Quantitative stratigraphy and geohistory analysis*

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The quantitative techniques in the stratigraphic analysis were introduced in hydrocarbon exploration in India in late nineteen-sixties. Initially simple statistical methods were used for classification and correlation of poorly fossiliferous sequences. Advanced quantitative techniques, alongwith computer graphics, were employed only after 1980, when magnetostratigraphy, automated paleoecological information-model, RASC program and geohistory analysis enriched the knowledge for sequence stratigraphy and stratigraphic trap exploration.

Key-words - Quantitative techniques, stratigraphy, geohistory analysis.

INTRODUCTION

Stratigraphy, like most geological sciences, is essentially empirical, which implies that it is firmly planted in a body of organised, cumulative observations. It has two main attributes:

i) The irreversible flow of time, and

ii) events as preserved in the geological record and their spatial and temporal relations.

The reconstruction of the likely-order and geographic extent of events and their placement within the geological time scale provide a frame-work called geological history.

There are many categories of events, each with special properties and significance to geological history. Lithostratigraphy, biostratigraphy, magneto-stratigraphy and seismic stratigraphy are general classification systems of such categories. International Sub-commission on Stratigraphic Classification (1976) provides rules for these systems for achieving precision and uniformity. Stratigraphically significant categories of events include:

i) Paleontological events characterised by first appearance datum (FAD), range, peak occurrence, co-occurrence and last appearance datum (LAD) of fossil taxa,

ii) paleoenvironmental events characterised by significant bathymetric changes, special environments (delta, reef), transgressions, regressions and eustatic changes,

iii) episodic events characterized by epeirogenic and orogenic changes, changes in provenance, changes in energy conditions, paleomagnetic reversals and by significant celestial changes, and

iv) cyclic events including a series of connected events which return to a starting point, and are predictable.

The study of these events in detail and their application enables Event Stratigraphy, which has a much higher resolution.

The paleontological events are results of the continuing evolutionary trends of life on earth. They differ from physical events in that they are unique, non-recurrent, and that their order is irreversible. Correlation lines established through paleontological events over an area are normally assumed to correspond to time planes.

Stratigraphy provides basic framework to hydrocarbon exploration, which is achieved through stratigraphic zonation, facies analysis and correlation. Quantitative techniques lead to a more objective stratigraphy and a better understanding of limitations. Such techniques include:

1. quantification of conventional stratigraphic attributes and their analysis, and
2. the application of multiple correlation criteria.

HISTORICAL BACKGROUND

Charles Lyell (1830-1833) probably was the first quantitative stratigrapher when he defined several of the Tertiary epochs based on percentage of living moluscan species. The Lyellian method is statistical as the

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percentages were derived from massive amounts of data (8,000 species and 40,000 specimens) and definitions furnished an identification rule for determining the age of unknown samples.

Quantitative stratigraphy languished for about 120 years but a major renaissance began in 1950's, which is continuing at an accelerated pace. The 1960's and 1970's have brought a plethora of algorithms.

An exhaustive review of quantitative stratigraphic techniques is not possible here. Some of the most outstanding contributions are: Harbaugh and Merriam (1968), Buzas (1970), Hay (1972), Park (1974), Perrier and Quiblier (1974), Schwarzacher (1975, 1980), Hazel (1971), Brower *et al.* (1980), Mann and Dowell (1978), Brower *et al.* (1979), Reyment (1980), Hardenbol *et al.* (1981), Agterberg and Nel (1982 a,b), Griffiths (1982), Davaud (1982), Ghose, (1982), Abry (1984), and Grandstein *et al.* (1985).

The quantitative stratigraphic studies received encouragement during 1978 with the adoption of IGCP Project 148: Quantitative stratigraphic correlation, with the main theme as 'Practical applications of quantitative stratigraphy'. The IGCP-148 has been concerned with the development and application of new quantitative stratigraphic techniques and new algorithms, which "think" along stratigraphic lines of reasoning.

Quantitative stratigraphy became feasible with the introduction of reliable time scale models based on a careful integration of biostratigraphy, magnetostratigraphy, seismic stratigraphy and radiometric dating (van Hinte, 1976 a, b, Jurassic and Cretaceous: Berggren, 1972; Hardenbol & Berggren, 1978, Tertiary). The resulting linear time scale forms the base for most of the advanced quantitative stratigraphic techniques.

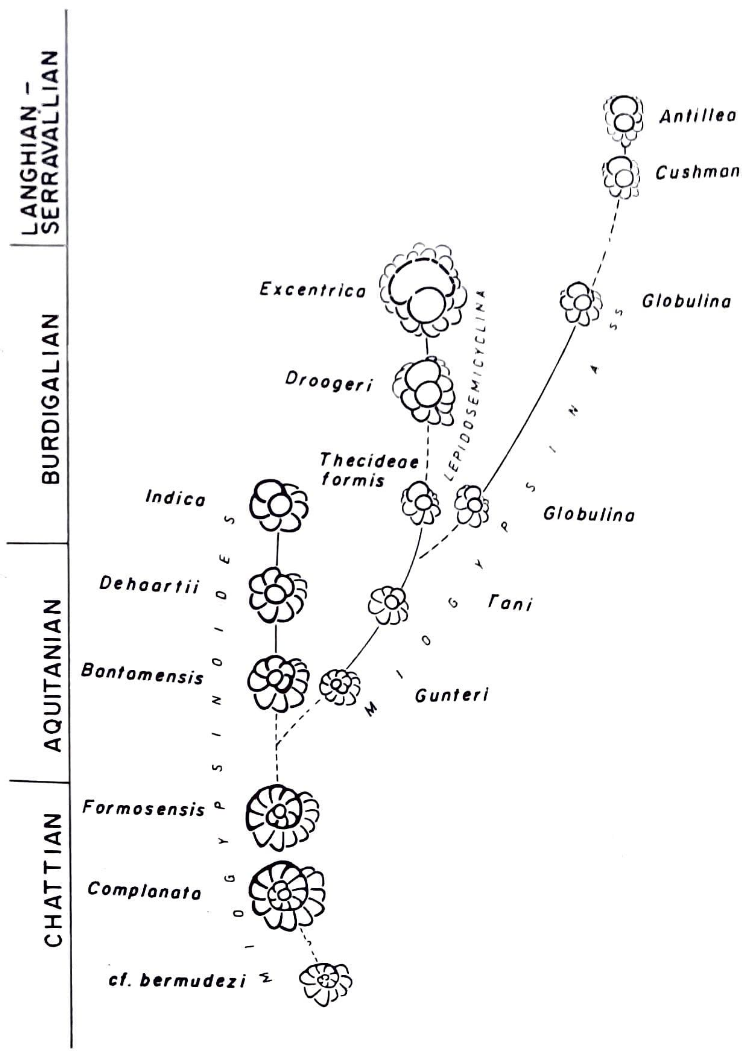
QUANTITATIVE TECHNIQUES IN INDIAN STRATIGRAPHY

The formative era in Indian stratigraphy was initiated with the formation of Oil and Natural Gas Commission in 1956. Prior to this date, exccept for parts of Assam-Arakan Basin where subsurface stratigraphic control was adequate, stratigraphy of most of the Indian basins was based on the knowledge of outcropping sequences. Stratigraphic data were insignificant and stratigraphic problems were not even properly appreciated.

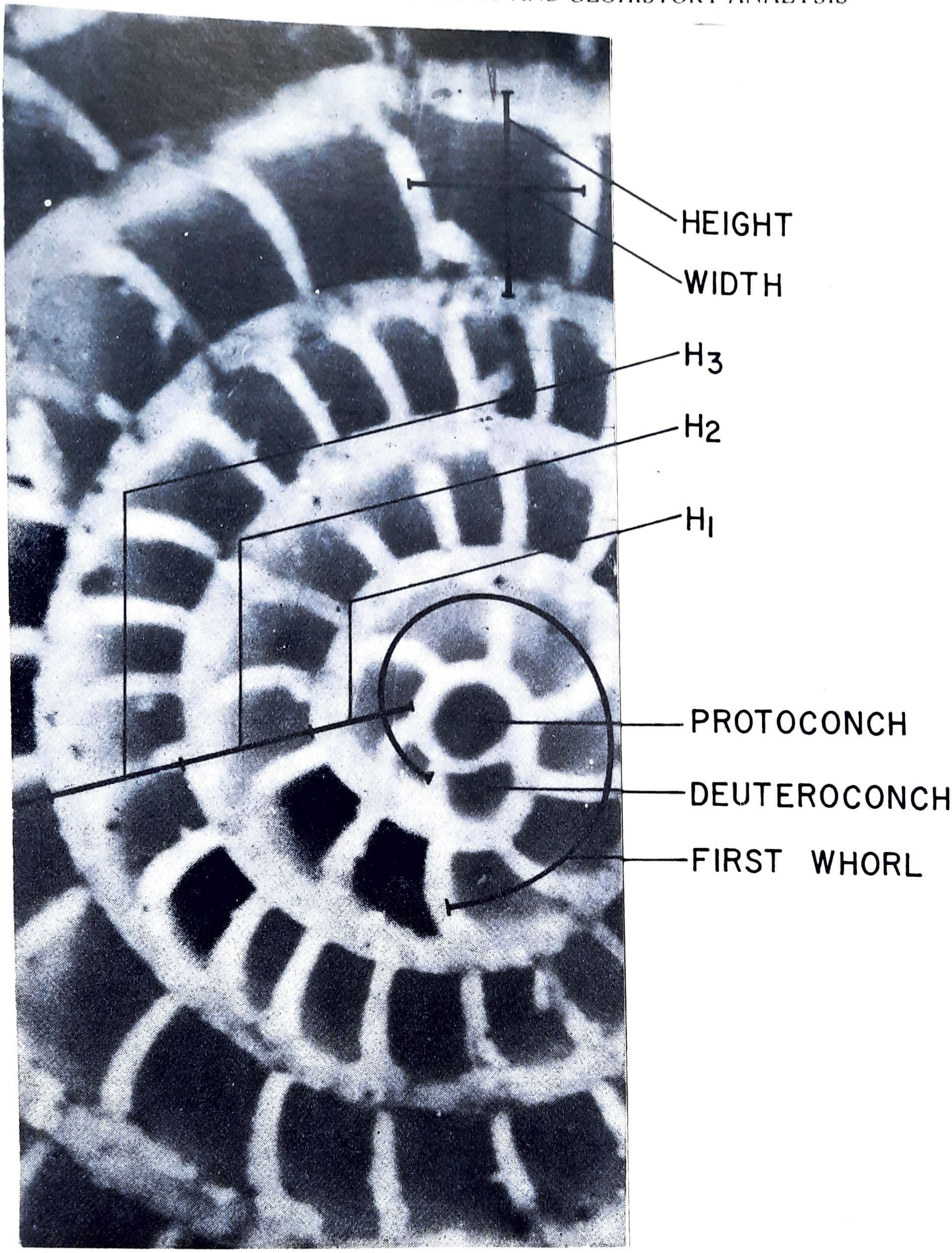
With the intensification of oil exploration, more and more subsurface stratigraphic information was generated. Identification criteria and interpretative techniques gradually developed to handle larger sets of data. With the growth of stratigraphic information and data generation, quantitative studies were initiated in the late sixties, and since then they attained a sustained growth.

QUANTITATIVE TAXONOMY

Raju (1974) carried out study of Indian Miogypsinidae based on simple statistical methods evolved by Drooger (1952, 1963). Counts and measurements were carried out on a number of characteristic biometric parameters as outlined by Drooger (1952, 1963) and Souaya (1961). Mean values and often their standard errors were calculated for each parameter and for each assemblage they were thought to be homogenous. Scatter diagrams were plotted in order to investigate the relationship between various parameters. The possibility of significant difference between the means of some parameters in different samples was tested by application of Student's t-test, following the formula suggested by Simpson (1960). All the 16 species of Miogypsinidae are defined quantitatively. With the boundaries between the species defined quantitatively, intra-basinal and inter-basinal correlation and hence



Text-figure 1. Phylogenenetic relationship and evolutionary history of Miogypsinidae (Raju, 1974). Distinct stages in nepionic acceleration define the miogypsinid species quantitatively.



Text-figure 2. Showing quantitative biometric parameters utilised by Shukla (1982-1986) for differentiation of nummulitid species. Scatter plots of these parameters for the three nummulitid species are given in Text-figures 3 & 4.

stratigraphy becomes unambiguous. The study established phylogenetic relationship and successfully demonstrated the evolutionary history of miogypsinid species. With reasonably short vertical ranges, the Miogypsinidae provide a finer biostratigraphic zonation for latest Oligocene to Early Middle Miocene sequence (Text-fig. 1).

Raju and Drooger (1978) initiated quantitative studies on Indian Planolindernia. The studies for Lepidocyclinidae were initiated in 1976. After a decade, further studies were resumed in 1986, which are aimed at rendering help in correlation of Oligo-Miocene sections, wherever Miogypsinidae are not present.

The quantitative criteria in the identification of nummulitid foraminifera were formally applied by Schaub (1951). Taxonomic standardisation for most of the European nummulitid species has since been achieved.

Stratigraphic ranges for the European species were refined and evolutionary lineages were worked out. Shukla (1982) initiated biometric analysis of Indian Nummulitidae with the objective of achieving finer stratigraphic zonations for shallow water Paleogene carbonates through taxonomic standardisation. Distinctive qualitative characters were used in distinguishing important morphometric groups of species (Shukla, 1986). Quantitative biometric parameters (Text-fig. 2) characterising each species within a morphometric group were established.

Biometric parameters for about 100 nummulitid species have been established. The scatter plots, as an example, for the biometric parameters of the three morphometrically similar species, *N. beaumonti*,*N. chavannesi* and *N. pulchellus* (Pl.1, figs 1,3,5) illustrated in Text-figures 3 and 4 provide criteria for identification. The quantitative taxonomic studies are also being extended to other foramineferal genera, including *Assilina, Discocyclina, Fasciolites* and *Globorotalia.*

QUANTITATIVE PALEOECOLOGY

The significance of paleoecology has been apparent to the petroleum industry for many years. Simple quantitative methods were gradually introduced to enhance the accuracy of interpretations. The concept of speciation (number of ranked species in an assemblage), Foraminiferal Number (number of individuals per gram of dry sediment), faunal dominance (percentage occurrence of dominant species in a faunal population), cummulative percentage plots, triangular plots of suborders Textulariina, Milioliina and Rotaliina, diversity indices (relationship of the number of species to the number of individuals in an assemblage) and similarity indices (similarity between samples) employed alongwith the sedimentary microfacies analysis provide a fairly accurate paleoecological reconstruction. Ratios of the two faunal groups, differing in their mode of life (planktonic/benthonic ratio) have also been utilised.

A computer software ECOMOD (ecological modelling) has been developed to standardise the paleontological data handling (Ganesh & Roy, 1984). The data input constitute the list of taxa with absolute numbers or frequency range of occurrence in accordance with their recorded stratigraphic/depth levels. ECOMOD output provides facilities for an echocheck of all input parameters, computational and sorting results on the printer and graphic display of Foraminiferal Number, α index, percentage of suborders, commulative percentage of taxa, similarity index and paleoecology (Text-fig.5), triangular plot for percentage of suborders (Text-fig. 6), faunal frequency and range charts (Text-figs 7,8), alongwith complete borehole record for paleoecological interpretations. Softwares for computation and plotting techniques for composite petrographic parameters have also been developed.

The Hutton's principle 'present is the key to the past' continued to be the basic assumption in paleoecological reconstructions, but precision in the interpretation improved alongwith the improvement in the knowledge about the recent ecological realms and their inhabiting fauna. As the oil exploration techniques advanced, involving the location of stratigraphic and subtle traps, the demand of accuracy in paleoecological interpretations further increased to suite the more sophisticated nature of exploration.

Kalyanasunder *et al.* (1986) applied appropriate statistical and computational techniques for quantification of ecological parameters, developed suitable algorithm for computer application and evolved an automated identification technique as a paleoecological information model.

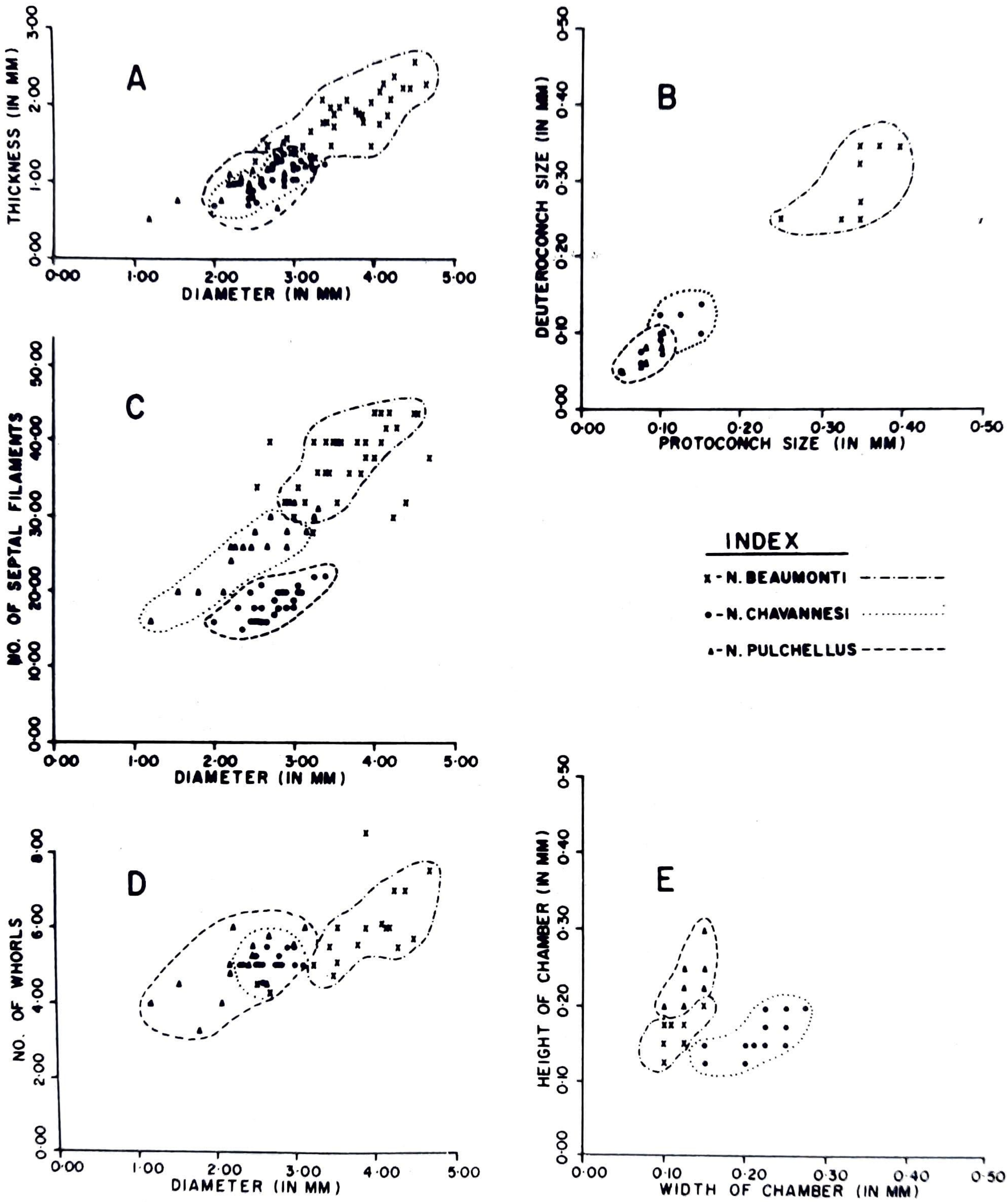
The study incorporates the recent foraminiferal data and physico-chemical parameters for more than 100 samples from western Continental Shelf of India, between 18°N and 22°N latitudes. Eight ecogroups (E1-E8) were recognised in the region in the depth range of 20 m to 2500 m, mainly on the basis of bathymetry, characterised by their physico-chemical parameters and the faunal assemblages. Two I-D matrices (samples from E1 to E8, alongwith their physico-chemical parameters in the rows and taxa in the columns), one with 170 species (I-D species) and the other with 61 genera (I-D genera) are developed and incorporated in the model (Text-fig. 9). The matching method based on Bayesian model is applied, whereby the taxa of an unknown ecology are compared with the description and properties of each ecogroup in turn, and the best matching ecogroup is identified (Text-fig. 10).

The information model is an online computer assisted system developed on VAX 11/780 computer. The input at a terminal is sample-wise list of foraminiferal species, with their actual number of individuals. The model can be updated and can be applied to any basin by tuning the I-D matrix for local conditions.

PLATE 1

Showing three *Nummulites species, N. pulchellus* (1,2), *N. beaumonti* (3,4) and *N. chavannesi* (5,6), which are morphologically similar. Equitorial sections (2,4,6) provide criteria for their differentiation. The biometric parameters for these species and their interrelationships are given in text-figures 3 & 4.

PLATE 1

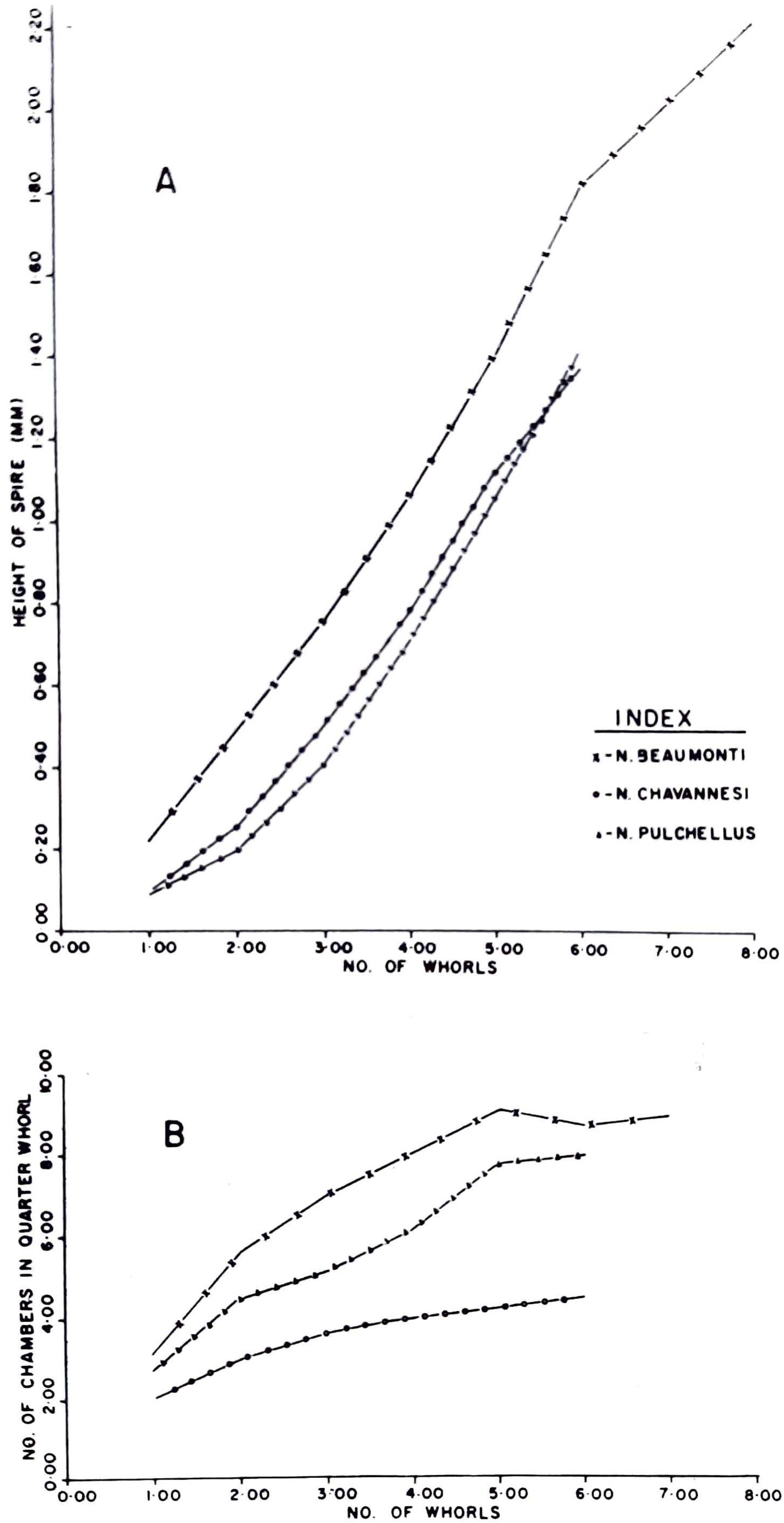


Text-figure 3. Scatter plots of biometric parameters of the three species illustrated in Plate 1, figure 3. The parameters for *N. beaumonti* (x) plot separately in all the five cases. *N. pulchellus* (▲) and *N. chavannesi*, (●) are more allied, and can be differentiated by the ratio of diameter and numer of septal filaments (C), and by the ratio of width and height of chambers (F).

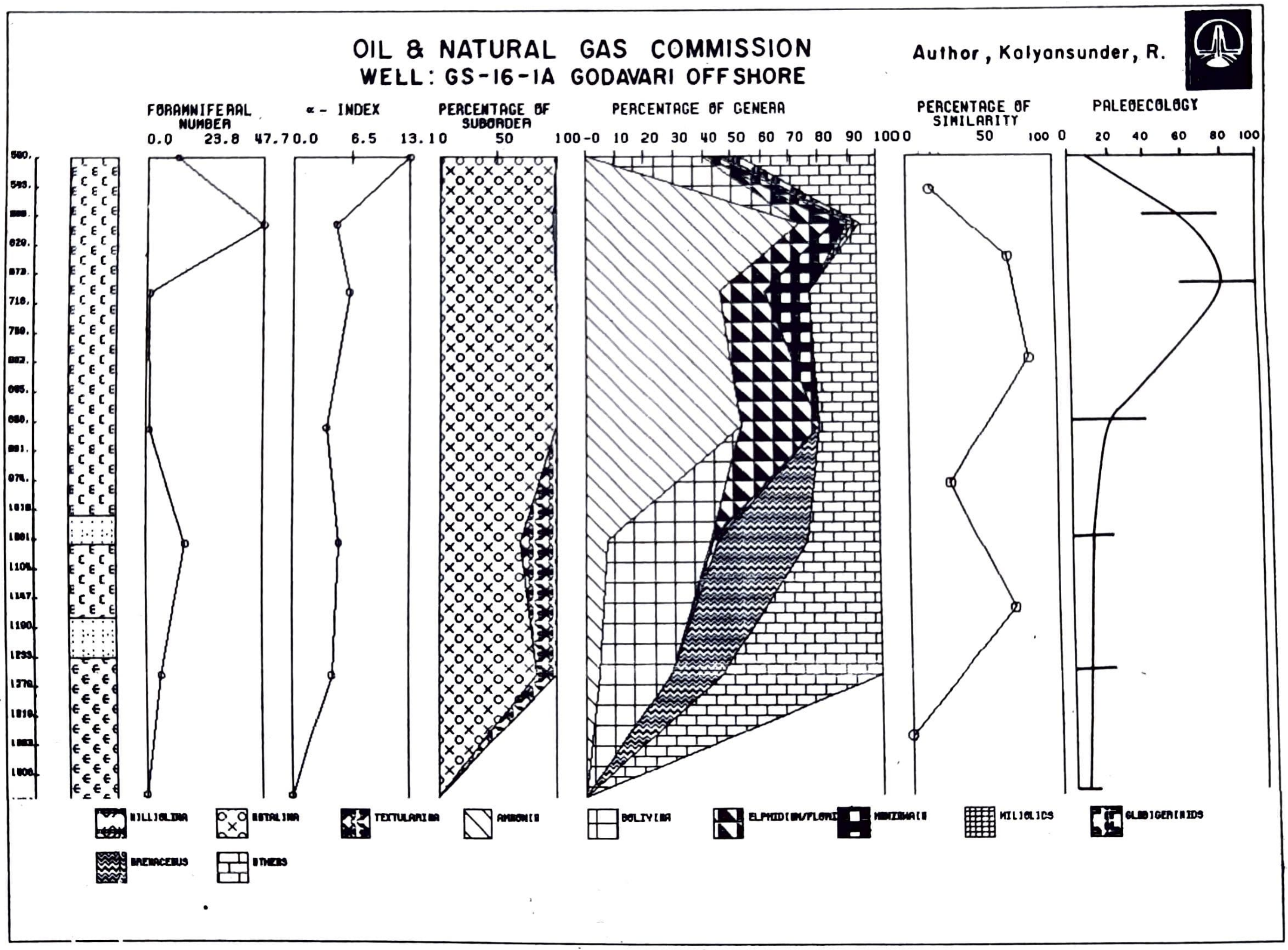
CORRELATION

A sedimentary sequence represents a stratified record of the physico-chemical conditions that existed during the deposition of the sediments. The energy factors and bathymetry that constitute the environments of deposition equally effect the contemporaneous sedimentation and biota. In general, the organic remains are more sensitive indicators of the depositional environments and serve well to infer the successive environmental changes.

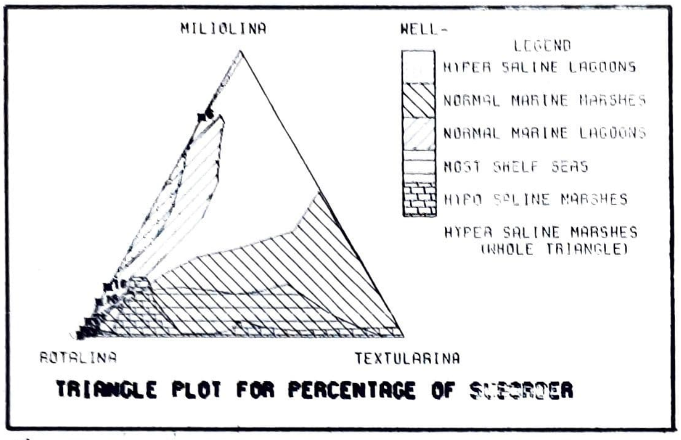
Pandey and Soodan (1971) studied the microfauna and established a sequence of paleobathymetric fluctuations,



Text-figure 4. Spiral diagram (A) and chamber pattern (B) for the three species illustrated in Plate 1. All the three species can be distinctly differentiated by both of the parameters.



Text-figure 5. Computer-graphics showing microfaunal parameters including Foraminiferal Number (number of individuals in one gram of dry sediment), α index (Fisher relationship index between number of species and total foraminiferal count), percentage of foraminiferal suborders and taxa and similarity indices, alongwith paleobathymetric interpretations.



Text-figure 6. Summary triangular plot showing the fields for different environments. Most of the samples in this example have a very high percentage dominance of Rotaliina and belong to a shallow shelf. Sample 6, however, is suggestive of hypersaline lagoons.

related ultimately to the local transgressions and regressions, in the Kopili Formation met in Disangmukh and Rudrasagar wells of Upper Assam. They (Pandey & Soodan, 1971, Text-fig. 1) demonstrated the utility of paleobathymetric trends in correlation. Simultaneously, Gerald R. Strude of Humble Oil and Refining Company, New Orleans, opined that in areas of regional transgressions and regressions, determining paleo-water depth fluctuations in sections of individual wells aids in the correlation of a biozone (Strude, 1971). He illustrated the correlation of three South Louisiana wells in different fault blocks by utilising paleo-bathymetric trends.

During the analysis of paleobathymetric trends, Pandey and Soodan (1971) observed that the number of rotalids (mostly *Rotalia)* in the faunal assembalage varies significantly with the paleobathymetric fluctuations. Mohan and Singh (1976), while attempting the correlation of Early Miocene carbonate reservoirs of Bombay High Field, observed that even a slight paleobathymetric change induces a compositional change in the faunal assembalage. Therefore, a quantitative assessment of species dominance, principal associations and percentage variation of species, specifically susceptible to bathymetric changes, can be directly utilised for correlation. Mohan and Singh (1976) carried out quantitative assessment of the faunal population to evolve paleobathymetric curves for the correlation of Early Miocene reservoirs in two wells of Bombay High (Text-fig. 11).

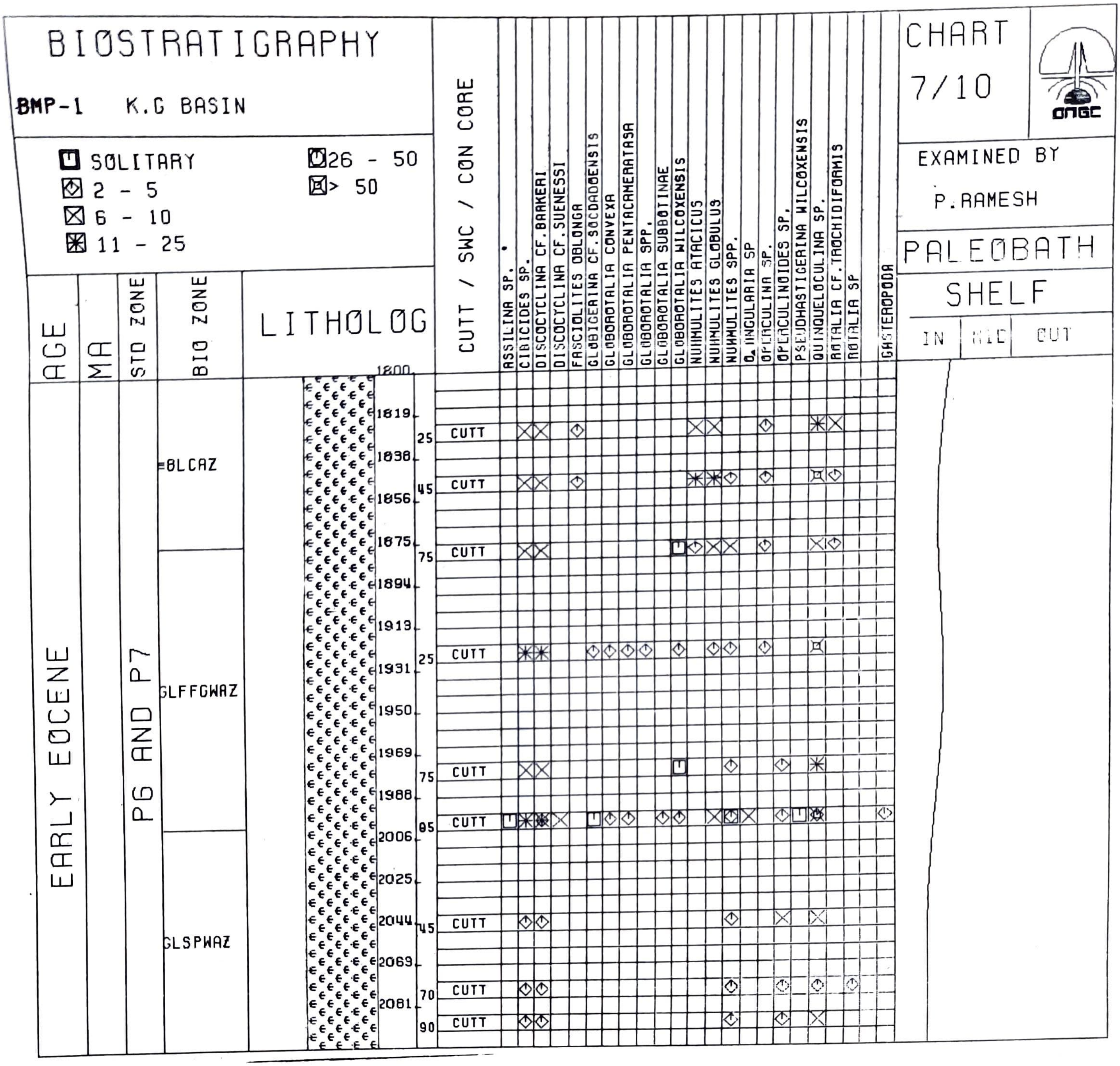
Stratigraphic data mostly include observations made along regular intervals of time or space, ideally comprising a time series. Simple operations by smoothening time series were initiated in the ONGC during mid-sixties in the areas where stratigraphic correlation was difficult due to the absence of index species. Stehli and Greath (1964) suggest the use of the ratios of the two faunal groups, differing in mode of their life, as a correlation tool. Pandey and Soodan (1971) consider that foraminiferal frequency variations in the brackish and deltaic sequences, such as the Barail sediments of Upper Assam, would reflect the subtle changes in the environment and can be used as a correlative tool. They correlated the Barail succession met in Rudrasagar wells. The trend analysis based on the Least Square Method was introduced to make the frequency correlation more effective. Mohan (1971) correlated Barail sequence met in three wells of Geleki Field (Text-fig. 12), where simple moving averages were also utilised alongwith foraminiferal trends.

Vistelius (1961) published a paper on sedimentation time trend function which created considerable interest in treating the quantised sedimentary data as a time series for stratigraphic correlation. A.T.R. Raju of ONGC experimentally applied Vilstelius's (1961) technique in small part of Mohand Anticline in the Siwalik hills, south of the Dehra Dun Valley (Pers. Com.). Raiverman (1972) and Raiverman *et al.* (1979) covered Himalayan foot-hills lying between the rivers Ravi and Yamuna (approx. area 12,000 sq. km.) in the course of a decade and brought out a new set of geological maps using time series correlation. Since these correlations are essentially based on a pattern of cyclic variation with time in the grain size of the sedimentary sequence, the fundamental stratigraphic unit raised by this procedure has been termed 'ENSEQ' (abbreviated from energy sequence; Raiverman *et al.*, 1983). Eight ENSEQs have been recognised in the Cenozoic sequence of the Himalayan foot-hill fold belt (Text-fig. 13). Raiverman (1985) recommends that multivariate approach should be applied to identify each ENSEQ.

Ranga Rao and Kunte (1985) applied Markov-chain analysis to the sedimentological data collected from the Lower Siwalik sequence of Jammu Hills, for detection of repetitive processes in the deposition of the sequence. They opine that the Lower Siwalik sequence of Jammu Hills was deposited in a complex fluvial regime.

Balan *et al.* (1986) analysed heavy mineral data from Himalayan foot-hills by factor (R-mode and Q-mode) and cluster analysis to identify stratigraphic units and to establish stratigraphic correlation between different sections. They observed that lithic fragments in the Cenozoic strata (sparsely fossiliferous) bear direct relationship with different stages of Himalayan Orogeny, and are significant tool for stratigraphic correlation.

Advanced quantitative methods in biostratigraphic correlation make use of the special properties of paleontological record, viz., their uniqueness, and non-recurrent and irreversible nature. The mathematical solutions in these correlations view the biostratigraphic sequence as random deviates from a true solution. In addition to the method of Unitary Association (Guex, 1977;

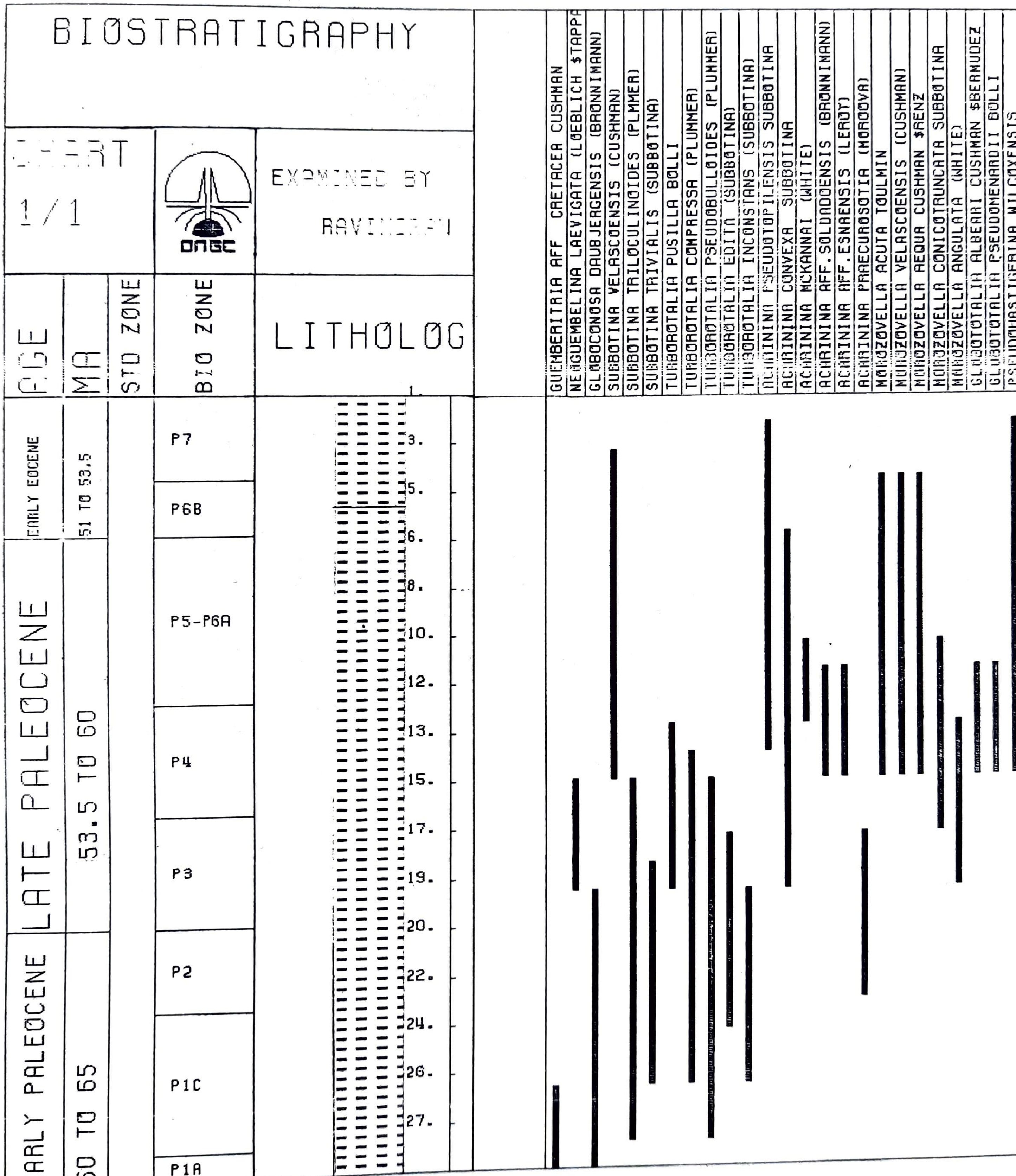


Text-figure 7. A typical example of foraminiferal frequency chart. Instead of faunal frequency (in symbols), exact numbers of the individuals can also be recorded. Program also takes care to calculate Foraminiferal Number and index , and is aimed to help in paleoecological interpretations.

Davaud, 1982) and Multivariate analysis (Hazel, 1977; Brower *et al.*, 1979; Reyment, 1979), which have been generally used, specific model studies have recently been proposed for measurement of biostratigraphic attributes, derivation of relative biostratigraphic values (RBV) of fauna (Brower *et al.*, 1979; Brower, 1984) and Ranking and Scaling (RASC) techniques (Agterberg & Nel, 1982 a, 1982 b).

Different fossils have different biostratigraphic values and complete spectrum exists in time correlation, ranging from the index fossil to a species that conveys no useful information. Index fossils have three attributes: 1) short vertical range, 2) facies independence and 3) widespread geographical distribution. In biostratigraphic, it is desirable to quantify these attributes. Different fossils have different relative biostratigraphic value. Values ranging from 1.0 (ideal index fossil) to 0.0 for a taxon with no stratigraphic information have been developed to quantify the RBV of particular species. The RBVs ideally serve to account the data for species in the multivariate analysis of assemblage zones.

The RASC programme was used to erect the Cenozoic



Text-figure 8. An example of classical range chart aimed at biochronological zonation of sequence. The input data includes FADS and LADS of different biostratigraphic events.

IDENTIFICATION MATRIX VALUES ARE :

A

CHARACTER		E: 1	E: 2
AMMONIA ANNECTENS	1-10%	40.0	12.0
AMMONIA ANNECTENS	11-15%	12.0	25.0
AMMONIA ANNECTENS	16-80%	25.0	12.0
AMMONIA BECCARII	1-5%	50.0	25.0
AMMONIA BECCERII	5-20%	1.0	25.0
A.BECCARII VAR.TEPIDA	0-5%	25.0	40.0
A.BECCAR[illegible] VAR.TEPIDA	5-50%	75.0	12.0
AMMONIA [illegible]NTATA	1-10%	40.0	25.0
AMMONIA DENTATA	11-65%	40.0	12.0
ANOMALINA SP.	1-5%	1.0	50.0
BAGGINA SP.	1-5%	25.0	1.0
BOLIVINA SP.	1-5%	12.0	25.0
BOLIVINA SP.	5-15%	1.0	12.0
BOLIVINA SPATHULATA	0-3%	1.0	25.0
BOLIVINA SPATHULATA	4-15%	40.0	1.0
BULIMINA MARGINATA	0-2%	25.0	12.0
CALCARINA CALCAR	1-20%	50.0	1.0
CANCARIS INDICUS	1-10%	50.0	25.0
CANCARIS OBLONGUS	1-15%	50.0	25.0
CASSIDULINA LAEVIGATA	1-10%	25.0	12.0
CASSIDULINA LAEVIGATA	11-30%	25.0	1.0
CIBICIDES MCKANNAI	1-5%	50.0	1.0
CIBICIDES MCKANNAI	5-15%	1.0	25.0
CIBICIDES LOBATULUS	1-25%	1.0	25.0
CIBICIDES REFULGENS	1-5%	12.0	1.0
DISCORBIS SP.	1-5%	12.0	25.0
ELPHIDIUM CRISPUM	1-10%	50.0	1.0
ELPHIDIUM INCERTUM	1-5%	75.0	1.0
ELPHIDIUM SP.	1-10%	40.0	12.0
EPONOIDES REPANDUS	0-1%	1.0	25.0
FLORILUS ASTERIZANS	0-2%	12.0	50.0
FLORILUS SP.	1-10%	40.0	12.0
GLOBIGERINA BULLOIDES	0-15%	1.0	50.0
GLOBIGERINITA GLUTINATA	1-20%	1.0	40.0
GLOBIGERINOIDES CONGLOBATUS	1-5%	1.0	50.0
GLOBIGERINOIDES RUBER	1-5%	12.0	0.0
GS.RUBER	5-25%	1.0	50.0
GS.SACCULIFER	0-5%	12.0	50.0
GYROIDINA SP.	1-5%	12.0	1.0
GYROIDINA SP.	5-10%	1.0	25.0
HANZAWAIA CONCENTRICA	1-25%	80.0	25.0
HYALINEA BALTHICA	0-3%	12.0	25.0
GLOBOQURDINA DUTERTRI	0-2%	1.0	25.0
PULINIATEINA UBLIQULOCULATA	1-5%	12.0	25.0
QUINQULOQULINA TROPICALIS	0-5%	50.0	1.0
QUINQULOQULINA LAMARCKIANA	1-5%	40.0	12.0
QUINQULOQULINA SEMINULUM	1-10%	25.0	50.0
TEXTULARIA GRAMEN	1-3%	1.0	40.0
TEXTULARIA GRAMEN	4-5%	12.0	1.0
TRIFERINA SP.	1-5%	1.0	25.0
UVIGERINA CANNARIENSIS	1-10%	25.0	75.0

B

CHARACTER		VSP INDEX PERCENT
BOLIVINA SP.	5-15%	0.2942
CIBICIDES REFULGENS	1-5%	0.2942
GYROIDINA SP.	1-5%	0.2942
TEXTULARIA GRAMEN	4-5%	0.2942
GLOBIGERINOIDES RUBER	1-5%	0.3249
AMMONIA ANNECTENS	11-15%	1.0192
AMMONIA ANNECTENS	16-80%	1.0192
BOLIVINA SP.	1-5%	1.0192
BULIMINA MARGINATA	0-2%	1.0192
CASSIDULINA LAEVIGATA	1-10%	1.0192
DISCORBIS SP.	1-5%	1.0192
HYALINEA BALTHICA	0-3%	1.0192
PULLENIATINA OBLIQULOCULATA	1-5%	1.0192
A.BECCARII VAR.TEPIDA	0-5%	1.9744
AMMONIA DENTATA	1-10%	1.9744
AMMONIA BECCARII	5-20%	2.6058
BAGGINA SP.	1-5%	2.6058
BOLIVINA SPATHULATA	0-3%	2.6058
CASSIDULINA LAEVIGATA	11-30%	2.6058
CIBICIDES MCKANNAI	5-15%	2.6058
CIBICIDES LOBATULUS	1-25%	2.6058
EPONOIDES REPANDUS	0-1%	2.6058
GYROIDINA SP.	5-10%	2.6058
GLOBOQURDINA DUTERTRI	0-2%	2.6058
TRIFERINA SP.	1-5%	2.6058
AMMONIA BECCARII	1-5%	5.8594
CANCARIS INDICUS	1-10%	5.8594
CANCARIS OBLONGUS	1-15%	5.8594
QUINQULOQULINA SEMINULUM	1-10%	5.8594
AMMONIA ANNECTENS	1-10%	6.0337
AMMONIA DENTATA	11-65%	6.0337
ELPHIDIUM SP.	1-10%	6.0337
FLORILUS SP.	1-10%	6.0337
QUINQULOQULINA LAMARCKIANA	1-5%	6.0337
BOLIVINA SPATHULATA	4-15%	9.9154
GLOBIGERINITA GLUTINATA	1-20%	9.9154
TEXTULARIA GRAMEN	1-3%	9.9154
FLORILUS ASTERIZANS	0-2%	12.3549
GS.SACCULIFER	0-5%	12.3549
ANOMALINA SP.	1-5%	18.2452
CALCARINA CALCAR	1-20%	18.2452
CIBICIDES MCKANNAI	1-5%	18.2452
ELPHIDIUM CRISPUM	1-10%	18.2452
GLOBIGERINA BULLOIDES	0-15%	18.2452
GLOBIGERINOIDES CONGLOBATUS	1-5%	18.2452
GS.RUBER	5-25%	18.2452
QUINQULOQULINA TROPICALIS	0-5%	18.2452
UVIGERINA CANNARIENSIS	1-10%	25.0000
HANZAWAIA CONCENTRICA	1-25%	30.1744
A.BECCARII VAR.TEPIDA	5-50%	39.0192
ELPHIDIUM INCERTUM	1-5%	51.6058

Text-figure 9. An example of I-D matrix with 39 species, from ecogroup E1 and E2. A Percentage abundance and per cent probability for selected 39 species characterising the ecogroups E1 and E2. B. Various Strain Potential (VSP) index per cent for the 39 species alongwith their percentage abundance. VSP index per cent helps to assess the merit of the species as a potential ecogroup separator.

foraminiferal stratigraphy of the Canadian Atlantic Margin (Gradstein & Agterberg, 1982). Srikanth and Kalyanasunder (1986) have successfully applied RASC programme for evolving Neogene foraminiferal stratigraphy of Krishna-Godavari Basin, utilizing the fossil event data from 7 offshore wells. RASC programme can be easily extended to carry out an automated correlation.

MAGNETOSTRATIGRAPHY

The magnetostragraphic studies were initiated in ONGC during 1979 in collaboration with the National Geophysical Research Institute, Hyderabad and Wadia Institute of Himalayan Geology, Dehra Dun (Ranga Rao *et al.*, 1982). Paleomagnetic measurements were carried out for samples from 208 sites of the Upper Siwalik, along Parmanandal-Utterbeni, Balli and Nagrota sections near Jammu. Bentonitized tuff bands present within the Upper Siwalik sequence were subjected to absolute dating by fission track method.

Direction and intensities of natural remanant magnetism (NRM) were measured at the National Geophysical

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PROGRAM AUTOECO FOR IDENTIFICATION OF AN UNKNOWN
WITH PRESENCE-ABSENCE DATA AGAINST AN
IDENTIFICATION MATRIX OF PERCENT POSITIVE
CHARACTERS OF THE TAXA.
THE NAME OF THE ID MATRIX IS:      I1MAT.DAT
        Q=  2   M=  61

LABEL OF UNKNOWN IS :
                           GRAB 4

    GRAB 4                 BEST IDENTIFICATION IS :E2 (40-50 MTS)
EMP:22.5-26.5 SALINITY:35.347-35.999 OXYGEN CONTENT:3.8-6.6 pH:7.85-8.32

SCORES TO       ON COEFFICIENTS :                        1              2              5

E2 (40-50 MTS)                                   0.10000000E+01 0.44523644E+00 0.28026408E+00

E1 (30-40 MTS)                                   0.43636166E-08 0.55022281E+00 0.36411592E+00


CHARACTERS AGAINST  E2 (40-50 MTS)

            CHARACTER                  PERCENT IN TAXON  VALUE INUNKNOWN

A.BECCARII VAR.TEPIDA       6-50%          12.00              +
BULIMINA MARGINATA          0-2%           12.00              +

CHARACTERS AGAINST  E1 (30-40 MTS)

            CHARACTER                  PERCENT IN TAXON  VALUE INUNKNOWN

AMMONIA ANNECTENS           11-15%         12.00              +
BOLIVINA SPATHULATA         0-3%            1.00              +
FLORILUS ASTERIZANS         0-2%           12.00              +
GLOBIGERINA BULLOIDES       0-15%           1.00              +
GLOBIGERINITA GLUTINATA     1-20%           1.00              +
GS.RUBER                    6-25%           1.00              +
PULLENIATINA OBLIQULOCULATA 1-5%           12.00              +
TEXTULARIA GRAMEN           1-3%            1.00              +

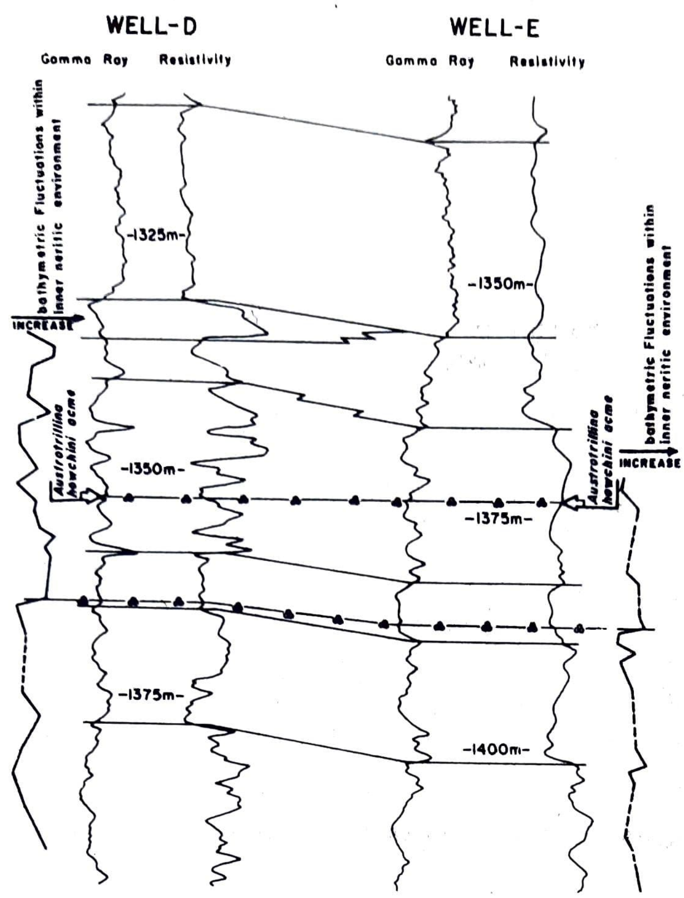
ADDITIONAL CHARACTERS THAT ASSISTS IN SEPARATING
E2 (40-50 MTS)                             FROM     E1 (30-40 MTS)
                                         PERCENT       PERCENT

ELPHIDIUM INCERTUM          1-5%           1.0          75.0
```

Text-figure 10. An example of best matching ecogroup based on Bayesian model. Grab-4 sample from the bathymetric group between 30-40 m was selected for testing the model and compared with E1 and E2 ecogroups in this sample. The coefficients (WILLCOX PROBABILITY, TAXONOMIC DISTANCE, STANDARD ERROR SCORE, GAUSSIAN INTEGRAL and PATTERN DISTANCE) based on VSP index per cent given in Text-fig. 9B) favour ecogroup E2 as best identification. Characters against ecogroup E1 and E2 are also separately printed.

Research Institute, on an astatic magnetometer. Stability tests were carried out to verify whether NRM is due to the primary magnetization, or it has been introduced by secondary components after the deposition of the beds. Alternating field (a.f.) demagnetization techniques were used for removal of the effect of the secondary components. Corrections for bedding orientation were also carried out.

Site mean directions were calculated using the statistics suggested by Fisher (1953). Text-figure 14 shows VGP latitudes against the stratigraphic positions of the sampling site in Nagrota section, where fifteen magnetic reversals were established. These were correlated with the polarity chrons by the evidence of vertebrate fauna and absolute ages of the bentonitized tuff bands. The Upper Siwalik sequence has been dated as Pliocene, Pleistocene (0 - 5 Ma) comprising Gilbert, Gauss, Matuyama and Brunhes polarity



Text-figure 11. Correlation of the Early Miocene reservoirs between two wells of Bombay High. Faunal correlation(-▲-) is based on paleobathymetric curves.

chrons.

The studies, since extended to cover the entire Siwalik sediments, have provided an approach for numerical age determination for precise subdivision and correlation of the Siwalik strata.

GEOHISTORY ANALYSIS

Geohistory analysis is a quantitative stratigraphic technique that combines the stratigraphic and paleobathymetric informtion in time depth framework. The technique in its modern quantified form was first described by van Hinte (1978), although relative time-depth diagrams were published much earlier (Lemoine, 1911; Bandy, 1953). Inspired by the work of van Hinte (1978), the studies related to Geohistory Analysis were initiated in 1980 to depict timing and magnitude of geologic events in Bombay Offshore Basin.

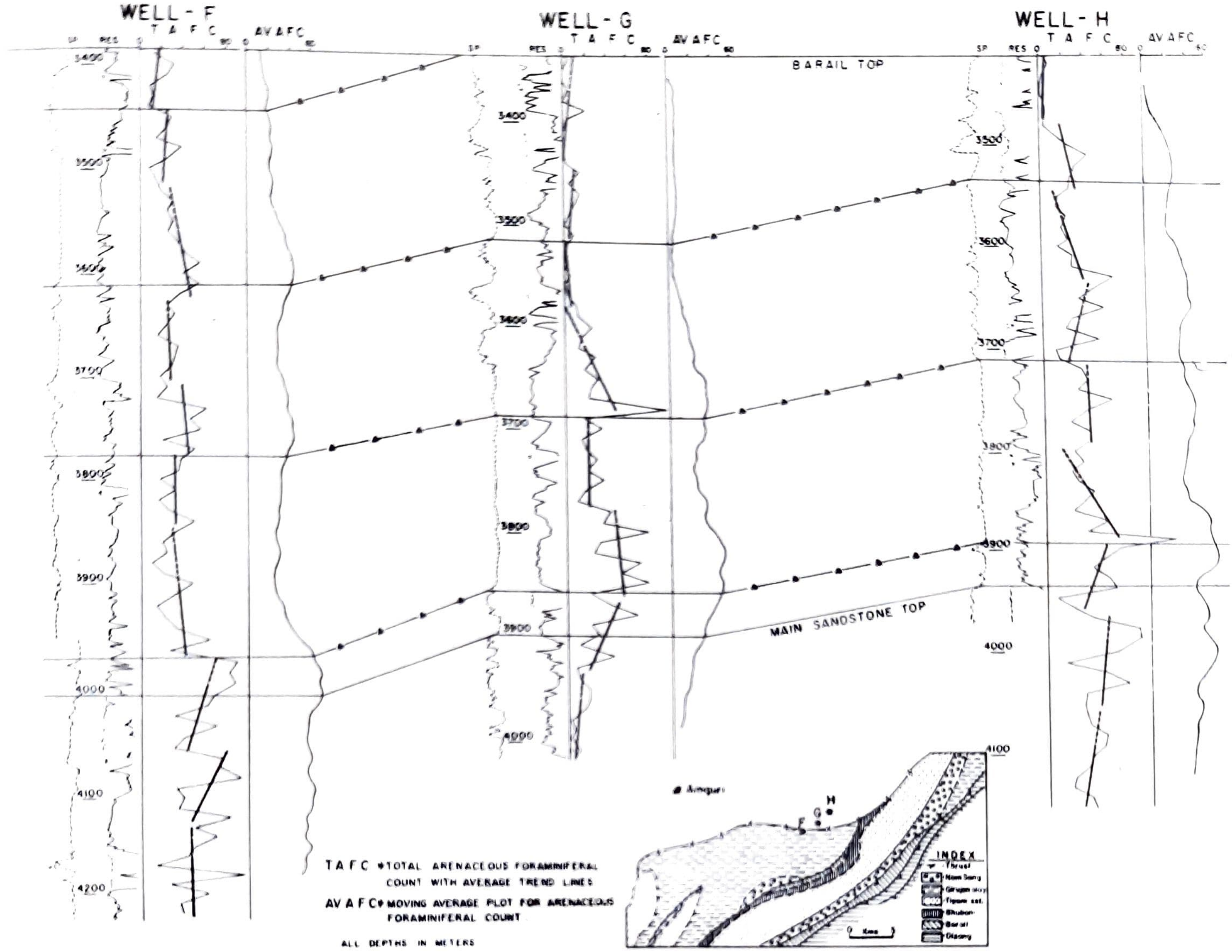
Sedimentation rate

The assignment of numerical ages to the paleotops or other stratigraphic markers had made it possible to compute the sedimentation rate (R). If the time span of the interval is expressed in Ma (10^6 years) and the thickness (T) in meters, then:

$$R = \frac{T}{Ma} \quad m/Ma \quad \text{.................................(1)}$$

The rates of sedimentation will be more meangingful if the thickness of units are restored to their initial thickness (To) by accounting for compaction. The compaction of shales is understood broadly and is beginning to be known in case of sands. However, compaction in carbonates is little investigated. Perrier and Quiblier (1974) opine that calcareous muds have compaction rates similar to those of clays but solubility of carbonate at shallow depth and the development of earlier lithification may lead to complexities in the sequence of compaction. Hardenbol *et al* (1981) utilised the porosity - depth function $\varnothing_z$ = **0.7/1+.001z** developed by Horowitz (1975), for accounting for the compaction in shaly sediments. For sandstone compaction, a relationship between porosity and depth of burial has been proposed by Horowitz in Hardenbol *et al.* (1981). They have assumed that reef carbonates undergo compaction comparable to the porosity reduction of sand. They further assume that grain carbonates compact like sand containing 30% shale, and micrites like shales containing 35% sand.

Neither the present thickness (Tp) nor the initial thickness (To) can be idealy used for calculation of 'pure'



Text-figure 12. Correlation of the Barail succession in three wells of Geleki Oil Field, Upper Assam, utilising arenaceous foraminiferal trends. The top of the Barail Main Sandstone has been marked by electric logs. The lowermost correlation line (-●-), based on arenaceous foraminiferal trends, correlates the top of a thin sand near the top of Barail Main Sandstone. Simple moving averages have also been considered (after Mohan, 1971).

rate of sediment accumulation, which can only be calculated from the net thickness (T_N).

$$R = \frac{TN}{Ma} \quad m/Ma \quad \text{..........(2)}$$

The net thickness (TN) where porosity = 0, can be calculated by:

$$TN = Tp\,(1 - Ø_p) \quad \text{..........(3)}$$

where Tp is present thickness and Øp. is present porosity, van Hinte (1978) emphasised the application of sedimentation rates in prediction of ages, deciphering eustatic changes, estimating time span of missing sections and the amount of removed thickness (erosional hiatus).

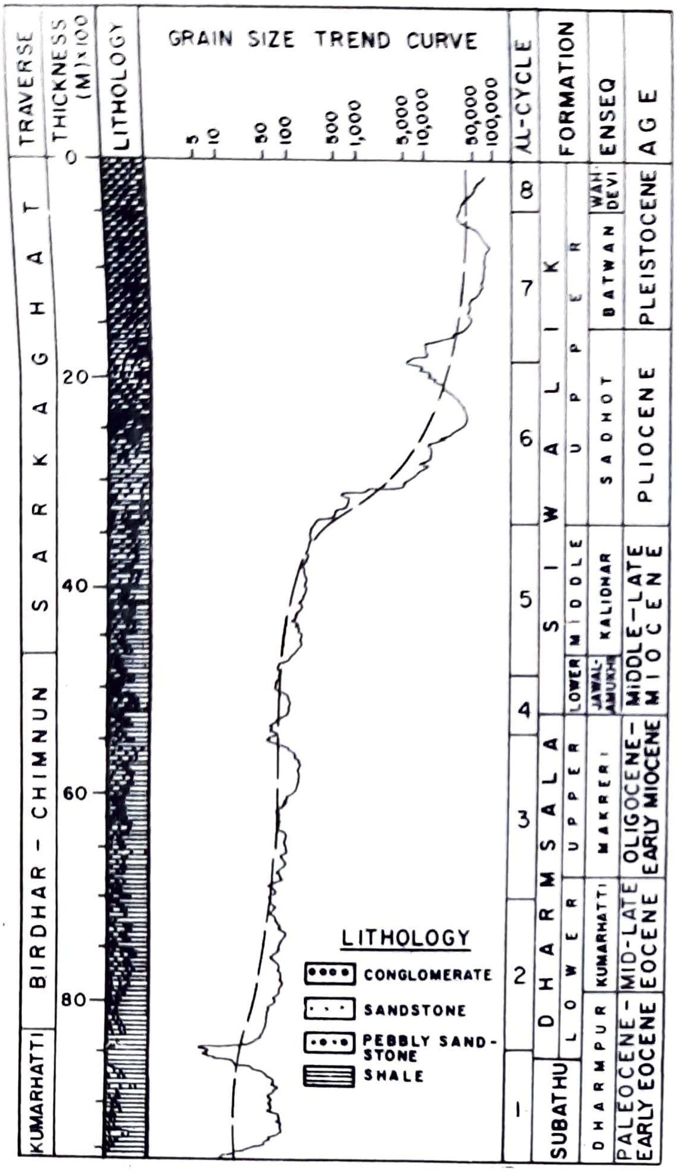
Mohan and Kumar (1982) established the sedimentation rates for the Paleogene and early Neogene sequence of Bombay Offshore region. They utilised the relationship between present thickness (Tp) and present depth of burial (DP), developed by Perrier and Quiblier (1974), to determine the initial thickness (To). For achieving the correlative significance of sedimentation rates, net thickness (TN) was graphically determined using the relationship established by Gretner and Labute (1969) between initial thickness (To) and net thickness (TN).

Mohan (1985, Fig. 8) established sonie porosity-depth relationship for Bombay Offshore region as:

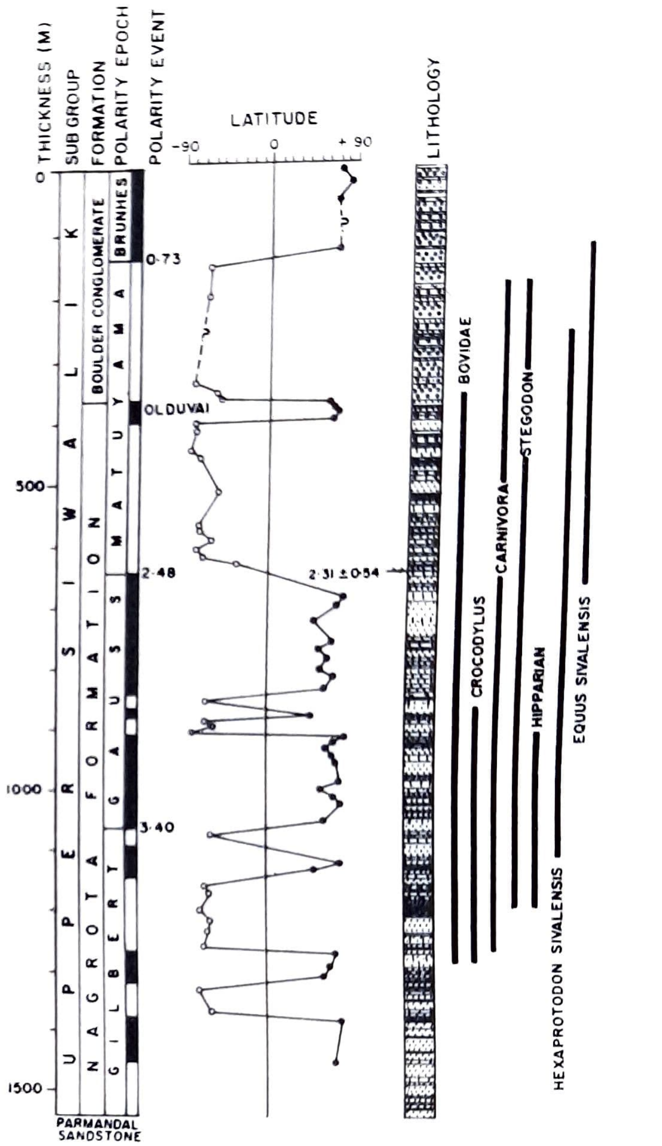
$$Ø_z = \frac{0.7}{1 + .0025\,z} \quad \text{..........(4)}$$

Where z is depth in meters. He (Mohan, 1985) utilised this relationship for calculation of compaction in shale and assumed that micrites compact 20% less than shales.

A comparison of sedimentation rates between Bombay



Text-figure 13. Classification of Tertiary sequence in Himalayan foothills, based on energy sequence (ensq) modelling (after Raiverman, 1985). Optimum grain size trend curve has been determined by utilising moving averages of 70 data points at regular intervals of 10 ft.



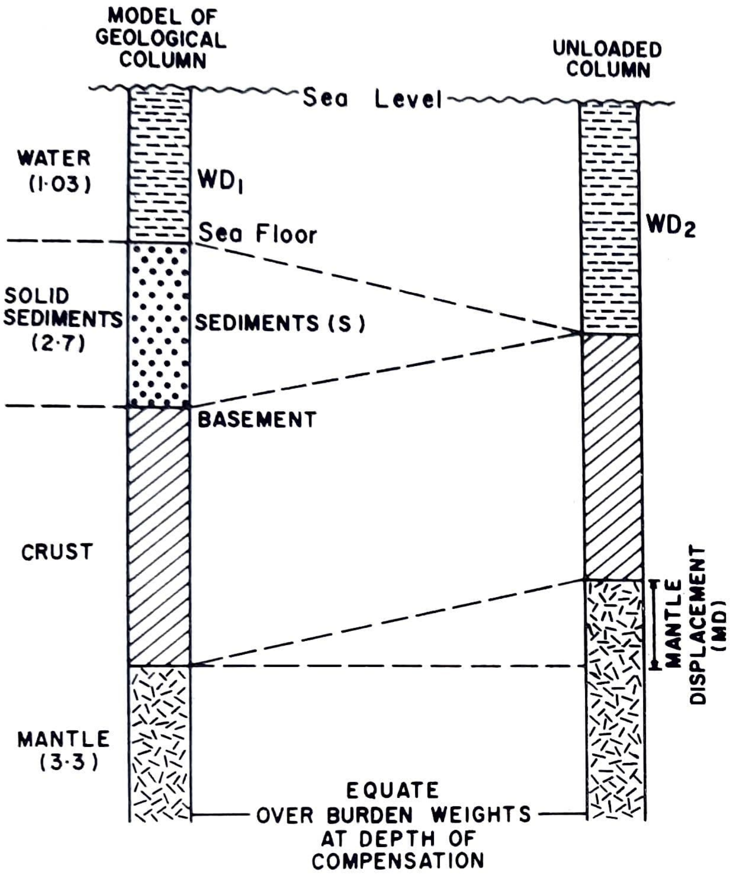
Text-figure 14. Magnetostratigraphy of the Upper Siwalik from Nagrota, near Jammu (after Ranga Rao *et al.*, 1982). The age of the upper limit of Gauss polarity chron is corroborated by absolute age determination of a bentonitic bed by fission and track method (2.31±0.54 Ma). Established ranges of vertebrate fossils in the Upper Siwalik sequence have also been indicated.

Offshore region and DSDP site 219 (Mohan & Kumar, 1982, fig. 4) suggests that the fluctuations in the trend of sedimentation rate are of regional nature, at least in the Indian region of the Arabian Sea, though actual rates may vary at different sites according to their local tectonic setting and by nature and topography of the clastic source.

The uncorrected rate of sedimentation (uR, rate without accounting for compaction) is useful in extrapolation of age at any horizon in estimation of thickness ahead of bit during drilling. Time span of missing sections was established by precise dating of the youngest bed from the succession below the unconformity and the oldest bed above the unconformity by extrapolation of sedimentation rate (Mohan & Kumar, 1982, figs 5,6,7; Mohan, 1985, fig. 7).

Subsidence rates

The subsidence curve for the basement can be plotted by restoring the sediment column above the basement to its original thickness at various times within the total depositional time span as demonstrated by van Hinte (1978) who also stresses that with shallowing or deepening the amount of subsidence would be, respectively, less than or



$$WD_1 + S = WD_2 + MD$$
$$MD = (WD_1 - WD_2) + S$$
$$MD = \cdot 726\ S$$

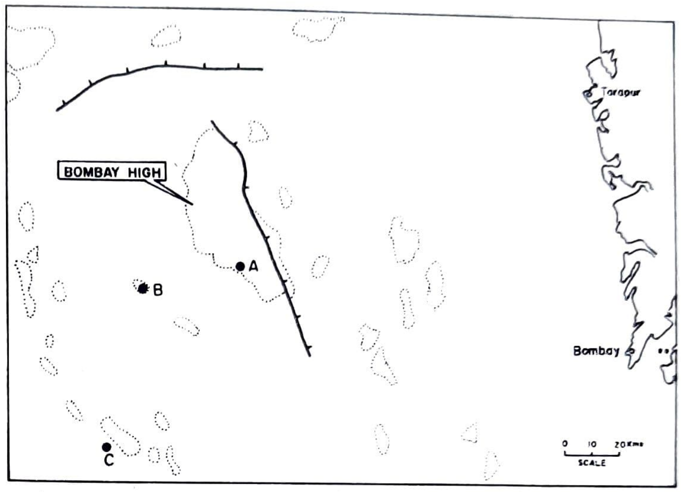
Text-figure 15. Isolatic backstripping model for Airy type of crust illustrating the impect of sedimentation on basement subsidence. The mantle displacement (MD) as a result of sediment loading is 0.7261 times the thickness of the solid sediment column.

greater than the sediment thickness (see Bandy & Arnal, 1960, fig. 13). Therefore, in order to establish subsidence rates, paleobathymetry (one aspect of the environment) is the most important analysis. Eustatic change during the deposition of the unit also effects the paleobathymetry. Rate of subsidence (Rs) can be written as:

$$Rs = \frac{To - (W + E)}{Ma} \quad \text{......................(5)}$$

Where, To is initial thickness of sediments, W is change in water depth and E is change in eustatic level.

Rate of subsidence stands for "average rate of subsidence with respect to sea level", if E is excluded from the form, and for "average rate of subsidence with respect to the geoid", if E is included in the form. Rate of subsidence



Text-figure 16. Location of three selected wells A, B and C in Bombay High Region.

(Rs) is the tectonic rate of subsidence (R_T), if bottom of the sequence is the basement.

Total resultant subsidence of the basement is mainly caused by accumulating sediment load, lithospheric cooling and tectonic activity. Eustatic sea level changes also effect the subsidence pattern. Horowitz (1975) suggests an isostatic loading model for Airy type of crust to calculate subsidence due to sediment load, which seems to be adequate for a loading correction in most basins as long as sediments are more or less uniformly distributed. The isostatic comparison is given by the equation:

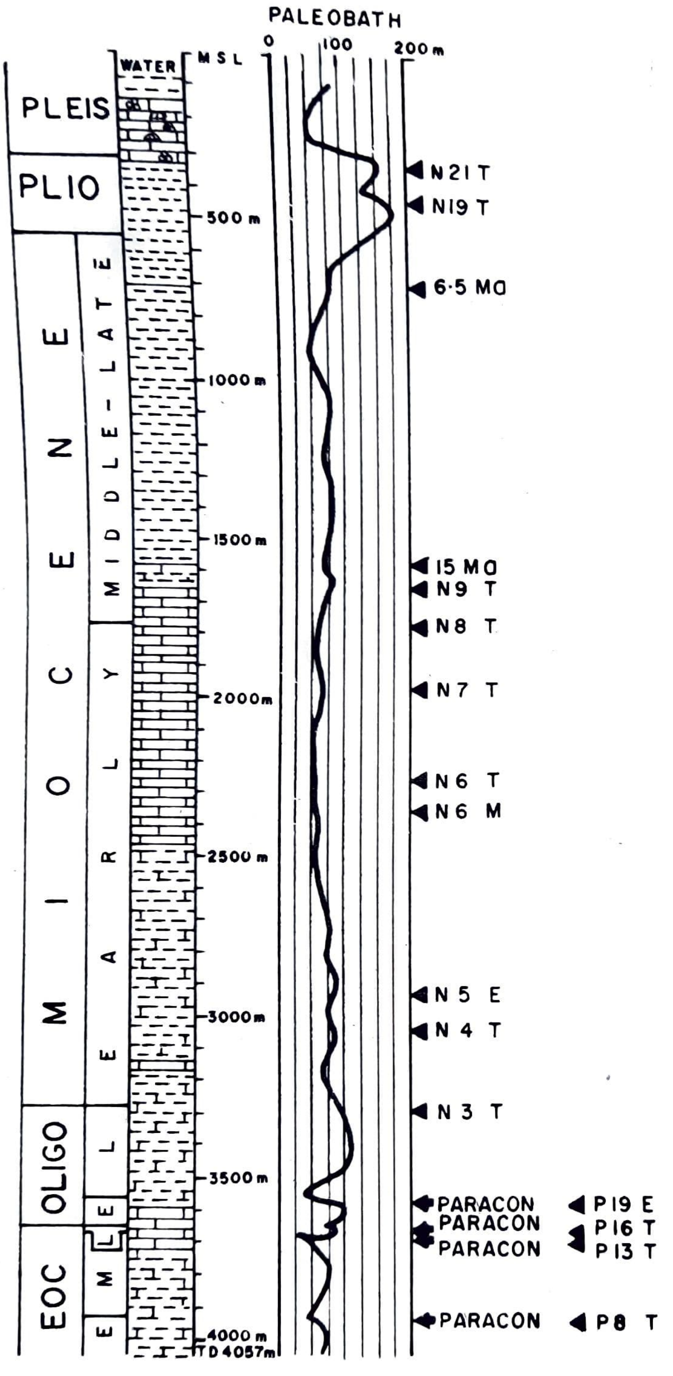
$$WDI + S = WD_2 + MD \quad \text{................. (6)}$$

Where s is sediment thickness, WD1 and WD2 are the water depths and MD is the mantle displacement after isostatic adjustment, and WD2 = WD1 + S = MD.

Steckler and Watts (1978) opine that depth of the basement below sea level (WD2), if the sedimentary column were removed, would be:

$$WD2 = WDI + \int_o^s \frac{Pm-PS}{Pm-Pw}\, dz + \int_o^s \frac{Ps-Pw}{Pm-Pw}\, \varnothing z\, dz \quad \text{.........(7)}$$

where, Pm is 3.33 gm/cm^3, Ps is 2.7 gms/cm^3 with no porosity, Pw is 1.03 gms/cm^3. Porosity, Ø z is considered zero for solid sediment. Substituting the value of WD2, equation (7) can be written as:



Tex-figure 17 . Stratigrapy and paleoecology of well c. P8, N21 etc. planktonic foraminiferal zones. T = Top, M = Middle, E = Early, Paracon - Paraconformity.

$$WDI+S-MD=WDI+\int_{o}^{s}\frac{Pm-Ps}{Pm-Pw}dz+\int_{o}^{s}\frac{Ps-Pw}{Pm-Pw}\varnothing\, z\, dz \quad ....(8)$$

Mantle displacement (MD) is a result of sediment loading works out to be 0.7261 times the thickness of the solid sediment column (Text-fig. 15).

Royden *et al.* (1980, see Hardenbol *et al.*, 1981, fig. 6) evolved the exponential subsidence curves for lithospheric cooling for the identification of thermal subsidence.

Eustatic changes and regional subsidence/uplift

Hardenbol *et al.*, (1981) suggested further improvements, such as correction for eustatic sea level changes. The calculation of long term eustatic sea level changes is based on an isostatic comparison of an Airy type crust and is given equation:

$$WD1 + TS = WD2 + EF + MC + Ru \quad .... (9)$$

Where, WD1 is original water depth, TS is thermal subsidence from model subsidence curve evolved Royden *et al.* (1980), WD2 is the present water depth, MC is the mantle compensation after an eustatic change and Ru is the present day expression of the regional uplift. Hardenbol *et al. (loc. cit.)* determined mantle compensation (MC) effects by:

$$MC = \frac{EF}{Pm-Pw} \quad ....0.45\ EF\ ....Pw.......... (10)$$

Where, EF is the eustatic level difference, Pw 1.03 gm/cm^3 and Pm 3.33 gm/cm^3.

Substituting the value of MC, Equation (9) can be written as:

$$EF = \frac{WD1 + WD2 + TS - Ru}{1.45} \quad ....(11)$$

Hardenbol *et al.* (1981). recommend that in other than water filled basins, isostatic compensation can be achieved by removing the sediments and restoring the water depth as follow:

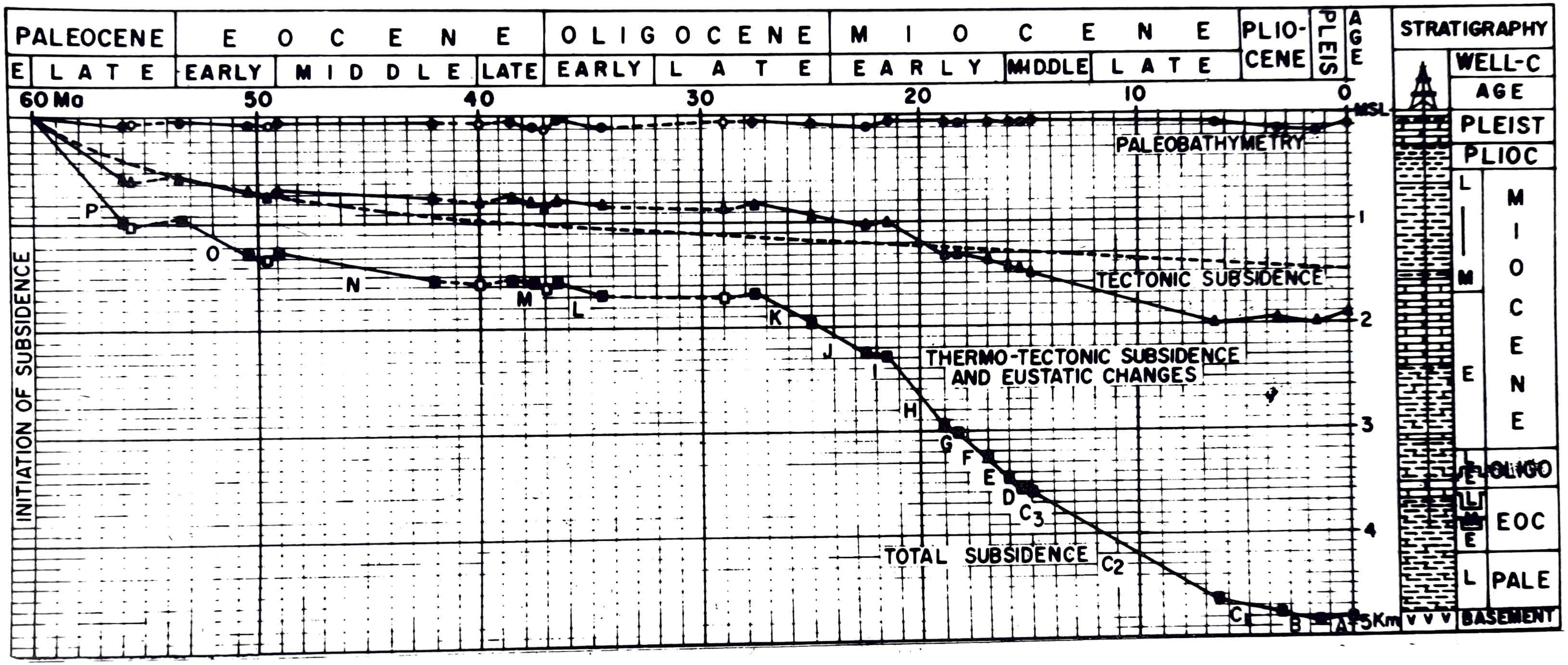
$$EF = \frac{WD1 - (WD2 + WR) + TS - Ru}{1.45} \quad ....(12)$$

Where, WR is restored water column after backstripping and taking into account unloading adjustment and porosity restoration of the underlying section.

Mohan (1985) suggests that established numerical values of the quantified globalsea level changes can be used for calculation of regional uplift (Ru) and regional subsidence (Rs).

$$RS = 1.45\ EF + (WD2 + WR) - WD1 - TS \quad ....(13)$$
$$Ru = 1.45\ EF - (WD2 + WR) + WD1 + TS \quad ....(14)$$

Mohan (1985) carried out geohistory analysis for three wells in Bombay High region (Text-fig. 16). Out of these three wells, in two wells A and B, the rapid thermal subsidence period (Paleocene-Early Eocene) is not at all documented. The well C only has sedimentation



Text-figure 18. Geohistory diagram for well C. For well location please refer Text-fig. 17. Total Subsidence (■) corrected for pseudosubsidence and compaction; tectonic subsidence (▲) also corrected for isosatic effects of sediment loading (Mohan, 1985). Stipled line gives predicated subsidence for for 60% oceanised continutal crust and pull-apart time 60 Ma (Royden *et. at.* and 1980).

AGE		ZONAL TOP	MO	LITHO	DEP.	UNITS	A	B	C1	C2	C3	D	E	F	G	H	I	J	K	L	M	N	O	P	TN*
PLEISTOCENE				SH + 70%L	84	A	241																		98
PLIOCENE		N21 (TOP)	1·5	SH + 20%L	325	B	100	125																	58
PLIOCENE		N19 (TOP)	3·5	SH	425	C1	290	351	399																196
LATE MIOCENE			6·5	SH	715	C2	867	972	998	1301															694
MIDDLE MIOCENE			15	SH + 30%L	1682	C3	59	59	60	60	89														50
MIDDLE MIOCENE		N9 (TOP)	15·5	Lst	1641	D	134	135	136	137	179	189													115
EARLY MIOCENE	BURDIGALIAN	N8 (TOP)	16	Lst	1775	E	190	191	192	193	245	255	270												165
EARLY MIOCENE	BURDIGALIAN	N7 (TOP)	17	Lst	1965	F	285	286	287	290	333	346	370	409											252
EARLY MIOCENE	BURDIGALIAN	N6 (TOP)	18·5	Lst	2250	G	100	100	100	101	110	113	116	124	144										89
EARLY MIOCENE	AQUITANIAN	N6(Middle)	19	SH + 30%L	2350	H	575	577	580	585	634	644	659	693	814	897									520
EARLY MIOCENE	AQUITANIAN	N5(Lower)	21·5	SH + 10%L	2925	I	105	105	105	106	111	111	112	114	118	119	168								96
EARLY MIOCENE	AQUITANIAN	N4 (TOP)	22·5	SH + 30%L	3030	J	245	246	246	247	256	258	261	265	271	274	346	386							225
LATE OLIGOCENE		N3 (TOP)	25	SH + 30%L	3275	K	260	261	261	262	270	272	274	277	282	283	321	334	411						240
EARLY OLIGOCENE		P19(Lower) / P18	27·6 / 34·5 / 36·5	SH + 70%L	3535	L	115	115	115	116	118	119	120	121	122	123	133	135	146	175					107
LATE EOCENE		P16 / P16	37·5 / 38·5	SH	3650	M	25	25	25	25	26	26	26	26	27	27	28	29	31	35	41				23
MIDDLE EOCENE		P13 / P10	42 / 49	SH + 20%L	3675	N	250	250	250	251	258	259	260	262	265	266	283	288	304	350	390	400			233
EARLY EOCENE		P8(Lower) / P6b	50·6 / 53·5	SH + 10%L	3925	O	340	340	341	342	349	350	351	354	357	362	375	379	391	418	430	437	551		318
LATE PALEOCENE		P4	56	SH + 10%L	4265	P	535	535	536	538	548	549	550	553	557	558	577	581	593	612	623	624	661	870	504
BASALTIC BASEMENT			60		4800																				
BURIAL DEPTH							4716	4673	4631	4554	3526	3491	3369	3198	2957	2909	2231	2132	1876	1590	1484	1461	1212	870	
PALEOBATHYMETRY							84	150	125	75	60	75	65	65	55	50	50	100	70	100	100	50	75	60	
TOTAL SUBSIDENCE							4800	4823	4756	4629	3586	3566	3434	3263	3012	2959	2281	2232	1946	1690	1584	1511	1287	930	
TOTAL NET THICKNESS (TNt)							3983	3885	3827	3631	2937	2887	2772	2607	2355	2266	1746	1650	1425	1185	1078	1055	822	504	
TNt x ·726 (SUBSIDENCE DUE TO SED. LOAD)							2892	2820	2778	263	2132	2096	2012	1893	1710	1645	1267	1198	1034	860	783	766	597	366	
THERMO-TECTONIC SUBSIDENCE AND EUSTATIC CHANGE (TC + EU)							1824	1853	1853	1918	1394	1395	1357	1305	1247	1264	964	934	842	730	701	695	615	504	

* - NET THICKNESS (TN)
- LIMESTONE ARE ASSUMED TO COMPACT 20 % LESS THAN SHALES
- PRESENT WATER DEPTH 84 m
- ALL VALUES ARE IN METERS

Table 1. Stratigraphic information, present thickness, initial thickness and restored thickness for units in well C of Bombay Offshore Region, with TD as 4057 m. Thickness and lithology of lower units have been estimated from seismic stratigraphy and adjacent well data.

representing early synrift phase (stratigraphy and paleoecology illustrated in Text-fig. 17). The total post-Middle Paleocene subsidence curve for the basement at the site C (Text-fig. 18) has been plotted by restoring the sediment column above the basement to its original thickness at various times within total depositional time (Table 1).

The study suggests that most of the Paleogene unconformities have been caused by fall in eustatic level (Text-fig. 19). Regional subsidence history can be determined with adequate stratigraphic and paleobathymetric control and with the knowledge of the magnitude of sea level changes. The subsidence history of Bombay Offshore region reveals a distinct phase of active subsidence, related to the active spreading on the Mid Indian Ocean Ridge during the Late Miocene (9 Ma) as established by Parker and Gealey (1983).

CONCLUSIONS

The quantitative stratigraphic techniques have had a major renaissance since past 30 years. After an initial formative stage of stratigraphic data generation, simple statistical methods were employed to enhance the stratigraphic resolution during late 1960's and early 1970's. The advanced quantitative methods alongwith computer graphics, however, became popular only in 1980's with introduction of magnetostratigraphy, automated paleo-ecological information model, RASC correlation programme and geohistory analysis.

The quantitative techniques are at the take off state and are expected to have a large scale adoption, where automated interpretative techniques may flourish. Kriging approaches and computer graphics will have special role, and spatial statistical methods may develop further to achieve integration of stratigraphic information which holds the promise for intensive exploration of stratigraphic traps.

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