

Shape analysis of the nucleococonch of *Lepidocyclina* from Kutch - A taxonomic interpretation

Suresh Muthukrishnan¹ and Pratul Kumar Saraswati²

¹Department of Earth & Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907

²Department of Earth Sciences, Indian Institute of Technology, Mumbai - 400 076

email: sureshm@purdue.edu

ABSTRACT: The status of the two subgenera *Eulepidina* and *Nephrolepidina* of the genus *Lepidocyclina* is debated by many. The nature and arrangement of perieembryonic chambers are considered to be features of primary importance in classification. These, however, are not often visible for several reasons. In view of this, in the present study the nucleococonch shapes of the two subgenera are analyzed for comparison. Well-prepared, oriented sections with perieembryonic chambers clearly visible in the two subgenera are used for shape analysis of nucleococonchs. The examined species include *L.(E.) ehippoides*, *L.(N.) isolepidinoides* and *L.(N.) sumatrensis* from the Oligocene-Miocene succession of Kutch. Results from closed form Fourier analysis revealed that the nucleococonchs of the two subgenera distinctly differ in shape. The 3rd, 4th and 5th harmonics are found to be significantly different in the power spectrum of the two subgenera. It is therefore concluded that *Eulepidina* and *Nephrolepidina* are taxonomically valid subgenera. The Fourier shape analysis is also carried out for the nucleococonchs of phylogenetically related species *Lepidocyclina* (*Nephrolepidina*) *isolepidinoides*, and *Lepidocyclina* (*Nephrolepidina*) *sumatrensis*. The results show that this method is also effective at species level differentiation.

INTRODUCTION

The sub-generic classification of *Lepidocyclina* was first proposed by Douville (1911) with two subgenera *Eulepidina* and *Nephrolepidina*. Since then more than 15 subgeneric names were suggested by different authors. Two of the names, *Helicolepidina* and *Polylepidina* are now found to be the valid genera of the subfamily Helicolepidinae. Among the rest of the names, there is a broad consensus among paleontologists since 1960's about the validity of *Lepidocyclina*, *Eulepidina* and *Nephrolepidina*. However, there is difference of opinion in further reducing the number of subgenera and in according generic and subgeneric status to these names. This is primarily due to differences in the selection of morphological feature in the classification. Most of the workers have relied upon the characters of the megalospheric nucleococonch while others based their classifications on stolon systems and shape of chambers. The latter features were discredited for use at subgeneric level (Eames et al. 1962).

The characters of the megalospheric nucleococonch as a basis of classification were questioned by Cole (1960) due to the extreme intraspecific variability he observed in the shape of embryonic chambers. He found all inter-gradations between eulepidine and nephrolepidine types of embryonic chambers and consequently combined *Nephrolepidina*, *Eulepidina*, *Trybliolepidina* and *Multilepidina* into a single subgenus *Eulepidina*. Eames and others (1962) differed from this proposal of grouping *Nephrolepidina* and *Eulepidina* together. Later, Cole (1968) considered even *Eulepidina* as a junior synonym of *Lepidocyclina* (s.s.). This view was not carried further by other paleontologists. Adams (1987) presented a critical discussion on the morphological characters used in the sub-generic classification of *Lepidocyclina*. He considered the three names *Lepidocyclina*, *Eulepidina* and *Nephrolepidina*, as valid. The nature and arrangement of perieembryonic chambers and not the embracement of the embryonic apparatus were considered by

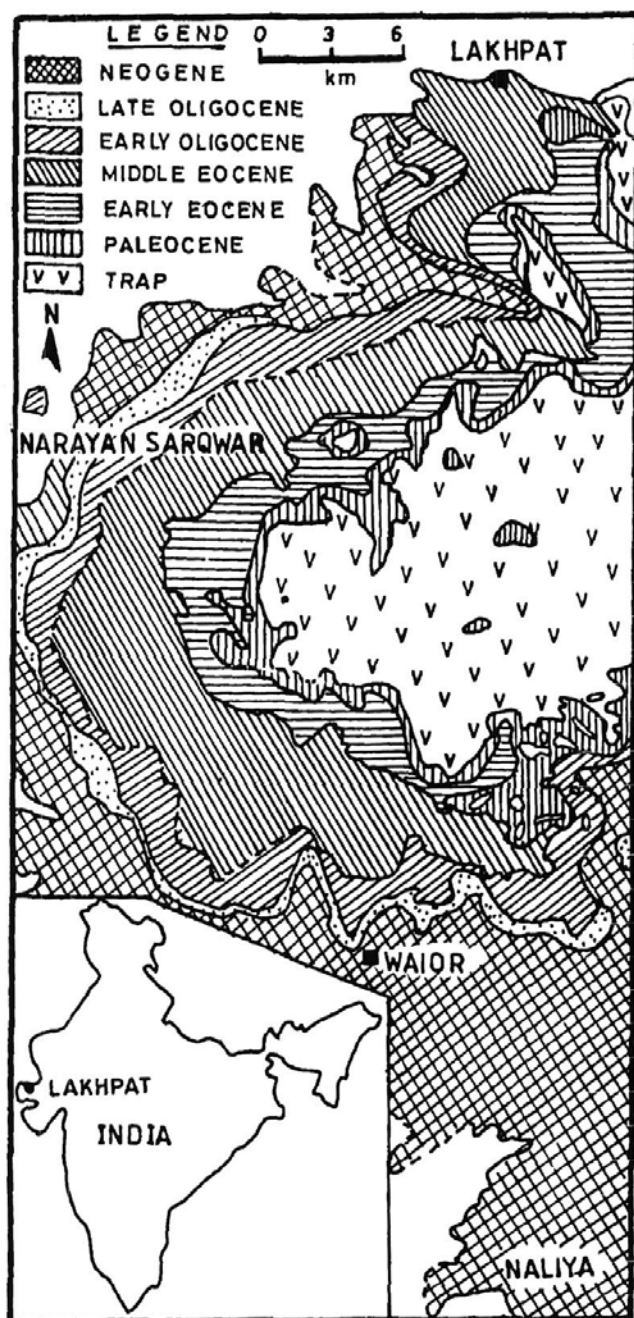
him to be features of primary importance. Earlier, Fortuin (1970) observed that in the type species of *Eulepidina*, the perieembryonic chambers do not lie in the same equatorial plane. In view of this, it is necessary to identify criteria other than perieembryonic chambers to distinguish *Eulepidina* from *Nephrolepidina*. As an alternative, Saraswati (1995) carried out biometric analysis of the embryonic chambers and concluded that the subgenera *Eulepidina* and *Nephrolepidina* are taxonomically valid. A linear discriminant function was proposed to separate the two subgenera.

The present study is to examine if the shape of the nucleococonchs of *Eulepidina* and *Nephrolepidina* is a distinguishing feature to separate the two subgenera. Closed form Fourier analysis is used to compare the shapes of the nucleococonch of the two subgenera.

MATERIAL AND METHODOLOGY

The materials for the present study were collected from Lakphat (23°49'30" N and 68°47'00" E and Waior (23°25'05" N and 68°41'37"E) in northwestern Kutch (text-fig. 1). Stratigraphically, the samples are from Maniyara Fort Formation and Chhasra Formation of Early Oligocene to Early Miocene age. The sample details and size morphometrics of the examined forms are given in Saraswati (1994, 1995). The shape analysis is based on 16 equatorial sections of *Eulepidina* and 62 sections of *Nephrolepidina*. The two subgenera in this region are represented by the species *L.(E.) ehippoides*, *L.(N.) isolepidinoides* and *L.(N.) sumatrensis* (plate 1).

The x-y coordinates of outline of the forms are collected using a programmed co-ordinate digitizer MM1200 connected to a desktop computer (PC-AT). The MM1200 is a data tablet, which is an input device, which translates graphic information into digital information suitable for a digital device like the computer. Here the digitizer gives the reports as absolute



TEXT-FIGURE 1
Location map (after Mohan 1982).

co-ordinates and has the option of setting the x-y axis to a desired position other than the normal set up. The digitizer is designed to read the co-ordinates in two different modes. One is the point mode where the digitizer sends one report every time when the cursor button is pressed. The other option is the switch stream mode with increment, whereby the digitizer sends one report only when the cursor travels a minimum distance in x or y direction called the increment. After collecting the data from both the methods, the point mode has been selected, as in the case of switch stream mode, the number of data points that were

collected are not sufficient enough to define the outline of the form accurately. The resolution of the digitizer is 500 lpi with an active area of 11.7" x 11.7". The outline of each of the forms were digitized by keeping the photograph over the digitizer and tracing the outline with the help of a cursor, and the x, y co-ordinates were continuously stored in the computer.

For the statistical analysis, the software package STAT-GRAPHICS was used. For mathematical computations in the shape analysis, a computer program was written in C language to determine the centroid of the outline shape and for calculation of Fourier coefficients and variance.

Shape Morphometrics

According to Fourier theorem, every curve, no matter what its nature may be or in what way it was first obtained, can be exactly reproduced by superposing a sufficient number of simple harmonic curves. Hence, any shape can be built by piling up the harmonics (Reyment 1991). The part of the mathematics dealing with harmonics is known as Harmonic Analysis. The geometry of a two dimensional outline shape of lepidocyclines is analyzed here with the help of closed form Fourier Analysis. It is aimed to differentiate one family of shape from another. The assumption is that since the Fourier series is made up of a number of harmonics, where each harmonic is a contributor to the total shape of the figure, two objects of similar shape should give identical series. With this assumption, we can compare the amplitude spectra of two or more shapes term by term. The mathematical formulations in computing Fourier coefficients are discussed below.

After obtaining the outline of the form in X_i and Y_i coordinates, using a digitizer, the coordinates of the centroid were determined by finding the area included by the curve and using it in the following equations (Hall 1976):

$$\bar{X} = \frac{1}{6A} \sum_{i=1}^n (X_i + X_{i+1})(X_i Y_{i+1} - X_{i+1} Y_i) \quad (1)$$

$$\bar{Y} = \frac{1}{6A} \sum_{i=1}^n (Y_i + Y_{i+1})(X_i Y_{i+1} - X_{i+1} Y_i) \quad (2)$$

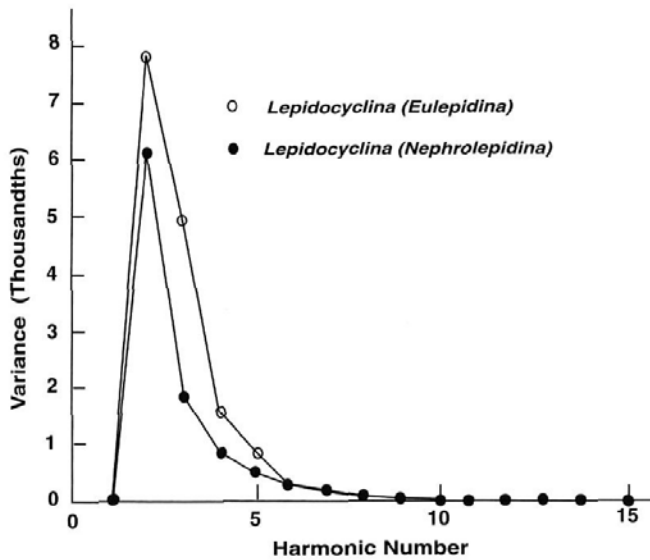
where \bar{X} is the x coordinate of the centroid, \bar{Y} is the y co-ordinate of the centroid and A represents the surface area of the two-dimensional shaped object, which can be positive or negative depending on the direction of the digitization (clockwise or anticlockwise) and is calculated by the following equation:

$$\text{Area}(A) = \frac{1}{2} \sum_{i=1}^n (X_i Y_{i+1} - X_{i+1} Y_i) \quad (3)$$

The Cartesian coordinates are then converted into polar coordinates - in the sense of radial distance between the center of area and the outline, and the angular orientation of these radial lines on the periphery. But since the original coordinates (set 1) are located with reference to the starting point of digitization, a new set of boundary points x_i, y_i (set 2) has to be defined from the original ones relative to the centroid of the figure by the following equations (Boon et al. 1982)

$$x_i = X_i - \bar{X} \quad (4)$$

$$y_i = Y_i - \bar{Y} \quad (5)$$



TEXT-FIGURE 2
Power Spectrum of nucleoconch shape for the two subgenera *Lepidocyclus* (*Eulepidina*), *Lepidocyclus* (*Nephrolepidina*).

where \bar{X} and \bar{Y} are the coordinates of the centroid of the figure and X_i and Y_i are the original coordinates. These boundary points are then transformed into polar coordinate form using the following equations (Boon et al. 1982),

$$r_i = \sqrt{(x_i^2 + y_i^2)} \quad (6)$$

$$\theta_i = \tan^{-1}\left(\frac{y_i}{x_i}\right) \quad (7)$$

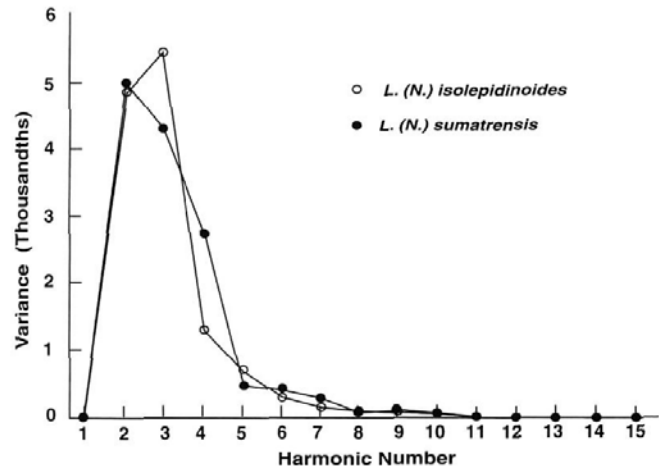
In order to carry out the Fourier transformation, the radii must be equally spaced around the outline in terms of the angles subtended by them. As the original data points that are collected from the digitizer are unlikely to be equally spaced, a new set of data points (set 3) was created along the perimeter using the transformed coordinates (set 2) by the method of linear interpolation as follows (Boon et al. 1982):

$$r_j = r_i + \frac{(r_{i+1} - r_i)(\theta_j - \theta_i)}{\theta_{i+1} - \theta_i} \quad (8)$$

here r_i and θ_i are as shown in equations (6), (7), and r_j and θ_j are the radius and angle of the interpolated points, where

$$\theta_{i+1} > \theta_j \geq \theta_i \text{ and } \theta_{j+1} = \theta_j + \frac{2\pi}{M}$$

In the present study, M is fixed at 96 points at an exact interval of $\pi/48$. The selection of this number is arbitrary (Foote 1989; Rholf and Archie 1984) but it should be large enough to preserve the original shape of the object. And also the number M should be at least double that of the number of harmonics that is to be calculated. As the shape being analyzed here is simple and geometric, approaching a circle or a deformed circle, the number of harmonics that are required to preserve the shape will be less compared to the other complex shapes. The preliminary



TEXT-FIGURE 3
Power spectrum of nucleoconch shape for the two species of *L. (Nephrolepidina)*: *Lepidocyclus (Nephrolepidina) isolepidinoides*, *Lepidocyclus (Nephrolepidina) sumatrensis*.

study showed that the number of harmonics that contributes significantly to the shapes are far less than 20 and hence to avoid any problem of aliasing, a maximum number $M=96$ is selected, from which up to 48 harmonics can be calculated.

Any continuous, single valued and periodic function over a period can be represented by Fourier series approximation (Boon et al. 1982), which can be used to represent the shape of the object as closely as possible by including sufficient number of harmonics.

The approximation is,

$$R(\theta) = R_0 + \sum_{n=1}^{N-1} R_n \cos(n\theta - \phi_n) + \frac{1}{2}(R_N \cos N\theta) \quad (9)$$

where, the function $R(\theta)$ is continuous, single valued and periodic with a period of 2π . Here N is the number of harmonics that is required, R_0 , the zeroth harmonic term and is equal to the mean radius of the outline shape, R_n is the amplitude and ϕ_n is the phase angle of the n^{th} harmonic. Since the objective is to find out the significance of the shape morphometrics, the effect of size is eliminated from the study by dividing all the radii by the mean radii of the outline figure. The Fourier coefficients A_n and B_n are calculated by the following equations,

$$A_n = \frac{1}{N} \sum_{j=1}^M r_j \cos(nj\Delta\theta) \quad i=1,2,\dots,N. \quad (10)$$

$$B_n = \frac{1}{N} \sum_{j=1}^M r_j \sin(nj\Delta\theta) \quad i=1,2,\dots,N \quad (11)$$

where M represents the number of equally spaced radii ($M=96$), r_j being the j^{th} radius and $\Delta\theta$ the angular increment ($2\pi/M$). The harmonic constants R_n and ϕ_n are calculated as follows,

$$R_n = \sqrt{A_n^2 + B_n^2} \quad (12)$$

$$\phi_n = \tan^{-1}\left(\frac{B_n}{A_n}\right) \quad (13)$$

Since the outline is regularly sampled at equally spaced points, the variance of these shapes are related to the amplitude of the wave form. The variance is defined as half the square of amplitude,

$$S_n^2 = \frac{A_n^2 + B_n^2}{2} \quad (14)$$

This directly expresses the contribution made by each harmonic to the shape of the figure. So we can plot the variance of successive harmonics which is called as periodogram or a discrete or line power spectrum, that is variance versus harmonic number plot. To carry out the above procedure, a computer program was developed that gave the harmonic coefficients and Variance as output.

DISCUSSION AND CONCLUSION

Lepidocyclina in the Indian region is represented by two subgenera - *L. (Eulepidina)* and *L. (Nephrolepidina)*. As discussed above, the taxonomic status of these subgenera are debated. The purpose of the morphometric approach is to examine if the two subgenera are taxonomically valid and to evolve criteria to discriminate the two subgenera in view of the fact that the adauxilliary chambers are not visible very often because of one or more of the following reasons:

1. the adauxilliary chambers may lie in different planes as in the type specimen of *Eulepidina* (Fortuin 1970)
2. the equatorial sections are not perfectly oriented while under preparation, and
3. identifications are often required in off-centred sections in random thin sections of limestone.

The Fourier Harmonic analysis of 78 nucleoconch outlines representing the two subgenera of *Lepidocyclina* are studied. The mean variance versus harmonic number plot, called the power spectrum, for the two subgenera are shown in text-figure 2. In view of the simplicity of the nucleoconch, relatively fewer number of harmonics contribute to the shape information. Even though 30 harmonics were calculated, only 15 are shown in the figure for the reasons discussed above.

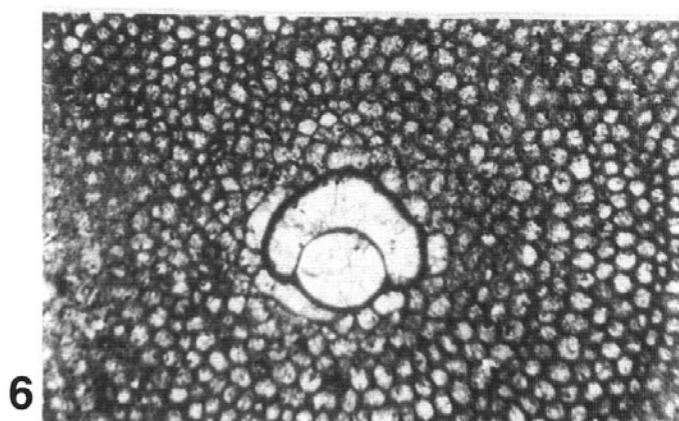
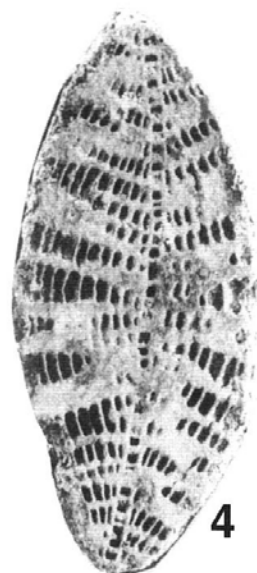
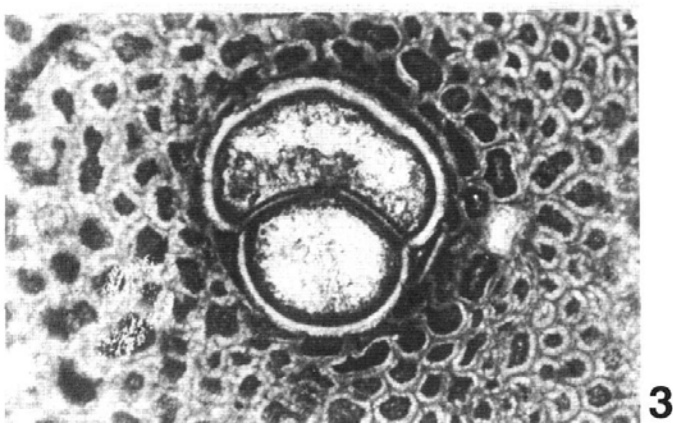
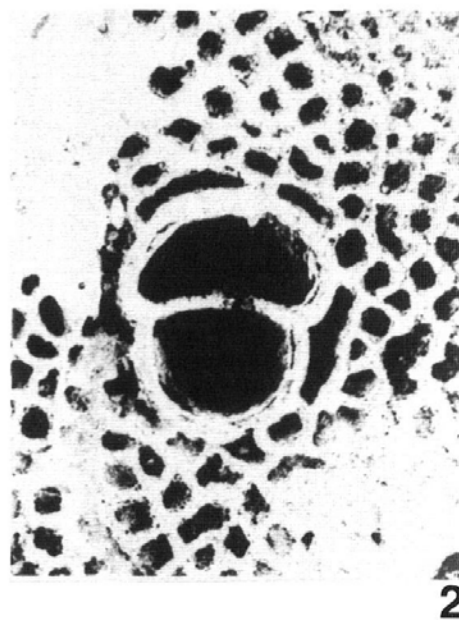
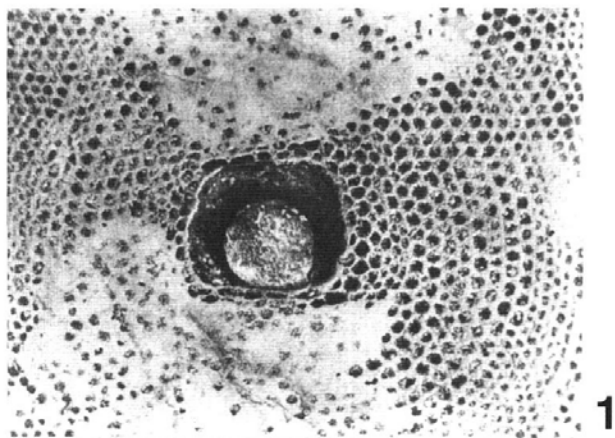
Difference in the shapes of the nucleoconch of *L. (Eulepidina)* and *L. (Nephrolepidina)* is reflected in the power spectrum for the two subgenera (text-fig. 2). Visually, the two subgenera consistently maintain a difference in the variance of second to seventh harmonics. A t-test (at $\alpha = 5\%$ level) is carried out to examine the significance of the difference between the two shape patterns. It is found to be insignificant for second harmonic but significant for the 3rd, 4th and 5th harmonics. It is again insignificant for 6th and 7th harmonics (no significance test was carried out for harmonics higher than 7th). As observed, the means of *L. (Nephrolepidina)* are consistently higher than the means of *L. (Eulepidina)* and this pattern is maintained for all the harmonics, and is not just the result of chance. The two subgenera thus differ significantly in the shape of their nucleoconchs. It supports the interpretation of earlier size morphometric analysis that the distinction between the two subgenera is valid.

The difference in nucleoconch shape between the phylogenetically related species *L. (N.) isolepidinoides* and *L. (N.) sumatrensis* is also reflected in their power spectrum (text-fig. 3). Except for the second harmonics, all the other harmonics (3rd to 7th) are found to be significantly different. It is to be noted that the relative positions of mean variance of the two subgenera remain consistently the same for all the harmonics, while they change irregularly at the level of species. Another feature of importance is that while the lower harmonics 2nd to 5th are significant in differentiating the subgenera, higher harmonics up to 7 contribute significantly in differentiating the species. The result is logical. The lower harmonics contribute to the gross shape (useful at the higher taxonomic level) compared to the higher harmonics, contributing to the finer complexities of the outline (thereby useful in differentiating taxa at lower taxonomic level).

The conclusion of shape morphometrics thus supports the interpretation of size morphometrics that the two subgenera *Lepidocyclina (Eulepidina)* and *Lepidocyclina (Nephrolepidina)* are taxonomically valid. The Fourier shape analysis is effective at both the subgeneric and species level differentiation in *Lepidocyclina*.

PLATE 1

- | | |
|--|--|
| 1 <i>Lepidocyclina (Eulepidina) ehippoides</i> , [equatorial section, $\times 10$] | 4 <i>Lepidocyclina (Nephrolepidina) sumatrensis</i> , [equatorial section, $\times 4$] |
| 2 <i>Lepidocyclina (Nephrolepidina) isolepidinoides</i> , [equatorial section, $\times 40$] | 5 <i>Lepidocyclina (Nephrolepidina) sumatrensis</i> , [equatorial section, $\times 40$] |
| 3 <i>Lepidocyclina (Nephrolepidina) sumatrensis</i> , [equatorial section, $\times 60$] | 6 <i>Lepidocyclina (Nephrolepidina) sumatrensis</i> , [equatorial section, $\times 40$] |



ACKNOWLEDGMENTS

Professor Pamela Hallock and Dr Brian Huber reviewed the manuscript and gave useful suggestions to improve it. Dr P.C. Pandey provided the digitizer facility. We are thankful to them.

REFERENCES

- ADAMS, C. G. 1987 On the classification of the Lepidocyclinidae (Foraminiferida) with re-descriptions of the unrelated Paleocene genera *Actinosiphon* and *Orbitosiphon* Micropaleontology, 33(4): 289-317.
- BOON, J. D., EVANS D. A., and HENNIGAR H. F. 1982 Spectral information from Fourier Analysis of digitized quartz grain profiles. Mathematical Geology, 14(6): 589-605.
- COLE, W.S. 1960 Variability in embryonic chambers of *Lepidocyclina*. Micropaleontology, 6, 133-144.
- COLE, W.S. 1968 More on variation in the *Lepidocyclina*. Bulletin of American Paleontology, 54, 295-325.
- DOUVILLE, H. 1911. Les foraminifères dans le tertiaire des Philippines, Phillipine Journal of Science, 6: 53-80.
- EAMES, F.E., BANNER, F.T., BLOW, W.H., CLARKE, W.J. and SMOUT, A.H. 1962 Morphology, taxonomy and stratigraphic occurrence of *Lepidocyclina*. Micropaleontology, 8(3): 289-322.
- FOOTE, M. 1989 Perimeter-based Fourier analysis: a new morphometric method applied to the trilobite cranidium. Journal of Paleontology, 63(6): 880-885.
- FORTUIN, A. R. 1970 The Early ontogenetic stages in *Eulepidina dilatata*. Proceedings Koninklijke Nederlandse Akademie Van Wetenschappen. Ser. B, 73(3): 196-208.
- HALL, J. K. 1976 Algorithms and programs for the rapid computation of area and center of mass, Computers & Geosciences, 1: 203-205.
- MOHAN, M. 1982 Palaeogene Stratigraphy of Western India. The Palaeontological Society of India Special Publication No. 1, 21-36.
- REYMENT, R.A. 1991 Multidimensional Palaeobiology, Pergamon Press, 99-120.
- RHOLF, F.J. and ARCHIE J.W. 1984 A comparison of Fourier methods for the description of wing shape in mosquitoes (*Diptera; Culicidae*). Systematic Zoology, 33(3), 302-317.
- SARASWATI, P.K. 1994 Biometric study of *Lepidocyclina* (*Nephrolepidina*) from Kutch, Saurashtra and Qilon (India). Journal of Geological Society of India, 44: 79-90.
- , 1995 Biometry of early Oligocene *Lepidocyclina* from Kutch, India. Marine Micropaleontology, 26: 303-311.

Manuscript received December 19, 1999

Manuscript accepted March 6, 2000