummulites fichteli, Nummulites vascus* and several species of *Lepidocyclina*. The overlying beds have abundant *Nummulites clypeus* and associated taxa (Fig. 4.9). The coral limestone member of this formation has abundant corals forming massive limestone bioherms showing excellent porosity. The coral limestone is glauconitic, suggesting marine origin. The uppermost part of this formation yielded species of *Grzybowskia, Heterostegina, Lepidocyclina* and *Spiroclypeus ranjani* suggesting the middle–late Oligocene age. The corresponding formations in the offshore area are often referred to Narain-Sarovar Formation (Well KD-1), Godhara Formation (Well SP-1-1) and Khari Nadi formation. In the Oligocene succession of Berwali river section, besides the species of *N. fichteli*, the associated smaller benthic foraminifera include *Anomalina* sp., *Cibicides* sp., *Florillus* sp., *Elphidium* sp*., Rotalia* sp., *Pararotalia* sp., *Trifarina* sp., Miliolids and other forms.

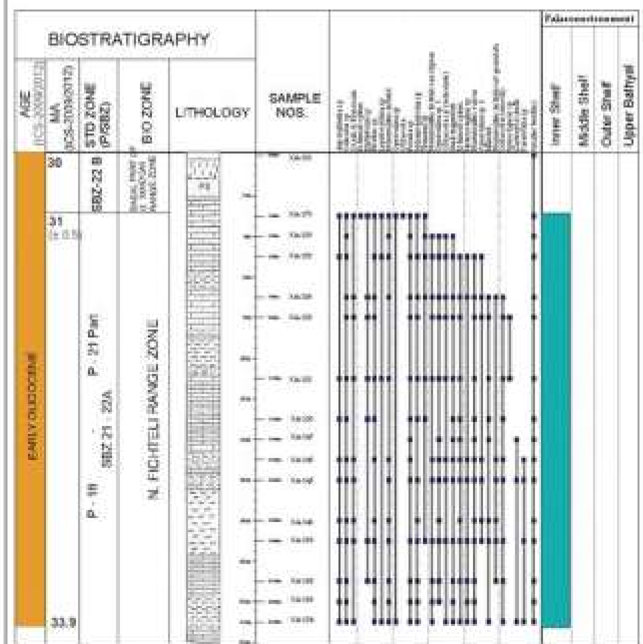


FIG. 4.9 EARLY OLIGOCENE IN BERWALI RIVER SECTION,KACHCHH

4.3 TETHYAN SHALLOW BENTHIC ZONES

4.3.1 PALEOCENE-EOCENE SHALLOW BENTHIC ZONES

In order to achieve finer biostratigraphic correlations and chronostratigraphic comparisons, biostratigraphers are also bringing in new concepts and high impact biostratigraphic tools developed at academia or in the E & P companies. One such scheme is shallow benthic zones (SBZ) proposed by Serra-kiel et al. (1998) under the aegis of the International Geological Correlation Program (IGCP-286). This biostratigraphic zonation tool comprises twenty zones covering the Paleocene - Eocene time spans (32 M.A) and represents faunal assemblages of both concurrent and mutually exclusive species from key-levels and key-localities. According to Serra-kiel et al the Shallow benthic zones foraminiferal scheme is the outcome of a revision of classical biozonation based on alveolinids, *Assilina* and *Nummulites*, established in 1960's by earlier workers. The SBZ are largely "Oppel zones" with key foraminifera representing central point of each biozones along with the association of other taxa spread over vast areas in the Tethyan region. Each SBZ has one or more key elements, multiple FAs (First appearance) and LAs (Last appearance) and concurrence of several taxa. The individual zones are non-continuous separated by intervals and not by boundaries while key locality assemblages represent central point of each biozone The SBZ scheme is also linked to the standard planktic / nannofossil zonations. The Indian inputs to Serra-Kiel scheme are from south-Shillong outcrop area, mostly representing the Paleocene zonation (SBZ 2-4) and other nearby (Salt Range, Pakistan) inputs belong to SBZ 4-8.

Paleogene larger foraminiferal zonation based on the SBZ was proposed by Shukla et al. (2005) for the selected wells from Assam - Shillong shelf, under which 23 wells spread over the entire shelf area were analyzed and incorporated to create a framework for biostratigraphic correlation on the lines of IGCP-286 scheme. Several other wells were also studied for micropaleontological data during the study, however, because of relatively poor biostratigraphic controls observed in these wells such data was excluded. The main objective of the study was to provide a viable biostratigraphic tool for stratigraphic trap exploration. In the process, use of local bio-events and their mapping across the shelf to create stratigraphic framework became essential aspects of the study. Top of *Assilina sp*. has been taken as the correlation datum and all the wells have been correlated along this plane. The *Assilina* top in most of the Assam shelf wells, roughly corresponds to the top of Middle Eocene and barring for few early ecological eliminations, the same could be traced all through the basin. While dealing with the *Assilina* top the problem of respective *Assilina* species tops i.e. *Assilina papillata* top; *A. hamzehi* top or A*. spira* top vis a vis the generic top which is slightly higher to the mentioned species, was observed. Therefore, following the SBZ scheme, *A. papillata* top in all the wells are referred to SBZ 15 and *Assilina* sp. top to SBZ 17. For the purpose of correlation, the zonal tops are joined together with the nearby wells, after deciding and interpreting the faunal assemblages present in each well. The working problem exists in the vertical demarcation of smaller zones, by the study of ditch cuttings, which are often mixed with the caved in foraminifera too. Identification of various useful datum, based on the age boundaries / zonal boundaries or the first down-hole occurrence of index foraminifera and tracing the lateral extent of the zones has helped demarcate finer biostratigraphic zones. Indian equivalents to the non-representative species in different SBZ was essential and has also been done, in order to make the application of SBZ scheme easy and focused on our sedimentary areas. The modified scheme applicable in both the western and eastern Paleogene sediments is presented in Table 4.

Table 4 part1

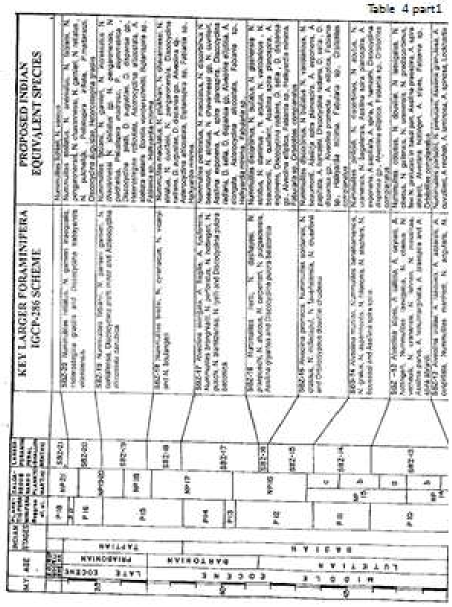


Table 4 part2

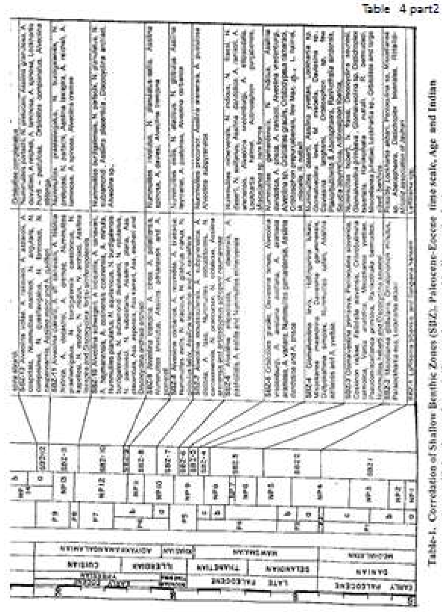


Table-1. Correlation of Shallow Benthic Zones (SBZ), Paleocene-Eocene time scale, Age and Indian stages with key larger foraminifera and proposed indian equivalent.

4.3.2 OLIGOCENE-MIOCENE SHALLOW BENTHIC ZONES

In 1997, Bruno Cahuzac and Armelle extended the LBF zonation into the Oligocene and Miocene of southern Europe, especially Mediterranean and Atlantic from Portugal to the Aquitaine. This period is characterised by a general global cooling, and a strengthening of the latitudinal temperature gradient. Since large benthic foraminifera are (sub)tropical organisms, this cooling and regional tectonic events (reduction in marine basins, increased topography in the hinterland) resulted in a deterioration in the conditions for LBF in SW Europe, and, as a result, in a reduction in diversification. The following definitions are only minimally modified from the definitions in Cahuzac and Poignant (1997).

SBZ 21 (early Rupelian): The base (correspondencing to the Eocene-Oligocene boundary) is defined by the first appearance of *Nummulites fichteli* and *N. vascus*, following the extinction of the discocyclinids. The upper limit corresponds to the first appearance of the lepidocyclinids in Europe. SBZ 21 can be correlated to P18-19 and NP21 pars – NP 23 pars zones. LBF Assemblages show high diversity: *Nummulites bouillei*, *Operculina complanata, Spiroclypeus* cf *blanckenhorni ornate, Heterostegina* spp., *Neorotalia lithothamnica, N. verriculata, Halkyardia minima, H. maxima, Bullalveolina bulloides, Borelis sp., Praerhapydionina delicata, Austrotrillina paucialveolata, Peneroplis armorica*.

SBZ 22 (late Rupelian-early Chattian): The base is defined by the appearance of *Nephrolepidina praemarginata* and *Eulepidina formosoides,* and the upper boundary by the appearance of the first *Miogypsinoides.* SBZ 22 can be correlated with P20-P21 and NP23 *pars*-NP25 (lowermost part) zones. It corresponds to the Upper Rupelian and Lower Chattian. It can be divided into 2 subzones, SBZ 22A and SBZ 22B:
* SBZ 22A with lepidocyclinids, *Nummulites* and *Bullalveolina;* the upper boundary is marked by the occurrence of *Cycloclypeus* (*C. mediterraneus* lineage)*;*

* SBZ 22B with lepidocyclinids, *Nummulites* and *Cycloclypeus* (*C. mediterraneus* lineage)*.*

SBZ 23 (late Chattian): The base is defined by the appearance of *Miogypsinoides;* the upper boundary, defined by the occurrence of *Miogypsina* gr. *gunteri,* coincides roughly with the Oligo-Miocene limit. SB 23 is of a Chattian age and is correlated with P22 and the largest part of NP25. The assemblages are fairly rich: *Nummulites bouillei, Operculina complanata, Spiroclypeus blanckenhorni ornata, Heterostegina spp., Grzybowskia assilinoides, Cycloclypeus eidae,* lepidocyclinids, *Miogypsinoides* (and its evolutional anagenetic forms from *M. complanatus), Neorotalia lithothamnica* and *N. viennoti* well known in the peri-Mediterranean area, *N. verriculata, Planolinderina escornebovensis, Victoriella aquitanica, Borelis pygmaea, B. inflata, Praerhapydionina delicata*, *Austrotrillina* spp.

SBZ 24 (Aquitanian): The base is defined by the appearance of the marker *Miogypsina* gr. *gunteri.* At the upper limit bispiralled *Miogypsina* occurs. This biozone coincides to the Aquitanian stage (Bordeaux area stratotype), but indeed the correlations of the biozones with the stages depend on the accurate limits which will be adopted for the stages. The Oligocene-Miocene boundary corresponds to the SBZ 23-SBZ 24 boundary. SBZ 24 can be correlated with *N4-(N5pars?)* and NN1-base of NN2. Larger foraminifera are less diverse than in older SBZ; *Nummulites, Cycloclypeus, Victoriella* become extinct just as the genus *Praerhapydionina* and most species of *Spiroclypeus at* the end of SBZ23. Significant taxa are: *Operculina complanata, Heterostegina* spp., *Nephrolepidina morgani,* unispiralled *Miogypsina, Neorotalia lithothamnica, Planolinderina escornebovensis;* the genus *Miogypsinoides* seems to disappear (at least in the

Aquitaine basin) during SBZ 24. *Miolepidocyclina* occurred first with *M. socini* and later *M. burdigalensis* within this zone. The presence of *Borelis* and *Austrotrillina* is very doubtful since these genera are absent from all the Aquitanian levels whose age has been revised.

SBZ 25 (Burdigalian): The base is characterized by the appearance of *Miogypsina* gr. *globulina,* the upper limit by the extinction of *Miogypsina.* SB 25 closely corresponds to the Burdigalian stage. This zone includes N5 *pars-N7* and NN2 *pars-NN4 pars.* Its top can be correlated with N7-N8 boundary. Larger foraminifera assemblages are still rather diverse *Operculina complanata, Heterostegina* spp., *Nephrolepidina tounioueri, Miogypsina globulina, M. intermedia, M. cushmani, M. mediterranea, Miolepidocyclina burdigalensis, M. negrii,*and very rare *Planolinderina.*

SBZ 26 (Langhian-Tortonian): Species diversity declines as lepidocyclinids and miogypsinids became extinct in Europe. The base of SB 26 is defined by the first occurrence (in the Mediterranean domain only) of *Borelis* gr. *melo* and the disappearance of *Miogypsina.* The upper limit is tentatively placed at the extinction of some groups of *Heterostegina* at about the Tortonian-Messinian boundary. From the Middle Miocene, a diversification can be noticed in two genera only: *Heterostegina* and *Borelis. Neorotalia lithothamnica* and *Operculina* are present in the Middle Miocene, and at about the base of the Tortonian *Discospirina* appears in Mediterranean and is still living.

In recent literature (Mohan, (1982); Pandey and Dwarkanath (1974); Schaub (1981); and Shukla & Bajpai, (2013); the Oligocene has often been referred to either two divisions i.e. the lower and the upper Oligocene (bipartite division) or three divisions i.e. the lower, the middle and the upper Oligocene (tripartite division). Both the schemes are useful so long the divisions are clearly defined and stratigraphically identifiable. In industrial biostratigraphic work, even finer divisions are welcome as the corresponding reservoirs get more precisely correlated across wells and fields. Thus in India, the *N. fichteli* Partial Range Zone would correspond to SBZ 21 and 22A, as per the Bruno Cahuzac and Armelle (1997) scheme. The *G. tandoni* Range Zone corresponds to the SBZ 22B and may be utilized in finer biochronostratigraphic division of the Oligocene under tripartite scheme. In the tripartite division scheme, the *G. tandoni* R.Z. corresponds to the middle Oligocene i.e. upper part of SBZ 22 (SBZ 22B). On planktic foraminifer scale, the interval may correspond to *Cassigerinella chipolensis - Pseudohastegerina micra* Zone to *G. kugleri / G tripartita* or *Globorotalia opima opima* Zone; corresponding to P-18 to P-21 zones. This interval also corresponds to the Ramanian stage in the Kachchh and Rupelian stage of the European Basins. It has also been observed that the LAD of *Nummulites fichteli* corresponds to the top of Rupelian = Ramanian stages and no true *Nummulites* has been observed in the late Oligocene interval. Development of *Neonummulites* (or probably *Operculinoides*) at least at two levels during the Miocene (basal Miocene and middle to upper Miocene) indicates reappearance of forms close to the *Nummulites,* commonly occurring during the Paleogene.

Miogypsinoides complanata-bantamensis (x=11± 0.2) Range Zone corresponds to the SBZ 23 and is clearly restricted to the late Oligocene only. In some wells, association of *Cycloclypeus* spp. and *Bulalvelina* sp. in the upper part of the SBZ 22 is observed, however, in the surface sections exposed in the Berwali river section such association is non-apparent. On planktic scale this interval corresponds to *Globigerina ciperoensis ciperoensis* and *Globigerina ciperoensis angulisuturalis* biochronozones; in turn corresponding to P-22 and N-4a of the European stage Chatian. In India, the interval is known to correspond to Waiorian stage represented by basal Sandstone and overlying calcareous sediments in the south western Kachchh and other areas. Associated foraminifera of the SBZ 23 include a number of *Miogypsinids* belonging to *Miogypsinoides* and *Miogypsina (M.* g*unteri* plexus). *Spiroclypeus ranjani* earlier believed to be restricted in the Oligocene has been observed to extend into the basal Miocene all over the western continental shelf of India.

4.4 INDIAN BIOCHRONOSTRATIGRAPHIC STAGES AND THEIR RELATIONSHIP WITH THE SHALLOW BENTHIC ZONATION

The Geologic Time Scale 2004 by Gradstein, Ogg and Smith (2004 and subsequent revisions upto the year 2012), provided very useful account of historical and current status of the Geological Time Scale. The limitations in the application of biostratigraphy data in global correlations is brought out with notes on the stratigraphic ranges of different fossil groups globally. Resolution achieved in biochronostratigraphy on the basis of multimicrofossils such as planktic foraminifera, shallow benthic zonation, calcareous nannoplankton, dinoflagellate cysts and other fossil groups are actually applied in hydrocarbon industry. However, a large number of biochronozones need to be calibrated with internationaly acceptable parameters. The Indian biochronostratigraphic stages were recently compiled in the ONGC special publication (Vol 44; no.2) by Raju and Misra (2010). Relevant stages and their relationship with the Shallow Benthic Zonation (S.B.Z.) as applicable to Indian Paleogene sediments were also presented (Shukla et. al., 1998). The Indian biochronostratigraphic stages have been proposed / compiled by several previous workers (Fig. 4.10), but do not have established correlation with stratotypes, GSSPs and universal acceptance as is the case of European / Mediterranean stages (Lutetian, Rupelian etc.). The Indian stages, namely Meghalayan, Mawsmaian and Khasian belong to Paleocene age and were described from the Um-Sohryngkew river section, Meghalaya by Pandey and Ravindran (1988). The Adiyakkamangalamian Stage, Babian Stage and Taptian Stage are from the Eocene and described mostly from the Cauveri basin and western Indian shelf. The Oligocene has been divided into Ramanian Stage, Waiorian Stage and Suratian Super Stage, all of which are also described from the western Indian shelf. There have been some efforts by recent workers (Shukla et. al., 2010) to link and correlate the Indian biochronostratigraphic stages with the European stages, Shallow Benthic Zones, P and N Zones besides correlations with other multimicrofossil groups.

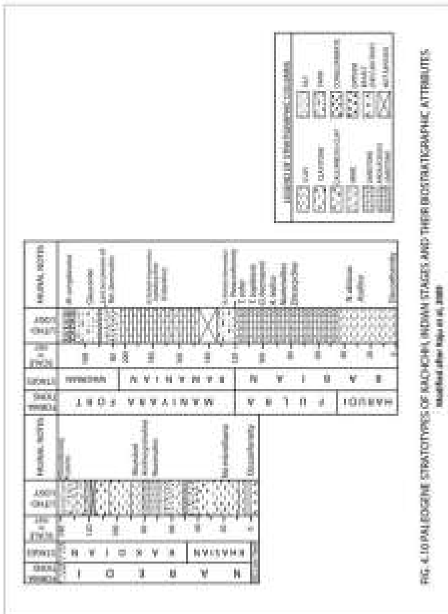


FIG. 4.10 PALEOGENE STRATOTYPES OF KACHCHH, INDIAN STAGES AND THEIR BIOSTRATIGRAPHIC ATTRIBUTES

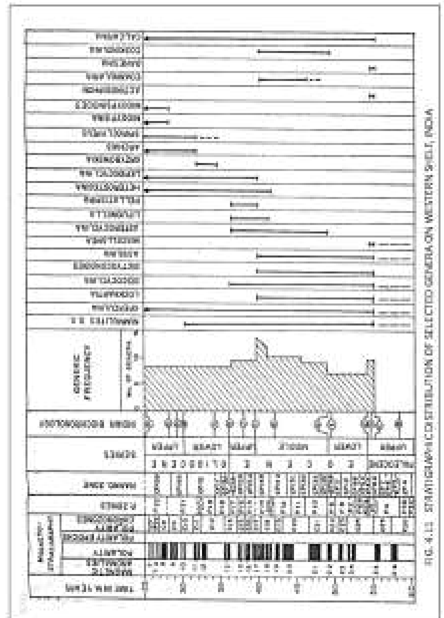
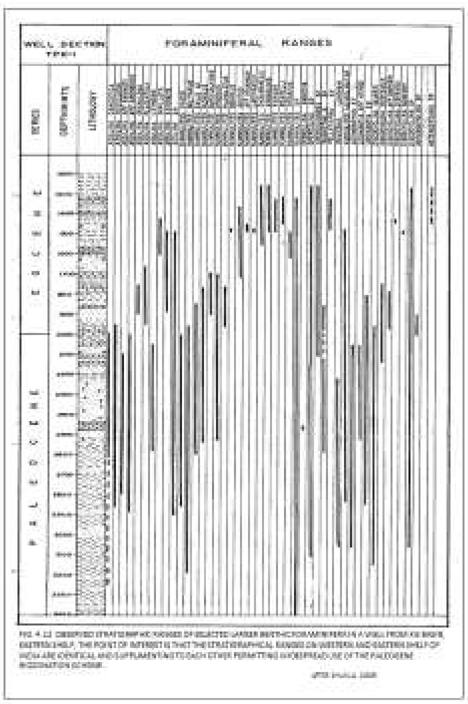


FIG. 4.11 STRATIGRAPHIC DISTRIBUTION OF SELECTED GENERA ON WESTERN SHELF, INDIA

4.5 FORAMINIFERAL BIOZONATION IN WESTERN INDIA

The oil exploration activities on the western shelf provided impetus to the biostratigraphic studies in the western India. Earlier the foraminifera studies were only confined to the outcrops in the Kachchh, Cambay and Rajasthan basins. However, during the exploratory drilling, the subsurface information from these basins and the offshore areas (Mumbai offshore Basin) added considerable knowledge of foraminifers. The stratigraphic distribution of selected genera on western Indian shelf alongwith the observed stratigraphic ranges of selected larger benthic foraminifera in a well from KG basin, eastern Indian shelf are provided in the Figs 4.11 and 4.12, respectively. This gives an idea about the entire larger foraminiferal occurrence and correlatibility in India. Part of this valuable information is available in the public domain as the research papers and publications by the Oil company workers, whereas, the remaining information is available only in the form of unpublished reports. In the present thesis, a period of about 36 Ma was analysed encompassing late Paleocene to late Oligocene larger benthic foraminifera (Fig. 4.13).



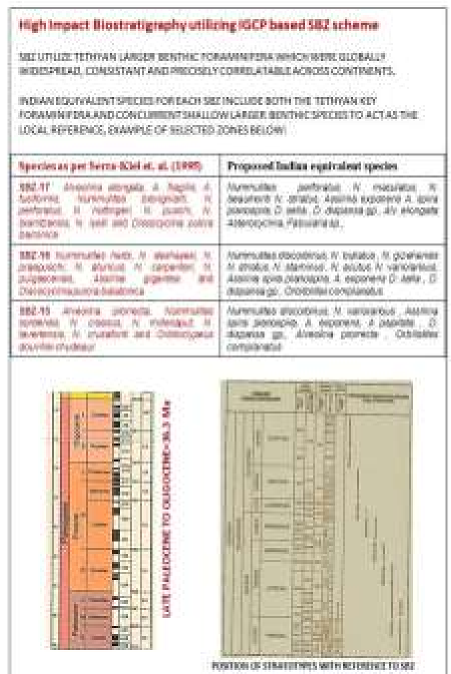


FIG. 4.13 GEOLOGICAL TIMESPAN UNDER STUDY IN PRESENT THESIS

4.5.1 MODIFIED LARGER FORAMINIFERAL BIOZONATION ON WESTERN INDIAN SHELF

Several formal and informal foraminiferal biozonations were proposed by different workers for the Paleogene period in different geographical areas. However, the first *Nummulites* biozonation was proposed by Shukla (1990) for the western offshore basins (Shelf) on the basis of both surface and subsurface record of index larger foraminiferal species. The present modified biozonation is immensely applicable to intra-basinal and inter-basinal correlations and has reference to the Shallow Benthic Zones scheme. The biozonation is modified in the present work and briefly discussed below:

4.5.1.1 BARREN ZONE

Reference section: Kakdi River, near village Naredi, Kutch.

Thickness in reference section: About 1.75m, (samples XA-52 to XA-55)

Formation: Madh Formation

Definition: Informal zone, represents interval between the top of Deccan traps to the sideritic band at 2.00m; largely represented by blocky reddish-brown and grayish claystone; carbonaceous shale with coal; ocher shale and interbedded grey slaty gypseous shale. The top of this zone is marked at the first appearance of *N. deserti* and associated fauna.

Characterization: This interval is characterized by the absence of nummulitids and associated fauna, and is supposedly of fresh water origin.

Age: Late Paleocene, on the basis of stratigraphic position.

4.5.1.2 *NUMMULITES DESERTI* PARTIAL RANGE ZONE

Reference section: Kakdi River, near village Naredi, Kutch.

Thickness in reference section: About 1.00m, (samples XA-56 and XA-57)

Formation: Madh / Naredi Formation; comprising sideritic band and splintery shale.

Definition: Interval between the first and last occurrence of *N. deserti* in reference section (theoretically defined).

Characterization: This interval is characterized by the presence of *N. deserti* alongwith *N. sp.* (pustular forms), *A. postranikoti* n.s., *Discocyclina sp*., other benthic foraminfiera and ostracoda. The base of the zone, in the better developed carbonate facies would correspond to the base of first *Nummulites* in India.

Age: Late Paleocene; SBZ 3-4

4.5.1.3 *NUMMULITES GLOBULUS* (var. *INDICUS*) PARTIAL RANGE ZONE

Reference section: Kakdi River, near village Naredi, Kutch.

Thickness in reference section: About 8.0m, (samples XA-58 to XA-63)

Formation: Naredi Formation; largely consists of ochre shales.

Definition: Dominant occurrence of *N. globulus var indicus* in association with other taxa. The lower limit of this zone is defined by the last occurrence of *N. deserti* and the upper limit by the first occurrence of true *N. burdigalensis*.

Characterization: this interval is characterized by the occurrence of *N. burdigalensis*, *N. sp*. cf. *N. parvulus*, *A. postranikoti*, *Operculina sp*., *Operculinoides sp*., smaller benthic foraminifers, bivalves and ostracoda.

Age: Late Paleocene; SBZ 5-6

4.5.1.4 *NUMMULITES EXILIS - PLANULATUS – ASSILINA PUSTULOSA* ASSEMBLAGE ZONE

Reference section: Well GKS-1: interval 3410-3520m;

Thickness in reference section: 110m; also observed in wells GK-29-A1; GK17-1, KD-1-1, in the western offshore area.

Formation: Naredi Formation, equivalent limestone and shale.

Definition: Occurrence of *N. exilis - planulatus, N. globulus, Assilina pustulosa* and *Lockhartia hunti pustulosa* in the reference sections. The upper limit of this zone is defined by the last occurrence of *Assilina pustulosa* and species of *Fasciolites* and first occurrence of *N. burdigalensis* s.s. The lower limit is marked by the extinction of *A. dandotica.*

Characterization: The lower part of the zone in reference sections is characterized by a rich larger foraminiferal assemblage. Many species of *Assilina, N. precursor, Lockhartia hunti pustulosa* and *Fasciolites corbarica, F. subpyrennica* also occur in this zone.

Age: Basal Early Eocene (Illerdian); SBZ 7-9

4.5.1.5 *NUMMULITES BURDIGALENSIS* PARTIAL RANGE ZONE

Reference section: Kakdi River, near village Naredi, Kutch.

Thickness in reference section: 6m, (samples XA-64 to XA-81)

Formation: Naredi Formation; represented by limestone and shale and extended to overlying bioturbated sandstones.

Definition: Occurrence of *N. burdigalensis* in the reference section. The upper limit of this zone is theoretically extended up to sample no. XA-81 representing bioturbated sandstones above the limestone. The lower limit is marked by the first occurrence of *N. burdigalensis* s.s.

Characterization: The lower part is characterized by a rich larger foraminiferal assemblage. Many species of *Assilina* and other taxa occur in this zone in association with the zonal taxa.

Age: Early Eocene; SBZ 10-11

4.5.1.6 *NUMMULITES PRELUCASI* PARTIAL RANGE ZONE

Reference section: Well SS-1, from 4125m-4237m.

Thickness in reference section: About 112m (after Pandey and Guha, 1979).

Formation: Belapur Formation; equivalent to younger Cambay Shale in onland part of Cambay Basin.

Definition: Occurrence of *N. prelucasi* along with other taxa, the lower limit of this zone is defined by the last consistent occurrence of *N. burdigalensis* while the upper limit is defined by the last occurrence of *N. prelucasi*.

Characterization: The interval is characterized by a rich larger foraminiferal assemblage. *N. atacicus, N. discorbinus, N. partschi, N. sp. cf. N. lahirii* are some important nummulitids co-occurring in association with the zonal taxa.

Age: Early Eocene; SBZ 12

4.5.1.7 *NUMMULITES DOUVILLE* PARTIAL RANGE ZONE

Reference section: Berwali River, in the vicinity of village Harudi.

Thickness in reference section: About 9.0m, (samples XA-82 to XA-90)

Formation: Harudi Formation

Definition: Defined by the occurrence of *N. douville* in association with *Operculinoides sp*. The lower boundary of the zone is theoretically marked by first occurrence of nummulitids and other fauna. The upper boundary is marked by the first occurrence of *N. acutus* and associated taxa.

Characterization: This interval is characterized by the occurrence of *N. douville, Operculinoides sp., N. obtusus, miliolids,* ostracoda and shell fragments etc.

Age: Middle Eocene; SBZ 13

4.5.1.8 *NUMMULITES ACUTUS* PARTIAL RANGE ZONE

Reference section: Berwali River, Kutch.

Thickness in reference section: About 43m, (samples XA-91 to XA-119)

Formation: Fulra / Tuna limestone Formation

Definition: Interval defined by the occurrence of *N. acutus* along with *N pinfoldi, N variolarius and Fasciolites elliptica*. The lower limit is marked by the first occurrence of zonal taxa. The upper limit in the outcrop section is marked by the last *Fasciolites* in the section.

Characterisation: The zone is characterized by rich larger foraminiferal assemblage. Besides the zonal taxa, many species of *Nummulites* and other larger foraminifera occur, such as *N. striatus*, *N. cuvillieri, N. maculatus, N. bagelensis, N. pinfoldi*, *N. variolarius, N. stamineus, N. atacicus, N. sp. ex. gr.*

exillis-planulatus, Assilina exponens, Operculina pellatispiroides, O. sp. cf. mariannensis, Operculinoides floridensis, O. sp. 1, Discocyclina dispansa, D. sowerby, D. archiaci, D. sp., Asterocyclina sp. cf. A. alticostata, Asterocyclina sp., Eoannularia eocenica, Fasciolites elliptica and many other species of benthic foraminifera, ostracoda, corals etc.

Age: Middle Eocene; SBZ 14-16

4.5.1.9 *NUMMULITES BEAUMONTI - NUMMULITES CUVILLIERI - ASSILINA SP.* PARTIAL RANGE ZONE

Reference section: Berwali River, Kutch.

Thickness in reference section: About 10m, (samples XA-120 to XA-129)

Formation: Fulra / Tuna limestone Formation

Definition: Interval defined by the occurrence of *Nummulites beaumonti, N. cuvillieri,* along with small *Assilina sp.* The lower limit is marked by the first prolific occurrence of the zonal taxa and absence of *Fasciolites* in the outcrop section. The upper limit of this zone is marked by the last occurrence of *Assilina sp* and first occurrence of *N. fabianii* forma *primitiva*.

Characterisation: The zone is characterized by rich larger foraminiferal assemblage. Besides the zonal taxa, many species of *Nummulites* and other larger foraminifera occur, such as *N. striatus*, *N. cuvillieri, N. maculatus, N. acutus, N. pengaronensis, N. variolarius, Assilina exponens, Operculinoides floridensis, Discocyclina dispansa, D. sowerby, D. undulata, D. sp., Asterocyclina* *sp. cf. A. alticostata, Asterocyclina sp., Eoannularia eocenica* and species of benthic foraminifera, ostracoda, corals etc.

Age: Middle Eocene; SBZ 17-18

4.5.1.10 *NUMMULITES FABIANII* PARTIAL RANGE ZONE

Reference section: Well Tarapur-1, Tarapurian stage, (after Pandey and Guha, 1979)

Thickness in reference section: About 83m.

Formation: Tarapur Formation; largely represents limestone and shale sequence.

Definition: Occurrence of *N. fabianii* with other larger foraminifera. The lower limit of this zone is marked by the last occurrence of *N. perforatus* while the upper limit is marked by the last occurrence of *Discocyclina spp.* and *Pellatispira madraszi*, in the reference section. Represents upper part of Tarapurian Stage.

Characterization: The interval is characterized by the association *N. fabianii* with *N. stellatus, Discocyclina spp., Pellatispira madraszi, N. pengaronensis* and other taxa.

Age: Late Eocene; SBZ 19-20

4.5.1.11 *NUMMULITES FICHTELI* RANGE ZONE

Reference section: Berwali River, near village Bernani, Kutch.

Thickness in reference section: About 21m, (samples XA-134 to XA-179)

Formation: Maniyara fort Formation

Definition: Range of *N. fichteli* in the reference section. The lower and upper limits of this zone are marked by the first and last reported occurrence of zonal taxa.

Charaterization: This interval is also characterized by the rich larger foraminiferal assemblage. Important associated taxa include *N. fichteli* forma clypeus, *N. fichteli* forma *granulata*, *N. vascus* and *Operculina sp*. The interval largely consists of limestone and shale.

Age: Early Oligocene; SBZ 21-22A.

4.5.1.12 *GRZYBOWSKIA TANDONI* RANGE ZONE

Reference section: Berwali river near village Bernani, Kachchh, Well SS-1 (3185-3610m

Definition: Range of *G. tandoni* in the reference sections. The lower and upper limits of this zone are marked by the first and last reported occurrence of zonal taxa.

Characterization: This interval is characterized by the rich larger foraminiferal assemblage such as *N. fichteli forma clypeus, N. fichteli forma fichteli, N. vascus, Lepidocyclina* (L) *dilatata, Heterostegina spp.* and *Operculina* sp. along with the zonal taxa. The interval consists of limestone and shale in the reference section.

Age: Middle Oligocene.

SBZ Assignment: SBZ 22B

4.5.1.13 *MIOGYPSINOIDES COMPLANATA - BANTAMENSIS* (x=11± 0.2) RANGE ZONE

Reference section: Berwali river near village Bernani, Kachchh, Well B-12 (1822-1920m)

Definition: Range of *Miogypsinoides* spp. with x value ranging from 24 in the bottom to 11± 0.2 in the top section. The lower boundary may be taken at the LAD of *G. tandoni* and the upper boundary coincides with the last occurrence of zonal taxa.

Characterization: This interval is characterized by the rich larger foraminiferal assemblage such as *Miogypsinoides complanata, Miogypsinoides bermudazi, Miogypsinoides bantamensis* (x=11± 0.2*), Lepidocyclina* (L) *dilatata, Lepidocyclina* (L) sp., *Heterostegina spp., Cycloclypeus indopacificus, Cycloclypeus sp., Spiroclypeus ranjani, Lepidocyclina (Nephrolepedina) sumatrensis* and *Operculina sp.* etc. The interval consists of limestone, calcareous sandstone and clay in the reference sections.

Age: Late Oligocene.

SBZ Assignment: SBZ 23

4.6 DISCUSSION

4.6.1 PALEOCENE AND EARLY EOCENE FAUNAL ZONES

In the late Paleocene and Early Eocene sections observed in Kachchh, a number of larger foraminiferal species belonging to genera such as *Assilina, Discocyclina, Nummulites* and *Lockhartia* along with the smaller benthic foraminifera such as *Cibicides* sp., *Rotalia* sp., *Discorbis* sp., *Calcarina* sp., *Operculina* sp., *Operculinoides* sp., miliolids and associated bryozoans, molluscan and other shell fragments are observed in the *N. deserti* Partial Range Zone and *N. globulus / N. burdigalensis* Partial Range Zones (Fig. 4.5). The former is assigned to P4 standard zone on the planktic foraminiferal scale and SBZ 3 - 4 on the benthic foraminiferal scale. The *N. globulus* Partial Range Zone is assigned P-5 to P-6a zone on planktic foraminiferal scale and SBZ 5 - 7 on shallow benthic foraminiferal scale. Similarly the *N. burdigalensis* Partial Range Zone which occurs in the Early Eocene section, (within interval comprising both the hard limestone bands and intercalating shale) is assigned P6b - P9 on planktic foraminiferal scale and SBZ10 - 11 on benthic foraminiferal scale.

The basal section underlying the fossiliferous late Paleocene and Early Eocene sections has not yielded any foraminifera; however, this could be referred to the Madh (Matanomadh) Formation, based on the stratigraphic position and previous microfloral studies carried out by other workers (Saxena (1978; 1979). The sediments are probably deposited under the fluvial or continental paleoenvironment. The uppermost interval in the Kakdi stage section is assigned to SBZ - 12 and is largely unfossiliferous barring for only one significant larger foraminifera i.e. *N. prelucasi* which helps the zonal assignment.

The marine Late Paleocene to Early Eocene interval is suggested to be deposited under warm, stable, inner shelf environment with minor bathymetric fluctuations.

4.6.2 MIDDLE – LATE EOCENE FAUNAL ZONES

In the study area, the overlying Middle Eocene interval comprises two major biozones, the *N. douvillei* Partial Range Zone in the bottom part and the *N. acutus* Partial Range Zone in the upper part that constitutes the major part of the Fulra Limestone. The former is assigned to SBZ - 13 and the latter to SBZ 14 - 18 on shallow benthic foraminiferal scale. Together, both these zones constitute P-10 to P-15 interval on the planktic foraminiferal scale (Fig. 4.6). Both these zones roughly correspond to the Harudi Formation (being predominantly shale) and Fulra Limestone Formation (predominantly limestone and marls), respectively. Minor bathymetric fluctuations are possible at the micro-environment level; however, a generalized marine, inner shelf paleoenvironment is suggested for the entire section. The occurrence of genus *Alveolina* in the middle Eocene of the field sections is very typical, as most of the species belonging to this genus are found in five or six distinct bands within the Fulra Limestone and not throughout the middle Eocene. The selective occurrence of *Alveolina* may be attributed to the relatively few marly bands, within the formation. The occurrence of this genus appears to be favoured by paleoecological conditions involving increased argillaceous sedimentary influx in the carbonate depositional system, which otherwise is a typical example of larger foraminiferal bank facies.

Another point of interest is that when we compare the larger foraminiferal occurrences (Assemblages) in the middle Eocene and Oligocene limestone, it is clearly noted that the Oligocene limestone is more of a reefal build up having enormous amount of corals and bryozoans; whereas, the middle Eocene limestone depicts a typical clean larger foraminiferal (*Nummulites*) bank facies with its characteristic gradations. Extension of similar limestone in the offshore (Basinal) areas and continuation of similar foraminiferal assemblages on the shelf and beyond, in the offshore wells of the basin has also been confirmed in several exploratory wells studied by the author over last about twenty-five years. Common middle Eocene foraminifera in the study areas include several species of *Nummulites, Discocyclina, Operculina, Operculinoides, Alveolina, Assilina, Lockhartia, Dictyoconoides, Eoannularia, Lindarina, Smoutina* and associated smaller benthic foraminifera and shell fragments (Fig. 4.6). Bryozoans and corals also occur intermittently along with a small number of planktic foraminifera such as *Orbulinoides beckmanii* and *Truncorotaloides rohri.* Earlier workers have also reported some species of genera *Globigerina* and *Catapsydrax* from the middle Eocene formations (Mohan and Soodan (1970); Samanta, (1970); Tandon (1976). Rare brachiopods, vertebrate fossils and other fossil groups have also been reported from the same sequences.

The uppermost half meter of the Fulra Limestone near village Bernani has reported occurrence of reticulate forms such as *Nummulites prefabianii* in association with typical middle Eocene larger foraminiferal assemblage suggesting proximity to the middle / late Eocene boundary. However, it is believed that the late Eocene section in the onland Kachchh has largely been eroded, leaving a huge unconformity to the tune of about 3.00 Ma.; before the onset of fresh, Oligocene carbonate sedimentation. This phenomenon is clearly visible in the offshore / basinal areas, where the occurrence of late Eocene sediments is very well recorded with considerable thickness and comprises all larger foraminiferal assemblages, typical of the corresponding age unit.

In the Cambay basin, late Eocene outcrops are best located in the Narmada block, where in the vicinity of Tadkeshwar and Vastan lignite mines, several outcrops are located. Similarly in the river sections of Tapti and Amravati so also in several other nala (rivulet) and road sections, the late Eocene fossiliferous limestone and shale sediments are exposed. A typical section showing the late Eocene succession near Bodeli in the Tapti river area shows yellowish shale in the bottom part, successively overlain by yellow and reddish sandstone, yellowish *Discocyclina* limestone, yellow marls, ocherous clay and compacted grit. The limestone / marl and clayey sections are highly fossiliferous intervals and have yielded several genera of larger benthic foraminifera such as *Nummulites, Pellatispira, Discocyclina* besides associated other fauna (Fig. 4.7).

A similar outcrop section comprising limestone and marls from the Tadkeshwar area has also yielded identical foraminifera belonging to late Eocene age. Several well sections from the onland Cambay Basin and from the nearby western offshore areas have also yielded similar species of late Eocene age. In fact, towards the basinal side, the thickness of all the Paleogene formations outcropping on the land increases greatly along with the frequency and diversity of the foraminifera. The occurrence of the Paleogene and Neogene sediments in the offshore wells is very remarkable and several species which occur in the onland part also continue into the offshore areas with greater abundance.

4.6.3 OLIGOCENE FAUNAL ZONES

The early Oligocene in the study area comprises basal coralline limestone which is hard and compact as compared to the underlying middle Eocene Fulra Limestone and Harudi shales. The early Oligocene limestone is largely represented by the occurrence of reticulate *Nummulites* and is assigned to the *N. fichteli* Range Zone. Common larger foraminifera recorded from the sequence include *Nummulites fichteli* (with its three varieties), *Lepidocyclina* sp., *Operculina* sp., *Heterostegina* sp. and associated smaller benthic foraminifera such as *Anomalinella* sp., *Cibicides* sp., *Rotalia* sp., *Elphidium* sp., *Florilus* sp., *Trifarina* sp., *Sphaerogypsina* sp., *Pararotalia* sp. miliolids, shell fragments (Fig. 4.8). Limestone is coralline and forms part of the reefal build-up in the shallow marine inner shelf environment. Echinoid and bryozoan spines and coral fragments are common in the faunal assemblage. *N. fichteli* Range Zone is assigned to P18 - 21 (Part) on the planktic foraminiferal scale and SBZ 21 - 22a on the benthic foraminiferal scale.

This zone is overlain by *G. tandoni* Range Zone better represented in the offshore area. However, because of a distinct change in the lithofacies i.e. from carbonates to clastics (limestone to sandstone) in the outcrop area, the basal part of this zone in the outcrop area is largely unfossiliferous with only a few smaller benthic foraminifera. A minor unconformity is postulated at the top of the *N. fichteli* Range Zone in the Berwali river sections. Further up, the late Oligocene is also highly fossiliferous, lithologically argillaceous and carbonates. It yields a new suite of the larger foraminifera belonging to the family Miogypsinidae and other groups. However, the Miogypsinidae is beyond the scope of the present study, and is not being discussed here. The phylogenetic relationship in one commonly occurring stock of *Nummulites* in India is also presented in the Fig. 4.14 and shows evolution of various species through time and their index value for biostratigraphy.

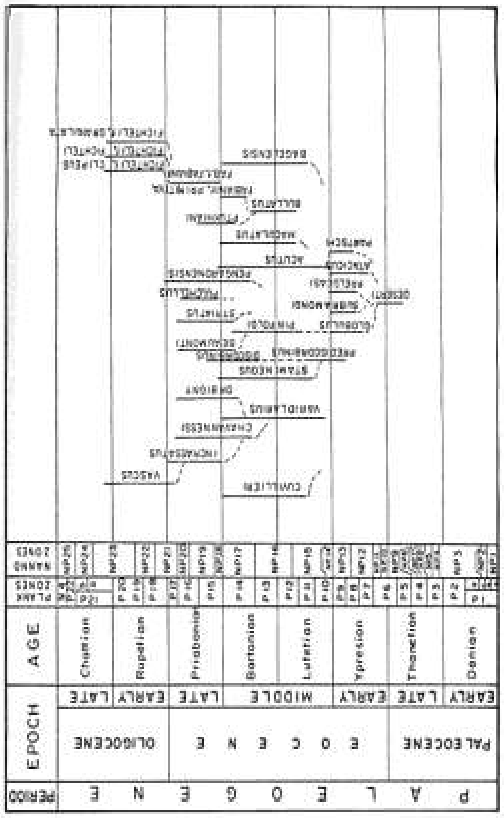


FIG. 4.14 PHYLOGENETIC CHART: NUMMULITES DESERTI STOCK

CHAPTER 5: PALEOENVIRONMENT AND HYDROCARBON PROSPECTS

5.1 LARGER FORAMINIFERA AS PALEOECOLOGICAL INDICATORS

The larger foraminifera generally depict shallow open marine environmental conditions and are regarded as very good indicators of paleoenvironment, both in the carbonates and finer clastic sediments (Fig 5.1). In fact, besides their biostratigraphic value, larger foraminifera help in developing carbonate build ups and limestone deposits in shallow seas (Cole, 1957; Gupta, 1993; and Drobne, 2003); Larger benthic foraminifera along with the algal bryozoans and other microfossils constitute almost entire rock building material in the limestone / carbonate sediments and help in defining the micro-environments in marine shallow water, carbonate setups (Fig 5.2 and 5.3). Since the test size in larger foraminifera is usually greater than 1mm and may go up to several centimetres, their abundance in the foraminiferal banks and other sheet carbonates helps define even minor fluctuations in the paleoenvironmental conditions (Biswas, 1981; Haq and Boresma, 1980). Larger foraminifera and their algal symbionts and corals are characteristic of “reefal build-ups / foraminiferal banks” in the photic zone.

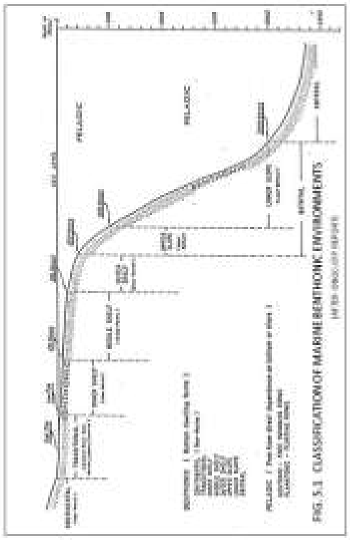


FIG. 5.1 CLASSIFICATION OF MARINE BENTHONIC ENVIRONMENTS

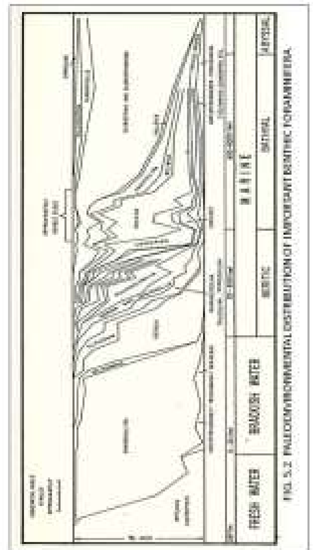
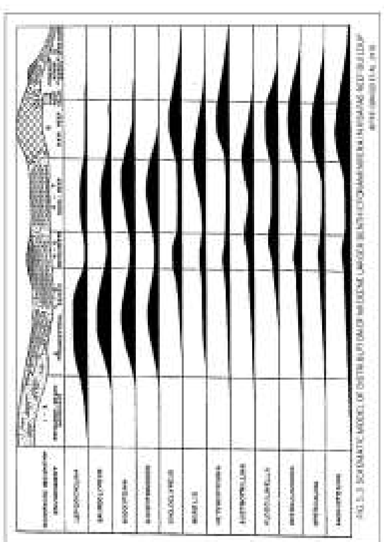
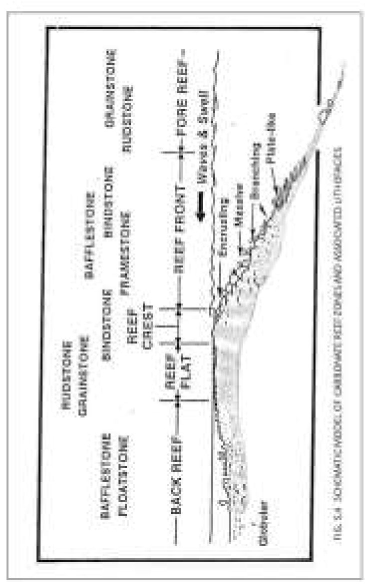


FIG. 5.2 PALEOENVIRONMENTAL DISTRIBUTION OF IMPORTANT BENTHIC FORAMINIFERA

The co-occurrence of smaller and bigger test (form A and B) denotes favourable environmental conditions with sufficient food and light supplies. The evolution of larger foraminifera and complex internal structure of different genera / species exhibits rapid growth and rapid evolution during the warm periods of Paleogene and Early Neogene. These groups of microfossils are generally less susceptible to salinity changes and are typically stenohaline with 30-45% tolerant limits making them valuable biostratigraphic tools during the Late Cretaceous to Paleogene and Early Miocene periods. Very high salinities and very low salinities are detrimental to rapid evolution of foraminifera. Slightly hyper saline shallow water lagoons are characterized by forms such as Alveoliniids, Soritiids, Peneropliids and miliolids. *Amphistegina, Ammonia, Miogypsina, Operculina, Nummulites* and Orbitoids have relatively more tolerance level and occur in rather a bigger range as compared to other forms (Murray, 1973; Mukhopadhyay and Shome, 1996).

Occurrence of Paleogene larger foraminiferal banks on the shelf with characteristic larger and smaller foraminifera is common in the tropical and some part of sub-tropical areas. This has also been referred to “Carbonate factories” by sequence stratigraphers (Petroleum systems & sequence stratigraphy of different basins (ONGC), 2008; Deshpande et. al., 1983). A typical *Nummulites* bank sequence comprises of lower **fore bank facies**, the middle **bank complex** and the upper most **bank crest facies** (Fig. 5.4). The upper most part of the facies being coarsest and randomly sorted, with a lot of bioclastic debris and coral and bryozoan elements. Most of the larger benthic foraminifera characterize high concentration of dissolved $CaCO_3$ in the Marine system. The *Cycloclypeus, Operculina, Nummulites, Assilina, Discocyclina,* other orbitoids, *Planoperculina, Miogypsinoides* etc. are all indicative of high calcium carbonate, shelf / reef / foraminiferal bank facies (Fig. 5.5).





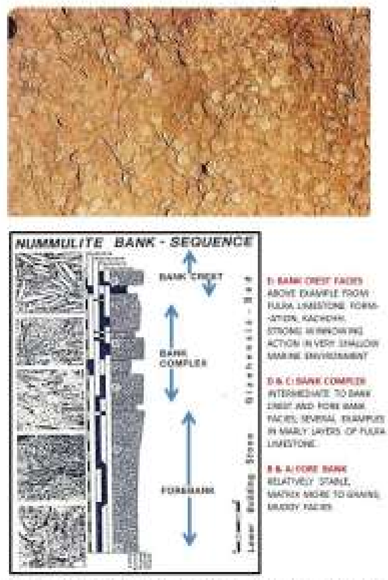


FIG. 5.5 TYPICAL NUMMULITES BANK –SEQUENCE AND ITS DEPICTION IN FIELD SAMPLE (FULRA LIMESTONE FROM BERWALI RIVER SECTION

Larger foraminifera generally exhibits tolerance for environmental conditions in the present and past warm, marine shelf and are frequently reported from a variety of lithological associations (Murray, 1973). They often show carbonate affiliation, but also frequently occur in the finer clastic sediments such as clay, shale and siltstone. Amphisteginiids maintain a very good algal symbiotic relationship and occur in reefs associated with high content of dissolved carbonates. Their distribution is wider as compared to the nummulitids. Boliviniids and uvigeriniids are typically deep water forms and are most diversified towards the continental slope and deeper water areas (Murray, 1973). They are also indicative of very fine grained substratum and low energy conditions.

5.2 PALEOENVIRONMENT FOR STUDY AREAS

5.2.1 BASIN SEDIMENTATION

Sedimentation in the Kachchh basin began in Bathonian time with eastward transgression of the sea over eroded platform of Delhi fold belt sloping towards the south west. The island belt, Wagad and mainland Kachchh areas were the remnants of this fold belt (Deshpande et. al., 1983). During the Callovian time marine shale of Jumara formation represents the maximum paleobathymetry. Post-Callovian to Neocomian saw regression towards the eastern part of the basin and the median high along with the hinge zone came into existence in the offshore part. The Mesozoic sedimentation ended with the regional uplift during the Early Cretaceous diastrophism which ended with the Deccan trap lava flow (Biswas, 1981). The advent of Tertiary was a period of peneplanation and lateritization during Paleocene and the mud series sediments were deposited.

The first marine transgression during Thanetian - Ypresian continued in Lutetian, the top of which is marked regression represented by absence of most of the Late Eocene sediments in the onland part of south western Kachchh (Shukla, 2008). A new transgression occurred in Oligocene and was persistent till post Chatian which saw a regression. The sea again transgressed during Aquitanian and continued upto Burdigalian the close of which is marked by a prominent regression, uplift and erosion. Deltaic sedimentation continued during Pliocene and the further uplift resulted in regression during the early Pleistocene and recent times.

5.2.2 BASINAL ENVIRONMENT

Paleocene was the period of erosion in several areas of western shelf. However, the marine sedimentation was extensive in south Rajasthan Basins, south western part of the Kachchh and the southern part of the Cambay Basin. In the study area the lower part of the Kakdi stage and greater part of lower Eocene of the Cambay Basin were inundated by the marine conditions. The early and the middle Paleocene, however, have remained mostly on the continental or of brackish origin and form the syn - rift sedimentation in the post Deccan trap times. The Eocene sedimentation is largely marine with extensive carbonate development throughout the Eocene. Two pronounced regressions; one at the close of Ypresian and another at the close of Lutetian have resulted in the deposition of paralic sediments (Saravanan et. al., 2006). This coincided with the total absence of any sedimentation and / or erosion i.e. creation of major unconformities, which merge into the correlative conformities towards the basinal side.

The middle Eocene sea was the most extensive sea and spread through the embayments between the existing highlands, for example: The presence of middle Eocene rocks in the Chorar hills indicates presence of Eocene sea in the eastern part of Kachchh. The middle Eocene shoreline encircles around the Kathiawar peninsula and extends into the Cambay basin as north - south oriented narrow gulf. The late Eocene in the Kachchh and south Rajasthan shows uplift and erosion, hence westward marine regression beyond the limits of present day coastline is observed, however, at the same time, the late Eocene was the period of subsidence in Cambay basin, more particularly the south Cambay basin, where the development of larger foraminiferal carbonate deposits near the Vastan-Tadkeshwar area is already mentioned. Oligocene was the period of marine transgression in the Kachchh basin whereas the Rajasthan area continued to be uplifted with further westward regression of the shoreline. The close of Oligocene was again marked by regression both in the Kachchh; Rajasthan and Cambay areas. An unconformity of differing magnitude characterises the top of the Oligocene in all these areas before the renewed transgression of the early Miocene sea (Deshpande et. al., 1983).

5.3 GENERALIZED HYDROCARBON PROSPECTS

The hydrocarbon prospects are here discussed in a generalized way and often go well beyond the Paleogene period, which is the main focus of the present study. This is imminent as the complete petroleum system comprising the *Generation, Migration* and the *Entrapment* cycle (GME cycle) can only be visualised by taking into account the entire geological and tectonic history through which the basin has undergone. The entire gamut of search of *Source rock, Reservoir Rock* and the *Seal (Cap) rock* is not restricted within the specific stratigraphic subdivision, although several times, the individual 'Plays' may well contain all of them. Whereas the Mesozoics of Kachchh, especially the Jurassic Jhurio / Jumara formations and the Cretaceous Jhuran and Bhuj formations have reportedly good occurrence of reservoir rocks in the form of medium to fine-grained sandstones, siltstones and minor arenaceous limestone providing ample space for hydrocarbon capture and entrapment. The Bhuj Sandstone is coarse and thick and its basinal extension towards the offshore areas provide even greater thicknesses, as has been observed in several offshore wells.

The Eocene - Oligocene part of the Kachchh basin is marked by good development of both clastic and carbonate reservoirs, especially in the Babian, Taptian, Ramanian and Waiorian (Indian) Stages which are dominated by very rich biota including foraminifera, spore pollen, dinoflagellate and other micro and mega fossil groups. The early and the late Paleogene are clastic facies whereas the rest is reservoir grade carbonates and marls. The Neogene, too, has similar lithofacies and reservoir characterization. However, good source rock is mostly absent in the outcrop areas. In the offshore, development of better source rock and reservoirs has been proved by several hydrocarbon occurrences in the basin. So far as the hydrocarbon prospects of the area is concerned the Mesozoic sediments appear to have greater potential as compared to the

Tertiary sediments. Paleogene limestone have enormous biota so also source rock potential, especially in the basinal areas, however, being at very shallow depths in the onland part, there is no likelihood of generation of hydrocarbon from such a shallow source rock. The GME cycle i.e. the Generation, Migration and Entrapment of the hydrocarbons is an extremely scientific process with fixed variables, proven constants and requirement of conducive environments, all of which under the given circumstances may or may not generate the hydrocarbons.

This cycle is best depicted in the Fig. 5.6; showing the digenesis, oil generation, oil window and the katagenesis etc. In the offshore areas, the Mesozoic / Tertiary formations have been buried at greater depths and have provided a number of indications of oil and gas in the clastic reservoirs of late Cretaceous (Bhuj Formation) and the clastic / carbonate reservoirs of late Paleocene and Eocene Period. The late Cretaceous clastics are extensively developed and generally form better reservoir than the argillaceous limestone facies in the GK-BB / GK- BH areas. The area is close to the early Cretaceous kitchen in and around GK-BH / GK-C / SP-A low with good thickness of mature source rocks. The record of gas and oil finds in several offshore wells (GK-BI / GK-B0/ KD-KI / SP and other areas) and more recently the discovery of a big area (GK-BH / GK-DB) in the offshore Kachchh (Fig. 1.3) has upgraded this Category-IV basin on the oil and gas map of India to Category-I Basin. Gas was first discovered in the Tertiary sediments. Subsequently, discovery of oil and gas in multi-stacked reservoirs in the area and gas in well GK-DB area located south of GK-BH gave much desired boost to the development. The discoveries of hydrocarbons in commercial quantities in Tertiary sections over GK-BH and GK-DB structures helped in a new beginning in Kachchh Offshore Basin with gas discoveries and further development. These discoveries have established significant oil and gas reserves for the country.

It is worth mentioning here that in the western Rajasthan too, Jaisalmer, Bikaner-Nagor, Barmer-Sanchor basins and other areas have provided good hydrocarbon potential and finds due to the combined efforts made by several E&P companies over the last two decades. In Jaisalmer Basin, ONGC has discovered oil and commercial gas. In the Barmer-Sanchor Basin, CAIRN Energy and in the Bikaner-Nagor Basin OIL and Essar-Oil consortium have discovered oil and commercial gas from different geological levels. Further south in the Cambay Basin which is a more prolific oil and gas basin of India, the study area has shown development of good reservoir and source rock facies at several geological levels starting from Early Eocene to Middle Miocene. The Vastan Lignite Mines and other adjacent areas in the south Cambay Basin have also shown the presence of high quality source rocks in the Cambay Basin. Both the conventional and un-conventional hydrocarbon occurrences with new potential are present in this basin and exploration is currently being pursued by several E&P companies.

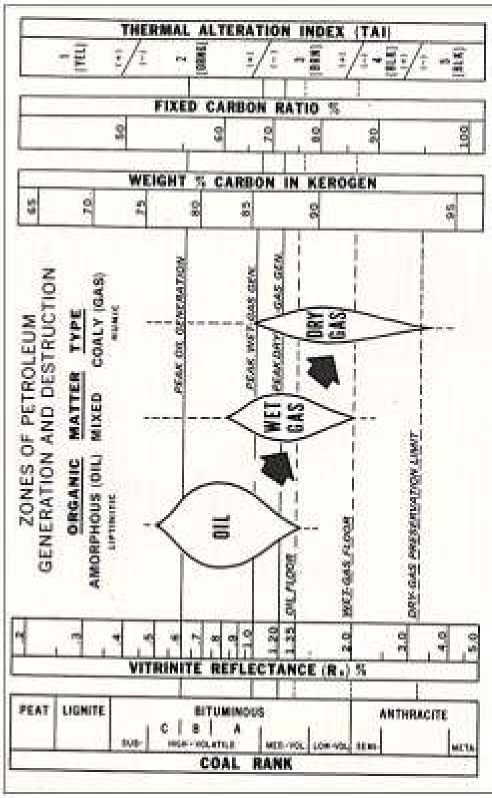


FIG. 5.6 HYDROCARBON GENERATION AND DESTRUCTION CYCLE (LEVERSON,1967)

CHAPTER 6: SUMMARY AND CONCLUSIONS

Larger benthic foraminifera occurring in the Paleogene formations across different sedimentary basins on the western shelf of India are extremely helpful tools to assign sediment age, formation demarcation and biofacies, stratigraphic correlation, palaeoecological analysis, palaeobathymetry and palaeolatitude determinations. Foraminifera, because of the rapid evolutionary changes and faster speciation more particularily during the Cenozoic period, constitute the backbone of the industrial micropaleontology with a number of index species characterising each biozone. This has facilitated local and regional biochronostratigraphy in conjunction with other geological and geophysical tools. In this context, important conclusions derived from the present study are outlined below:

1. The present thesis incorporates geological and biostratigraphic studies in the Paleogene outcrop areas of south-western Kachchh and southern Cambay Basin along with selected well sections from the western continental shelf of India. Kachchh basin witnessed deposition of the shallow water carbonate sediments and shale during the Paleogene, whereas the Cambay Basin was dominated by the argillaceous sediments during the same period. A relatively small volume of late Eocene carbonate was deposited in the southern onland part of the basin and is referred to the Dadhar Formation in the Cambay subsurface. This indicates different tectono-sedimentary regimes in the two adjacent basins, since

the Kachchh basin remained more or less passive margin basin whereas the Cambay basin remained a rift basin with huge rift fill clastic sediments. The rest of the continental shelf also remained in the passive margin phase with abundant limestone deposition.

2. The thickness of outcropping formations in the south-western Kachchh increases greatly towards the basinal (offshore) area and the Paleogene formations are extremely rich in foraminiferal assemblages besides other microfossils / other fossil groups. There is a striking similarity in the foraminiferal assemblages recorded in the onland and offshore areas suggesting widespread sedimentary continuation. This has facilitated the present study by two ways; firstly, by analysing a large number of fossils / assemblages collected from the surface samples and secondly, by erecting a biozonation which is widely applicable all over the Paleogene shelf.

3. Extensive field studies in both the basins were targeted at studying the outcropping formations with respect to the faunal content and their relation to the regional geology. Recovery of the faunal assemblages from the field samples was extensive and has facilitated the study of morphometric characters of the larger benthic foraminifera, especially since a large number of specimens of individual species were easily available. The Paleocene, early and middle Eocene (late Eocene exposures largely eroded in outcrop areas), and the Oligocene samples were studied from the onland Kachchh, whereas the late

Eocene samples were studied from the outcrop sections near Tapti / Tadkeshwar areas. The Late Eocene carbonate of the Cambay basin referred to the Dadhar Formation also exhibits similar features to Fulra Limestone (Kachchh) and is believed to be deposited under warm, shallow marine environment, typical of the foraminiferal bank facies.

4. Larger benthic foraminiferal assemblages from all the outcropping formations and selected well sections have been examined in great detail and discussed in the present work. Oriented sections (Equatorial and Axial), surface features and measurable parameters for each specimen helped record and compute morphometric criteria for the species level identification. The data was put to simple statistical computations for comparison of different species of the same lineage before arriving at their stratigraphic utility. The software *Stratabugs* has been used to plot key occurrences and data of the foraminiferal assemblages with respect to their stratigraphic ranges and distribution, along different epochs and sections.

5. Five species of *Assilina*, eleven species of *Nummulites*, two species of *Pellatispira,* four species of *Discocyclina* and one key species of other genera such as *Operculina, Lockhartia, Dictyoconoides, Dictyoconus, Acktinocyclina, Eoannularia* and *Linderina* are described in detail from the study areas. These species are taxonomically described, compared with reference to their biometric and qualitative characters and illustrated. The stratigraphic distribution and the

geological occurrence of these species are also established in the present work. A few morphotypes, significantly differing from the holotype characters are kept for further study for detailed comparison with the type materials, before their status of new species is confirmed.

6. The present thesis encompasses comprehensive Paleogene larger foraminiferal biostratigraphy on the western Indian shelf and establishes larger foraminiferal zonation with the demarcation of twelve larger foraminiferal zones over the basal "Barren Zone". The biozones are also referred to the P/N zones on planktic foraminiferal zonation scheme and the SBZ scheme. The proposed zonation is applicable to the entire western shelf, as also to similar facies on the eastern Indian shelf. The Tethyan shallow benthic zones, Indian biochronostratigraphic stages and their relation to different formations are also discussed.

7. The Shallow Benthic Zonation (Serra-Kiel et. al., 1998) with proposed Indian equivalent species to the SBZ scheme is also incorporated in the thesis. Being the first and only local comprehensive reference to this zonation, the proposed Indian species would serve as the link between the Mediterranean species and the Far-eastern Tethyan species. It is a matter of common observation that endemicity plays an important role in the occurrence and development of larger foraminifera at widespread locales; therefore, the importance of creation of local references cannot be underscored. Further, mapping of morphotypic variations

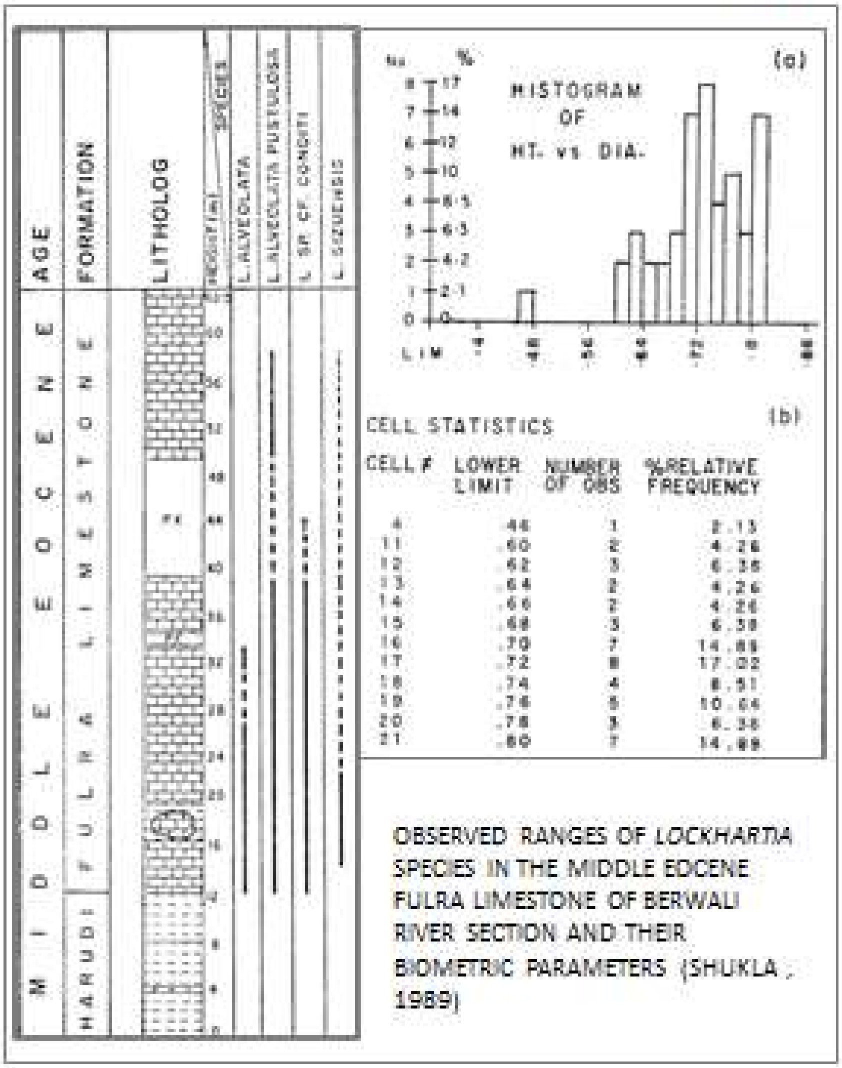
from the local references and closing on to the distant forms (occurring in basins located in different continents) is needed in order to establish inter-regional biostratigraphic correlations. The description of shallow benthic zones from Late Paleocene to Oligocene and their applicability in the Indian context is also the first such attempt from the Indian Paleogene.

8. The author, being associated with the premier national oil company of India for the last about thirty three years, had excellent opportunities to work on similar taxa from different basins. The present work has supplemented the earlier studies in stratigraphy and biochronology and has added significantly to the understanding of the current geology and tectonic setting in addition to the systematic palaeontology, biometric analysis and biostratigraphy concepts. Biostratigraphic determination and paleoenvironmental interpretation has contributed to our understanding of the geological history of the basin and the generalized hydrocarbon prospects of the region.

9. Tectonically, the syn-rift and post - rift sedimentation is more conspicuous in the Cambay Basin, where a distinct facies change is noted to have occurred during the process of sedimentation. In Kachchh Basin, the Paleogene and Neogene passive margin sequences are almost monotonous, predominantly with limestone and shale, and with minor sandstone (in the onland part). The relative abundance of reservoir grade coarser clastics increases towards the basinal side (offshore areas) to develop into very good reservoirs for lighter hydrocarbons.

The effects of neo-tectonism are also better visible in the Kachchh basin as compared to the Cambay basin. A major east-west strike fault (Katrol Hill fault) displacing the outcrop section (Fig. 1.4) and even visible on the satellite imagery.

TABLE: 5



CELL STATISTICS

CELL #	LOWER LIMIT	NUMBER OF OBS	%RELATIVE FREQUENCY
4	.46	1	2.13
11	.60	2	4.26
12	.62	3	6.38
13	.64	2	4.26
14	.66	2	4.26
15	.68	3	6.38
16	.70	7	14.89
17	.72	8	17.02
18	.74	4	8.51
19	.76	5	10.64
20	.78	3	6.38
21	.80	7	14.89

OBSERVED RANGES OF *LOCKHARTIA* SPECIES IN THE MIDDLE EOCENE FULRA LIMESTONE OF BERWALI RIVER SECTION AND THEIR BIOMETRIC PARAMETERS (SHUKLA, 1989)

Table- 6

GENUS: *Assilina* (All morphogroups)

BIOMETRIC PARAMETER / SPECIES	DIAMETER / THICKNESS RATIO	NO. OF SEPTAL FILAMENTS / DIAMETER	NO. OF WHORLS / DIAMETER	H / W RATIO (CHAMBER)	SIZE OF NUCLEOCONCH	AV. NO. OF CHAMBERS IN ¼ WHORL / NO. OF WHORLS	AV. RATE OF OPENING OF SPIRE
A. DAVIESI (FORM-A)	2.40-3.40	26-30/ 3.25-4..50	3.5-4.5	1.00-1.60	P=0.25-0.45 D=0.25-0.40 P/D=1.00-1.20	In 3rd wh. 6.73	In 3rd wh. 1.11
A. EXPONENS (FORM-B)	9.33-18.00	80-120/ 14.0-33.0	12-19	1.46-2.25	Microspheric	In 6th wh. 6.25	In 6th wh. 1.38
A. GRANULOSA (FORM-B)	8.54-17.7	48-64/ 8.20-12.40	6.5-10	1.60-3.55	Microspheric	In 6th wh. 7.22	In 6th wh. 2.07
A. GRANULOSA (FORM-A)	4.72-8.35	28-36/ 4.25-6.00	4-6	1.26-2.57	P=0.15-0.30 D=0.15-0.35 P/D=0.75-1.16	In 3rd wh. 5.36	In 3rd wh. 0.96
A. PLACENTULA (FORM-B)	5.65	26/ 5.65	8	2.00	Microspheric	In 6th wh. 5.00	In 6thwh. 1.95
A. PLACENTULA (FORM-A)	4.88-8.90	24-34/ 4.25-6.15	4.5-6.0	1.50-2.28	P=0.10-0.30 D=0.10-0.31 P/D-0.80-1.25	In 3rd wh. 5.20	In 3rd wh. 0.89
A. SPINOSA (FORM-A)	2.90-6.35	28-40/ 3.30-5.90	4-6	1.00-1.77	P=0.15-0.375 D=0.125-0.30 P/D=0.80-1.25	In 3rd wh. 4.93	In 3rd wh. 0.96

Table- 7

GENUS: *Nummulites* (Smooth / pustular surface, Radial septal filaments)

BIOMETRIC PARAMETER / SPECIES	DIAMETER / THICKNESS RATIO	NO. OF SEPTAL FILAMENTS / DIAMETER	NO. OF WHORLS / DIAMETER	H / W RATIO (CHAMBER)	SIZE OF NUCLEOCONCH	AV. NO. OF CHAMBERS IN ¼ WHORL / NO. OF WHORLS	AV. RATE OF OPENING OF SPIRE
N. ACUTUS (FORM-B)	2.58-5.60	40-64/ 4.00-15.75	7-15	0.75-1.75	Microspheric	In 6^{th} wh. 6.87	In 6^{th} wh. 2.47
N. ACUTUS (FORM-A)	1.42-2.00	22-32/ 3.15-4.80	3-4.5	0.71-0.85	P=0.10-0.55 D=0.15-0.40 P/D=0.66-1.37	In 3^{rd} wh. 4.22	In 3^{rd} wh. 0.91
N. BEAUMONTI (FORM-A)	1.75-2.66	28-44/ 2.55-4.70	4.5-8	1.20-1.75	P=0.25-0.5 D=0.25-0.375 P/D=1.00-2.00	In 3^{rd} wh. 7.0	In 3^{rd} wh. 0.77
N. BURDIGALENSIS (FORM-B)	1.77-3.68	32-48/ 1.95-4.25	5-7	1.42-3.20	Microspheric	In 6^{th} wh. 9.23	In 6^{th} wh. 1.65
N. BURDIGALENSIS (FORM-A)	1.45-2.91	22-35/ 1.25-2.45	3-4.5	0.81-1.50	P=0.40-0.125 D=0.40-0.15 P/D=0.74-1.50	In 3^{rd} wh. 5.20	In 3^{rd} wh. 0.51
N. DOUVILLE (FORM-B)	6.33	40/ 9.5	8.25	1.50-2.00	Microspheric	In 6^{th} wh. 8.00	In 6^{th} wh. 2.45
N. DOUVILLE (FORM-A)	2.75-4.00	26-32/ 2.55-4.70	2-3	1.62-2.20	P=0.35-0.70 D=0.30-0.65 P/D=0.61-1.66	In 2^{nd}/3^{rd} wh. 7.25	In 2^{nd}/3^{rd} wh. 1.98
N. GLOBULUS(FORM-A)	1.73-2.26	27-40/ 1.45-2.20	3.5-6	1.14-1.61	P=0.05-0.15 D=0.05-0.125 P/D=0.83-1.83	In 3^{rd} wh. 5.85	In 3^{rd} wh. 0.49
N. PINFOLDI(FORM-A)	1.44-1.94	36-52/ 2.10-4.25	4-7	1.16-1.75	P=0.15-0.30 D=0.10-0.25 P/D=1.00-1.50	In 3^{rd} wh. 9.30	In 3^{rd} wh. 0.98
N. VASCUS(FORM-A)	1.15-1.72	12-19/ 1.20-2.00	3-4.5	0.88-1.25	P=0.06-0.10 D=0.06-0.10 P/D=0.75-1.00	In 3^{rd} wh. 4.08	In 3^{rd} wh. 0.51

Table- 8

GENUS: *Nummulites*: Reticulate test

BIOMETRIC PARAMETER / SPECIES	DIAMETER / THICKNESS RATIO	NO. OF SEPTAL FILAMENTS / DIAMETER	NO. OF WHORLS / DIAMETER	H / W RATIO (CHAMBER)	SIZE OF NUCLEOCONCH	AV. NO. OF CHAMBERS IN ¼ WHORL / NO. OF WHORLS	AV. RATE OF OPENING OF SPIRE
N.FABIANII	2.79-3.80 (1.90 in one specimen)	Reticulate/ 2.00-4.80	5-8.5	0.57-0.80	P=0.22-0.50 D=0.18-0.50 P/D=1.00-1.20	In 3rd wh. 2.87	In 3rd wh. 0.66
N.FICHTELI FORMA CLYPEUS (FORM-A)	1.75-3.65	Reticulate septa 2.10-6.25	3-7 ¼	0.46-0.92	P=0.35-0.80 D=0.40-0.675 P/D=0.90-1.54	In 3rd wh. 3.43	In 3rd wh. 0.94
N.FICHTELI FORMA CLYPEUS (FORM-B)	4.92-7.24	Reticulate septa 11.50-20.00	20-38	0.64-0.85	Microspheric	In 4th wh. 3.14	In 4th wh. 0.35
N.FICHTELI FORMA FICHTELI (FORM-A)	2.80-5.31	Reticulate septa 4.25-6.00	6-7	0.46-1.00	P=0.40-0.75 D=0.30-0.675 P/D=0.83-1.43	In 3rd wh. 3.56	In 3rd wh. 0.90
N.FICHTELI FORMA FICHTELI (FORM-B)	3.70-6.50	Reticulate septa 10.0-22.0	15-38	0.44-0.83	Microspheric	In 4th wh. 4.06	In 4th wh. 0.31
GENUS: *Operculina*							
O. PELLATISPIROIDES (FORM-A)	3.42-5.38	16-22/ 2.55-4.85	2.5-4	-	P=0.05-0.175 D=0.05-0.175 P/D=1.00-1.20	In 3rd wh. 4.91	In 3rd wh. 1.61

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Also referred to several educational / professional websites related to the subject.

http://www.bgs.ac.uk

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http://www.geosociety.org/

http://www.micropress.org/micropress/

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PLATE-1

Figs.1-5 *Assilina daviesi* Cizancourt 1938,
Form-A

1. External X13; IPE/X01/04/5009
2. Equatorial X14; IPE/X01/04/5014
3. Axial X22; IPE/X01/04/5006
4. External X13; IPE/X01/04/5018
5. Equatorial X13; IPE/X01/04/5018

Figs.6-10 *Assilina exponens* Sowerby, 1840,
Form-B

6. Equatorial X2; IPE/X01/04/5038
7. Equatorial X2; IPE/X01/04/5033
8. Axial X4; IPE/X01/04/5053
9. Equatorial X5; IPE/X01/04/5038
10. External X5; IPE/X01/04/5032

PLATE 1

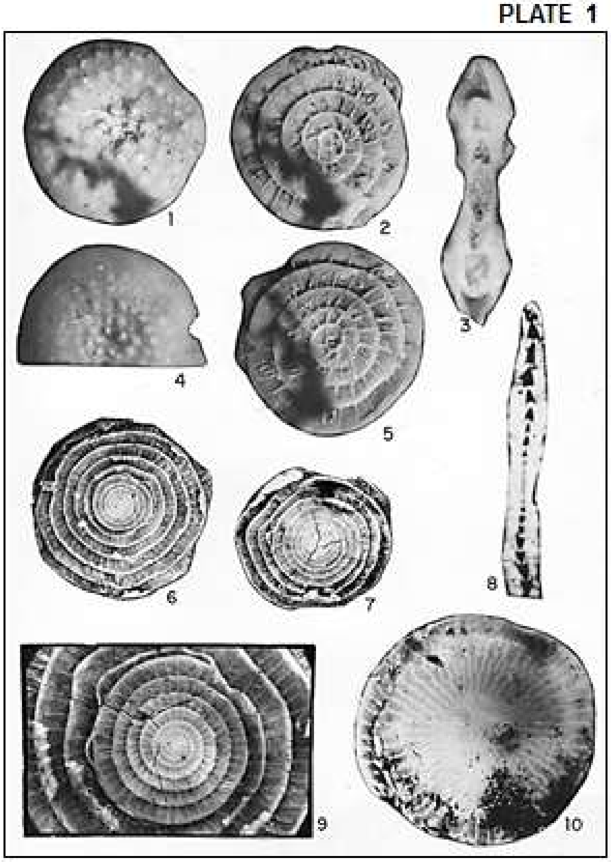


PLATE-2

Figs.1-10 *Assilina granulosa* d'Archaic, 1847
Form-B = 1-5, 7
Form-A = 6, 9-10

1. External X5; IPE/X01/04/6577
2. Equatorial X5; IPE/X01/04/6583
3. Equatorial X6; IPE/X01/04/6592
4. Equatorial X6; IPE/X01/04/6588
5. External X6; IPE/X01/04/6580
6. Axial X9; IPE/X01/04/5081
7. Axial X9; IPE/X01/04/6603

9. External X11; IPE/X01/04/5057

10. Equatorial X11; IPE/X01/04/5062

Figs. 11-15 *Assilina placentula* (Deshayes, 1838)
Form-B = 12
Form-A = 11, 13-15

11. External X12; IPE/X01/04/5086
12. External X10; IPE/X01/04/5088
13. Axial X12; IPE/X01/04/5111
14. Axial X14; IPE/X01/04/5113
15. Equatorial X14; IPE/X01/04/5097

PLATE 2

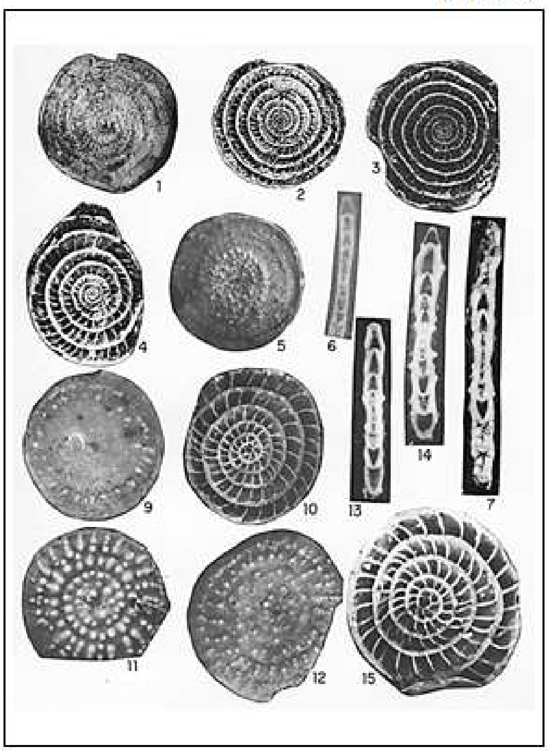


PLATE - 3

Figs. 1-7 *Assilina spinosa Davies*, 1937, Form-A

1. External X13; IPE/X01/04/5247
2. External X13; IPE/X01/04/5258
3. Equatorial X12; IPE/X01/04/5250
4. Equatorial X13; IPE/X01/04/5258
5. Axial X13; IPE/X01/04/5280
6. Equatorial X13; IPE/X01/04/5252
7. External X13; IPE/X01/04/5245

PLATE 3

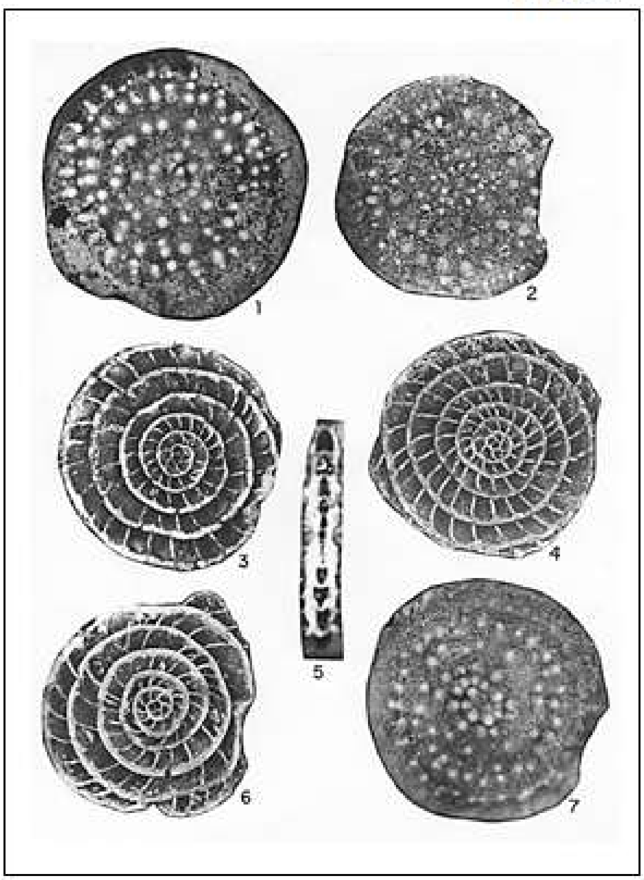


PLATE-4

Figs. 1-6 *Nummulites acutus* (Sowerby, 1840)
1-2 = Form-B
3-6 = Form-A

1. External X3; IPE/X01/04/5284

2. Equatorial X6; IPE/X01/04/5300

3. External X12; IPE/X01/04/5314

4. Equatorial X14; IPE/X01/04/5327

5. Equatorial X16; IPE/X01/04/5326

6. Axial X20; IPE/X01/04/5324

Figs. 7-9 *Nummulites beaumonti* d'Archaic and Haime, 1853,
Form-A

7. External X15; IPE/X01/04/5417

8. Equatorial X15; IPE/X01/04/5425

9. Axial X15; IPE/X01/04/5431

PLATE 4

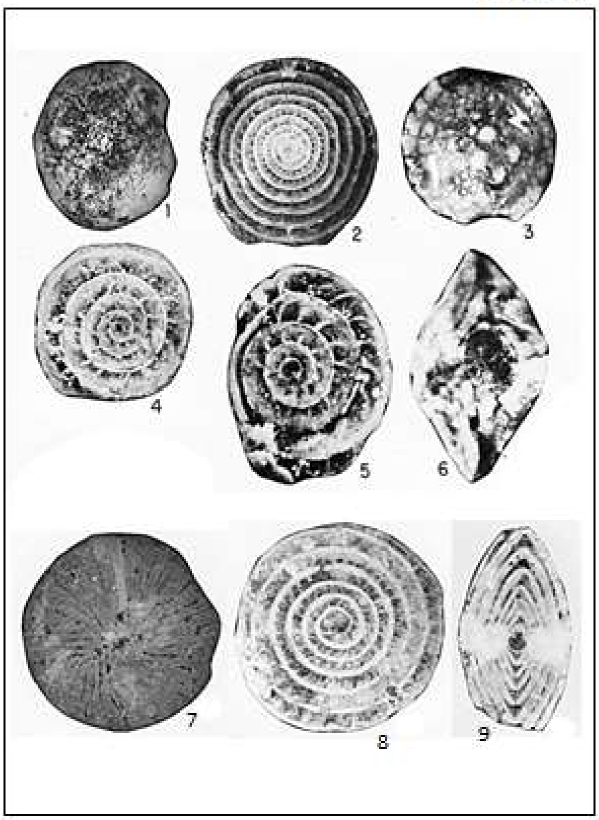


PLATE-5

Figs. 1-7 *Nummulites burdigalensis* de la harpe, 1926,
Form-B= 4-5, 7
Form-A= 1-3, 6

1. External X31; IPE/X01/04/5448
2. Equatorial X30; IPE/X01/04/5459
3. Equatorial X21; IPE/)1/04/5458
4. External X13; IPE/X01/04/5498
5. Equatorial X18; IPE/X01/04/5504
6. Axial X15; IPE/X01/04/5487
7. Axial X15; IPE/X01/04/5537

Figs. 8-13 *Nummulites douvillei* Vredenburg, 1906,
Form-B= 9,
Form-A=10-14

8. Equatorial X15; IPE/X01/04/5638
9. External X7; IPE/X01/04/5628
10. External X10; IPE/X01/04/5629
11. Axial X15; IPE/X01/04/5646
12. External X16; IPE/X01/04/5687
13. Equatorial X16; IPE/X01/04/5629

PLATE 5

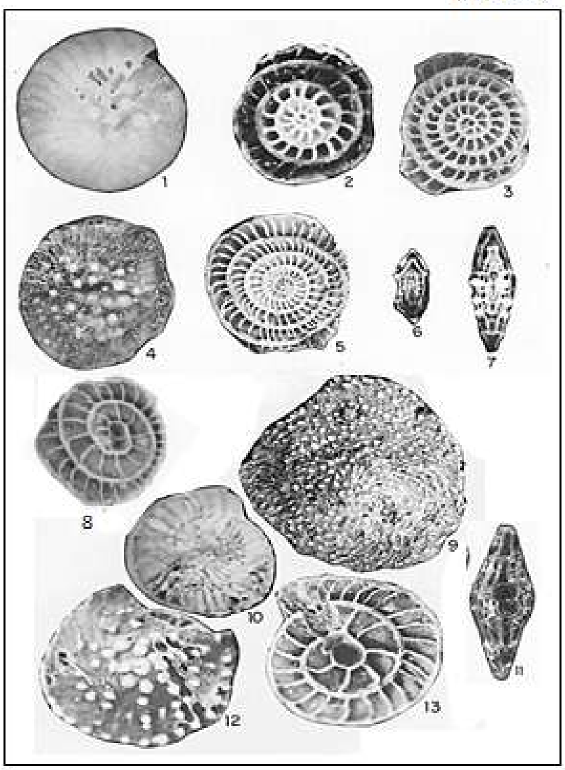


PLATE-6

Figs. 1-5 *Nummulites fabianii* (Prever, 1905) forma *fabianii*, Form-A

1. External X13; IPE/X01/04/5652
2. Equatorial X13; IPE/X01/04/5652
3. Axial X18; IPE/X01/04/5666
4. External X16; IPE/X01/04/5650
5. Equatorial X12; IPE/X01/04/5660

Fig. 6 *Dictyoconoides cooki*

6. Vertical section, X16; IPE/X01/04/7030

Figs.7-10 *Nummulites obtusus* (Sowerby, 1840), Form-B

7. External X8; IPE/X01/04/5934
8. Axial X7; IPE/X01/04/5946
9. External X3; IPE/X01/04/5927
10. Equatorial X7; IPE/X01/04/5939

PLATE 6

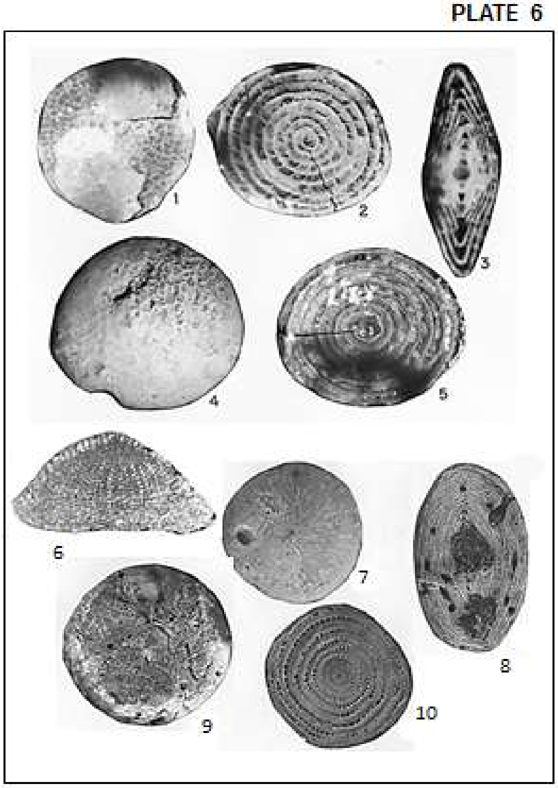


PLATE-7

Figs. 1-3, 5, 8, 12 *Nummulites fichteli* Michelloti forma *clypeus* Nuttal, 1926

Form-B = 5,8,12
Form-A = 1-3

1. External X13; IPE/X01/04/5692

2. Axial X18; IPE/X01/04/5716

3. Equatorial X11; IPE/X01/04/5693

5. External X3; IPE/01/04/5722

8. Equatorial X4; IPE/01/04/5731

12 Axial X6; IPE/X01/04/5729

Figs.4,6-7, 9-11 *Nummulites fichteli* Michelloti 1841,

Form-A
4. External X11; IPE/X01/04/5748

6. External X10; IPE/X01/04/5742

7. Equatorial X11; IPE/X01/04/5738

9. Equatorial X10; IPE/X01/04/5776

10. Axial X13; IPE/X01/04/5778

11. Axial X13; IPE/X01/04/5777

PLATE 7

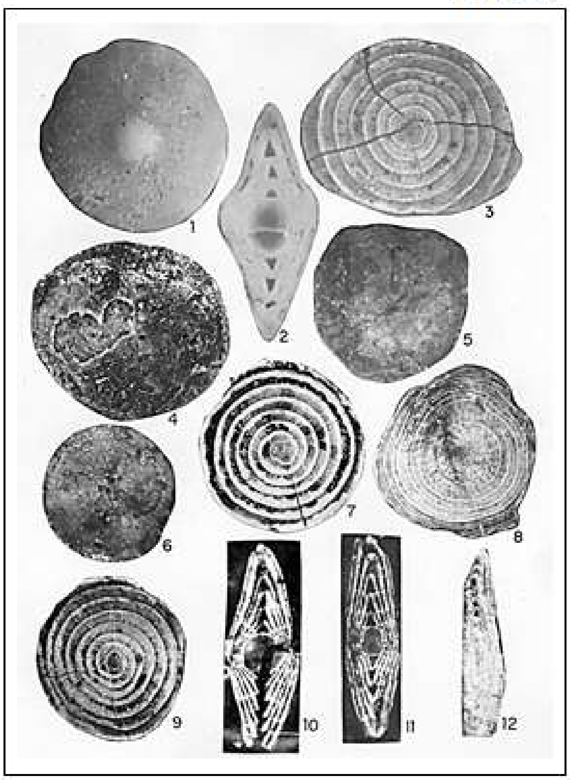


PLATE-8

Figs. 1-3 *Nummulites globulus* Leymerie, 1846
Form-B = 1
Form-A = 2-3

1. External X21; IPE/X01/04/5892
2. Equatorial X21; IPE/X01/04/5853
3. Axial X24; IPE/X01/04/5859

Figs. 4-6 *Nummulites pinfoldi* Davies, 1940,
Form-A

4. External X13; IPE/X01/04/6046
5. Equatorial X17/IPE/X01/04/6051
6. Axial X16; IPE/X01/04/6066

Figs. 7-9 *Nummulites vascus* Joly and Leymerie, 1848,
Form-A

7. External X16; IPE/X01/04/6347
8. Axial X16; IPE/X01/04/6364
9. Equatorial X16; IPE/X01/04/6354

Figs. 10-11 *Operculina pellatispiroides* Colom, 1954,
Form-A

10. External X20; IPE/X01/04/6392
11. Axial X18; IPE/X01/04/6404

PLATE 8

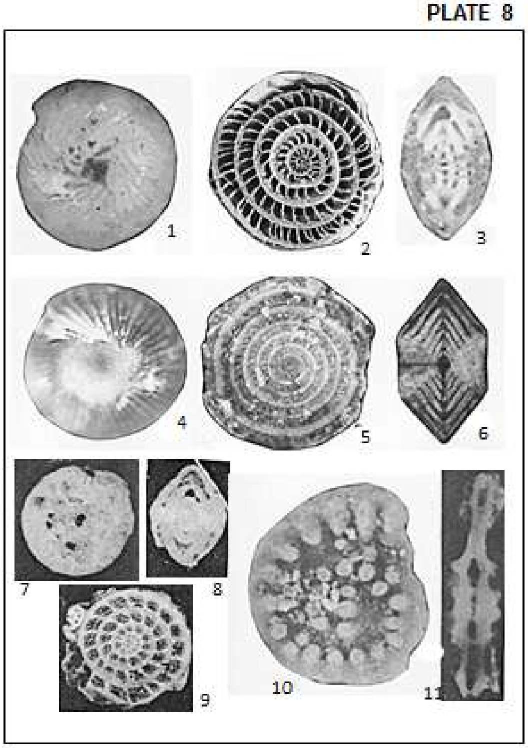


PLATE- 9

Figs.1-3 *Pellatispira inflata*, Umbgrove

1. External, x40; IPE/X01/04/7001
2. Equatorial, x21; IPE/X01/04/7002
3. Axial, x28; IPE/X01/04/7003

Figs.4-6 *Pellatispira madraszi,* (Hantken)

4. External x28; IPE/X01/04/7010
5. Equatorial x21; IPE/X01/04/7011
6. Axial, x21; IPE/X01/04/7012

Figs.7-9 *Lockhartia alveolata,* Silvestri

7. External X37; IPE/X01/04/7020
8. Vertical section, x50; IPE/X01/04/7021
9. External umbilical x38; IPE/X01/04/7022

Figs.10-11 *Dictyoconoides cooki,* (Carter)

10. External x8; IPE/X01/04/7031
11. Umbilical x15; IPE/X01/04/7032

PLATE 9

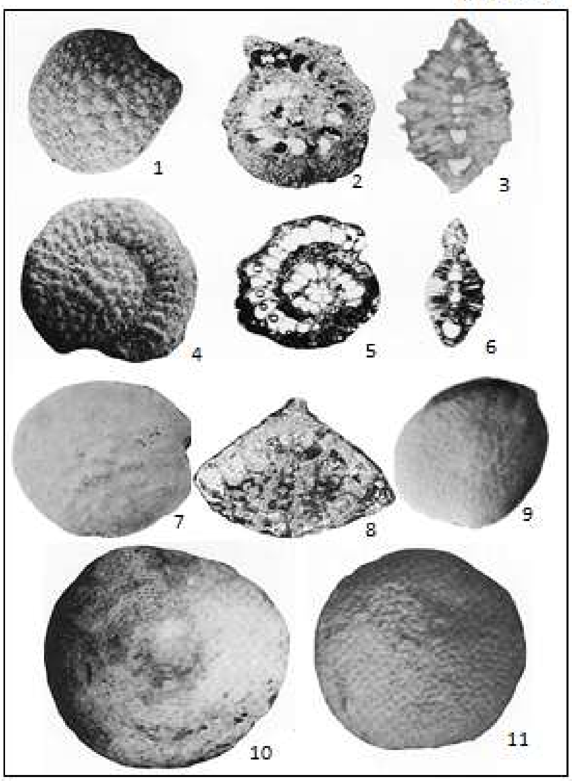


PLATE- 10

Figs.1-3 *Discocyclina dispansa*, Nuttall

1. External x22; IPE/X01/04/7041

2. Equatorial x8; IPE/X01/04/7042

3. Axial, x16; IPE/X01/04/7043

Figs.4-6 *Discocyclina sowerbyi,* (Sowerby)

4. External, x29; IPE/X01/04/7051

5. Equatorial x17; IPE/X01/04/7052

6. Axial, x16; IPE/X01/04/7053

Figs.7-9 *Discocyclina omphalus*, (Fritsch)

7. External, x16; IPE/X01/04/7061

8. Equatorial, x21; IPE/X01/04/7062

9. Axial, x18; IPE/X01/04/7063

PLATE 10

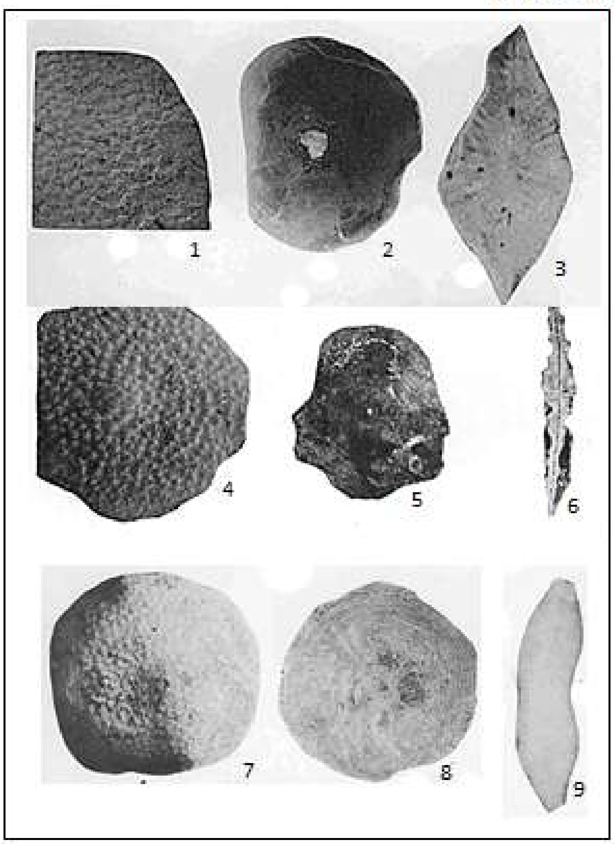


PLATE - 11

Figs.1-3 *Discocyclina undulata*, Nuttall

1. External, x8; IPE/X01/04/7071
2. Equatorial, x15; IPE/X01/04/7072
3. Axial, x23; IPE/X01/04/7073

Figs.4-5 *Acktinocyclina alticostata,* Nuttall

4. External, x32; IPE/X01/04/7081
5. Equatorial, x30; IPE/X01/04/7082

Figs.6-7 *Eoannularia eoceneca*; Cole and Bermudez

6. External, x37; IPE/X01/04/7091
7. Equatorial, x32; IPE/X01/04/7092

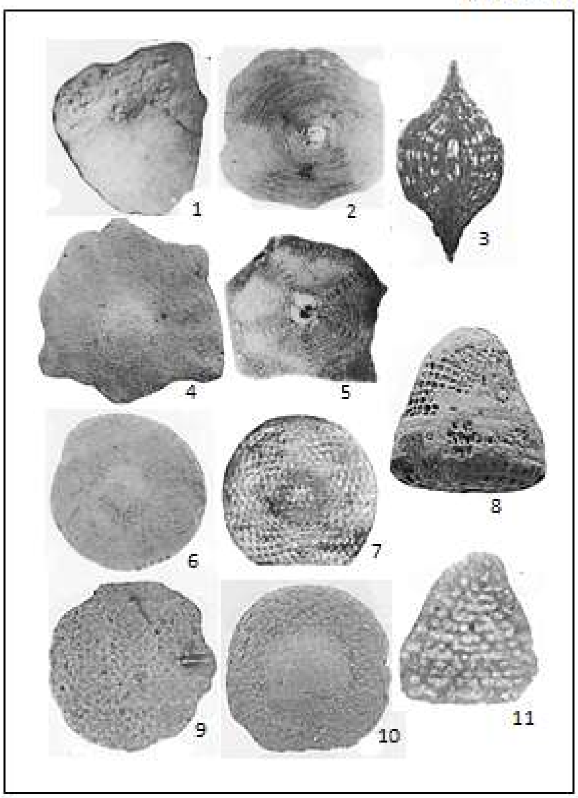
Figs. 9-10 *Linderina buranensis*, Nuttall

9. External, x43; IPE/X01/04/7101
10. Equatorial, x60; IPE/X01/04/7102

Figs.8, 11, *Dictyoconus indicus*, Davies

8. External, x43; IPE/X01/04/7111
11. Vertical section, x35; IPE/X01/04/7112

PLATE 11



ENCLOSURES

1. CHECK LIST OF FORAMINIFERA SPECIES DISCUSSED IN THESIS

Assilina daviesi

A. exponens

A. granulosa

A. placentula

A. spinosa

Nummulites acutus

N. beaumonti

N. burdigalensis

N.douvilleri

N. fabianii

N. fichteli forma clipeus

N. fichteli forma fichteli

N. globulus

N. obtusus

N. pinfoldi

N. vascus

Operculina pellatispiroides

Pellatispira inflata,

Pellatispira madraszi

Lockhartia alveolata

Dictyoconoides cooki

Discocyclina dispansa

Discocyclina sowerbyi

Discocyclina omphalus

Discocyclina undulata

Acktinocyclina alticostata

Eoannularia eoceneca

Linderina buranensis

Dictyoconus indicus

2. CHECK LIST OF LARGER FORAMINIFERAL BIOZONATION

1 BARREN ZONE

2 *NUMMULITES DESERTI* PARTIAL RANGE ZONE

3 *NUMMULITES GLOBULUS* PARTIAL RANGE ZONE

4 *NUMMULITES EXILIS- PLANULATUS– ASSILINA PUSTULOSA* ASSEMBLAGE ZONE

5 *NUMMULITES BURDIGALENSIS* PARTIAL RANGE ZONE

6 *NUMMULITES PRELUCASI* PARTIAL RANGE ZONE

7 *NUMMULITES DOUVILLE* PARTIAL RANGE ZONE

8 *NUMMULITES ACUTUS* PARTIAL RANGE ZONE

9 *NUMMULITES BEAUMONTI - NUMMULITES CUVILLIERI - ASSILINA* SP. PARTIAL RANGE ZONE

10 *NUMMULITES FABIANII* PARTIAL RANGE ZONE

11 *NUMMULITES FICHTELI* RANGE ZONE

12 *GRZYBOWSKIA TANDONI* RANGE ZONE

13 *MIOGYPSINOIDES COMPLANATA - BANTAMENSIS* (x=11± 0.2) RANGE ZONE

3. ABBREVIATIONS

ORGANISATIONS

IGC	International Geological Congress
IGCP	International Geological Correlation Project
ICS	International Commission of Stratigraphy
DSDP	Deep Sea Drilling Project
ONGC	Oil and Natural Gas corporation, India
ODP	Ocean Drilling Project
GTS 82	A Geological Time Scale (Harland et al 1982)
GTS 89	A Geological Time Scale (Harland et al 1990)
SEPM	Society for Sedimentary Geology
GTS 2004	A Geological Time Scale (Gradstein, Ogg & Smith 2004)
GTS 2012	A Geological Time Scale (Gradstein, Ogg & Schmitz & Ogg 2012)

GEOSCIENTIFIC CONCEPTS

FAD	First Appearance Datum
FOD	First Occurrence Datum
GPTS	Geo magnetic Polarity Time scale
GSSP	Global Stratotype Section and Point
GSSA	Global Standard Stratigraphic Age
HO	Highest Occurrence Level
LAD	Last Appearance Datum

LO Lowest Occurrence level

LOD Last Occurrence Datum

SYMBOLS

ka kilo annum i.e 10^3 yrs ago

kyr 10^3 yrs duration

ma mega annum i.e. 10^6 yrs ago

myr 10^6 yrs duration

Ga Giga annum i.e 10^9 yrs ago

Gyr 10^9 yrs duration

SL Le Système Internationale d'Unités

A annus (year)

S second

4. LIST OF RECENT PUBLICATIONS RELATED TO THESIS

Shukla, S., J Begum, J Baruah and S.K.Vyas (2008), Paleogene larger foraminiferal correlation zones of Assam- Shillong shelf - an example of High impact biostratigraphy. Presented in International Seminar on northward flight of India in the Mesozoic-Cenozoic: consequences in biotic changes and basin evolution, and published Jour. Pal. Soc. India, 2008, vol 53(2). pp 227-242

Shukla, S., (2008), MONOGRAPH titled Atlas of Taxonomic and bio-chronostratigraphic studies on Paleogene larger benthic foraminifera from Indian Sedimentary Basins. Published as Paleontographica Indica, vol 9. 2008, pp 1-183.

Shukla S., (2009), Larger benthic foraminiferal indices of the Indian Paleogene, Presented in SEPM Conference: Microfossils-II, at Houston, USA, March-2009.

Shukla, S. and Bajpai, S., (2013), Oligocene larger foraminiferal biostratigraphy & SBZ-zonation on western continental shelf, India; ONGC bulletin, Vol 48, no 5; pp 35-41.