Pratul Kumar Saraswati

Larger Benthic Foraminifera Through Space and Time

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Ranchi, India

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Preface

As a young doctorate student in 1979, it was exciting for me to pick larger benthic Foraminifera (LBF) in the field. I knew Foraminifera as microfossils, but I had no idea they could grow into "giants" in the middle Eocene outcrops of Kutch (India). It was even more exciting to learn that not only geologists but an army Colonel, CW Grant, and an army Surgeon, Henry John Carter, had investigated them initially in the early nineteenth century. My first job in a national oil exploration company was to keep drillers informed of the age of an offshore well's last drilled depth while drilling continued. The drill cuttings were full of LBF. Planktic Foraminifera were few in the well's shallow marine strata and not very helpful in determining the age. The experience taught me how essential LBF are in the biostratigraphy and paleoenvironmental interpretation of hydrocarbon-bearing rocks.

Nearly 350 million years ago, LBF evolved with architectural complexity and microalgae symbiosis. Symbiosis drove them to success, and they became major producers of carbonates during the Earth's globally warm periods. Due to their large size, these are readily amenable to experimental investigations, which have provided details about the growth, life cycle, respiration, and calcification in Foraminifera. Microsensors detected a changing carbonate microenvironment surrounding the test due to daily photosynthesis and host respiration cycles. It has aided in understanding its impact on stable isotope fractionation and trace element incorporation in foraminiferal carbonates. The use of stable isotopes and trace elements in LBF to interpret paleoclimate is still in its beginning. However, as some results have indicated, it has a high potential for reconstructing greenhouse climates and past hyperthermal events. Recent progress in geochemical proxies and X-ray computed tomography holds considerable promise for studying the paleobiology of LBF and, in extension, all Foraminifera.

The book is written to introduce various aspects of LBF to doctorate students and early-career researchers in biostratigraphy, paleoenvironmental analysis, and carbonate sedimentology. It will fill the gap between a generic micropaleontology textbook and more specialized works on Foraminifera. The reader is expected to be conversant with the fundamentals of Foraminifera studies. The book will also appeal to stratigraphers and people interested in the history of the Earth.

I am grateful to my friends DSN Raju and Ercan Özcan for sharing their insights about larger Foraminifera. Sadly, I recently lost them after many years of association. I also thank György Less for our numerous interactions on LBF collaborative works. I acknowledge my students and colleagues at IIT Bombay's Department of Earth Sciences for their continued assistance and cooperation. An anonymous reviewer is thanked for making valuable suggestions. Pamela Hallock generously volunteered her time to read and edit the text and offered her understanding of some of the topics in the book. I cannot thank her enough. I appreciate Springer Nature's Zachary Romano for quickly publishing the book and Nivetha M for supervising its production.

Ranchi, India Pratul Kumar Saraswati

About the Book

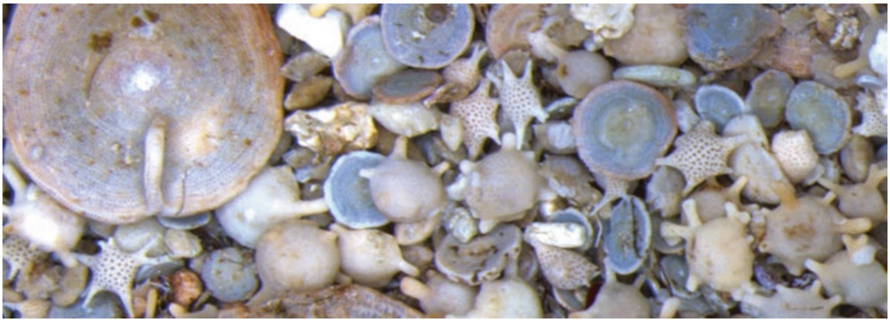
Larger benthic foraminifera are unicellular organisms with microalgae symbionts that live in shallow well-lit tropical marine waters. They are abundant as microfossils in massive carbonate deposits from Earth's warmer eras. In many sedimentary basins, these carbonates serve as hydrocarbon reservoirs. This profusely illustrated book covers larger benthic Foraminifera's biology, morphology, geochemical proxies, and distribution in space and time. It is for doctorate students and early-career researchers in biostratigraphy, paleoenvironmental analysis, and carbonate sedimentology. It will also appeal to stratigraphers and those interested in Earth's history.

Contents

About the Author

Pratul Kumar Saraswati taught Micropaleontology at the Indian Institute of Technology Bombay for over thirty years. He has published widely on Paleogene biostratigraphy and geochemical proxies of paleoclimate in larger benthic foraminifera. He has also authored two books entitled “Micropaleontology-Principles and Applications” and “Foraminiferal Micropaleontology for Understanding Earth’s History.”

Chapter 1
Introduction



Larger Benthic Foraminifera (LBF) are usually large, symbiont-bearing, and of intricate internal morphologies. They live in the present-day warm, well-lit, oligotrophic waters of shallow seas. Geologically, they were abundant and widespread in tropical, shallow-marine carbonates of the Permian, Cretaceous, and Paleogene Periods. People from different walks of life pursued their studies as a hobby in the nineteenth century. The oil industry promoted studies in the systematics, evolution, and environmental distributions of LBF for applications in the exploration of carbonate reservoirs. Field observations and experimental studies of living taxa have given insight into their growth and life history. The advancements in analytical and imaging techniques have opened new avenues for future research in climate proxies and paleobiology of the LBF.

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1.1 What Are Larger Benthic Foraminifera?

The Foraminifera are recognized as a phylum of single-celled organisms placed in the clade Rhizaria of the protists (Adl et al. 2019). The name Foraminifères was given by the French naturalist D'Orbigny in 1826. The fossil records of the Foraminifera extend back to the Cambrian Period (~540 Ma). The genetic findings, however, indicate that Foraminifera radiated between 690 and 1150 Ma (Pawlowski et al. 2003). Within this diverse phylum, both benthic and planktic life modes are found in coastal to deep-sea environments and a range of freshwater environments. Most foraminifers are smaller than 1 mm, although members of several have grown to sizes as much as 10 cm in length or maximum diameter. The term "larger Foraminifera" or "larger benthic Foraminifera" (LBF) is informally used for taxa whose members can achieve large sizes. It is not a taxonomic category, but its members share some common characteristic features as follows:

- (i) Their adults may be seen without a magnifying glass and range in maximum dimension from a few millimeters to several centimeters.
- (ii) Extant taxa host algal symbionts. However, not all algal symbiont-bearing foraminifers are large, and not all species that achieve large sizes host algal symbionts. Symbionts are found in small-sized *Asterigerina*, but not in large-sized *Notodendrodes* (an agglutinated foraminifer).
- (iii) Most have intricated internal morphologies that are thought to aid algal symbionts.
- (iv) Individuals can live for a few months to a few years, whereas tiny benthic foraminifers commonly live for a few days to a few months.
- (v) Most live in warm, shallow, well-lit, nutrient-deficient marine environments.

Protist-algal symbiont associations are common in modern coral reefs of tropical and subtropical seas (Fig. 1.1), where they contribute substantially to carbonate sediments (Lee 1995). LBF are also known for their exceptional abundance and widespread occurrences in shallow-marine limestones of the Permian, late Cretaceous, Eocene, late Oligocene, and early Miocene ages (Fig. 1.2). Some fossil LBF reached gigantic sizes, especially during the warm climates of the Eocene, that some authors are inspired to call them "protozoan dinosaur." Fossil LBF are also believed to have carried algal symbionts, in analogy with their living representatives. Evidence for photosymbiosis in many fossil LBF include (Brasier 2012):

- (i) occurrence restricted to the photic zone of tropical-subtropical habitat;
- (ii) shell-wall sufficiently transparent (for the passage of light to the test interior);
- (iii) chambers commonly divided into chamberlets (for efficient housing and cultivation of algal symbionts);
- (iv) the line of communication from the innermost chambers to the external environment may be shortened (for a quick movement of cytoplasm, ensuring energy-efficient manipulation of photosymbionts and photosynthates); and,
- (v) evolutionary trends toward gigantism (consistent with a long lifespan).

Fig. 1.1 The reef flat sediments of Okinawa (Japan) containing calcareous tests of LBF. The colored tests are due to microalgae symbionts (scale bar 0.5 cm)

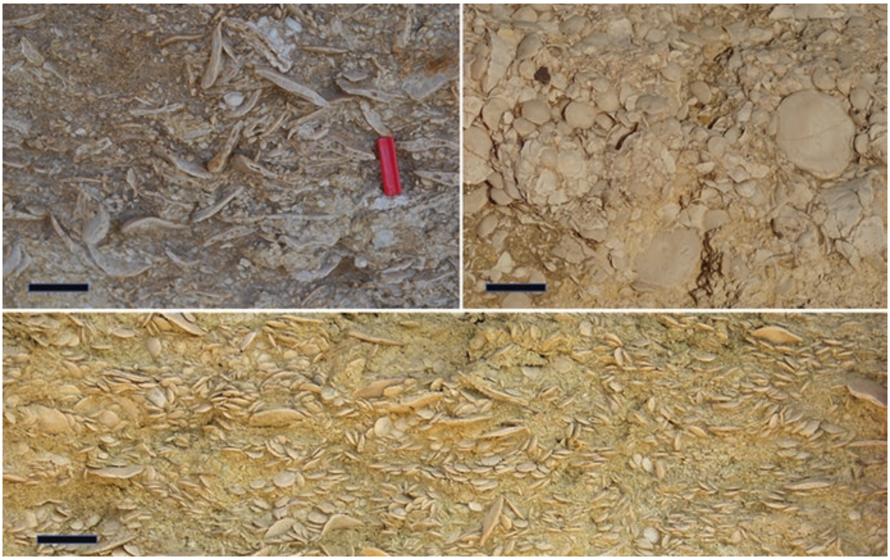

Fig. 1.2 LBF were key producers of Paleogene shallow marine carbonate deposits. The illustration depicts *Nummulites* (top left) and *Assilina* (top right) in the Eocene, and reticulate *Nummulites* (bottom) in Oligocene rocks of Kutch (India) (scale bar 1.5 cm)

Mathematical modeling of lifestyle traits of LBF establishes how delayed maturation, growth to large size, symbiosis, large embryon, and systematic suppression of sexual reproduction are crucial to their success in shallow water, relatively stable, and low-nutrient environments (Hallock 1985; Hallock and Seddighi 2022).

1.2 Historical Background

1.2.1 Early Studies

The ancient Greek historian Herodotus was the first to notice fossil foraminifers (*Nummulites)* on the slabs of the pyramids in Egypt in 500 BC. He, however, did not recognize them as originating from organisms, and foraminifers remained objects of curiosity until the sixteenth century (Galloway 1928). The organic origin of foraminifers was progressively realized through the seventeenth and eighteenth centuries. Alcide d'Orbigny (1802–1857) studied them systematically and named them Foraminiféres in his outstanding work entitled "*Tableau Methodique de la Classe*

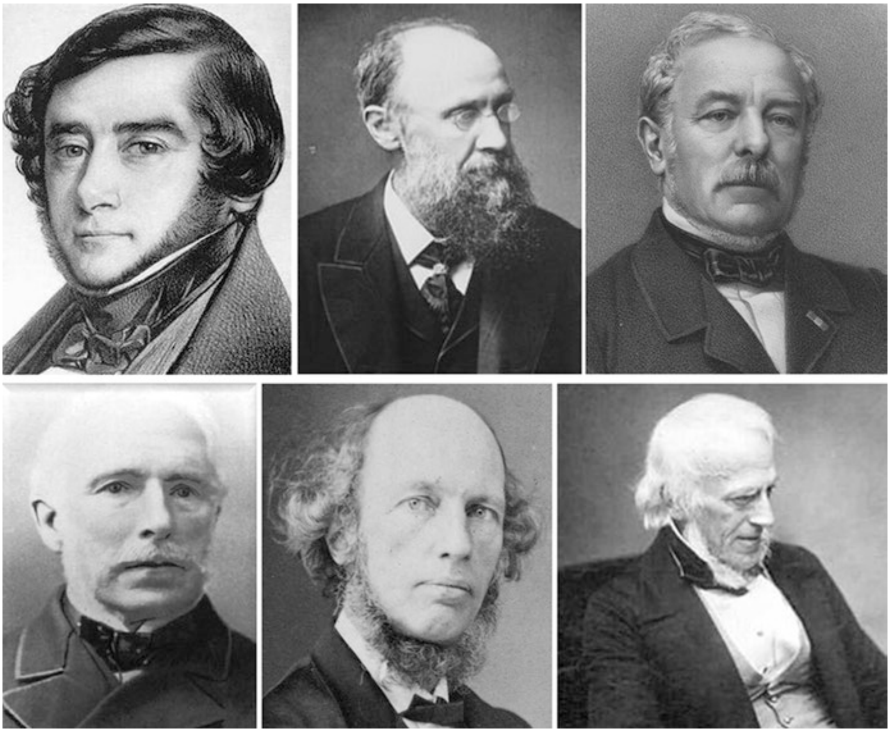

Fig. 1.3 The men of different professions who studied LBF as a hobby in the nineteenth century: (clockwise from top left) naturalist Alcide d' Orbigny, pharmacist Henry Bowman Brady, army lieutenant Adolphe d' Archiac, botanist and natural history artist James de Carle Sowerby, medical practitioner William Benjamin Carpenter, army surgeon Henry John Carter

des Cephalopods," published in 1826, assuming foraminifers to be micro-cephalopod. The foundation of the study of LBF was laid by people from varied walks of life in the nineteenth century who pursued it as a hobby (Fig. 1.3).

Adolphe d'Archiac (1802–1868) was a Lieutenant in the French Army but later specialized in studying *Nummulites* and other LBF fossils found in the Alps. Charles Schlumberger (1825–1904), a marine engineer, worked as a volunteer in the foraminiferal collection of the Museum National d' Histoire Naturelle (MNHN), Paris. He became interested in Foraminifera and realized that external morphological features are insufficient for studying LBF. He, therefore, prepared oriented thin sections to examine the internal structures of *Orbitoides*, *Lepidocyclina*, and *Miogypsina*. The collections of d'Archiac and Schlumberger are kept in the MNHN, Paris.

While deputed to India, Colonel Grant of the British Army collected LBF fossils from Kutch. He gave them to James de Carle Sowerby (1787–1871), one of the founders of the Royal Botanic Society. Sowerby described many new species from Kutch, including *Nummulites acutus*, *Nummulites obtusus*, and *Alveolina elliptica*. Henry John Carter (1813–1895), a surgeon in the Army of the East India Company,

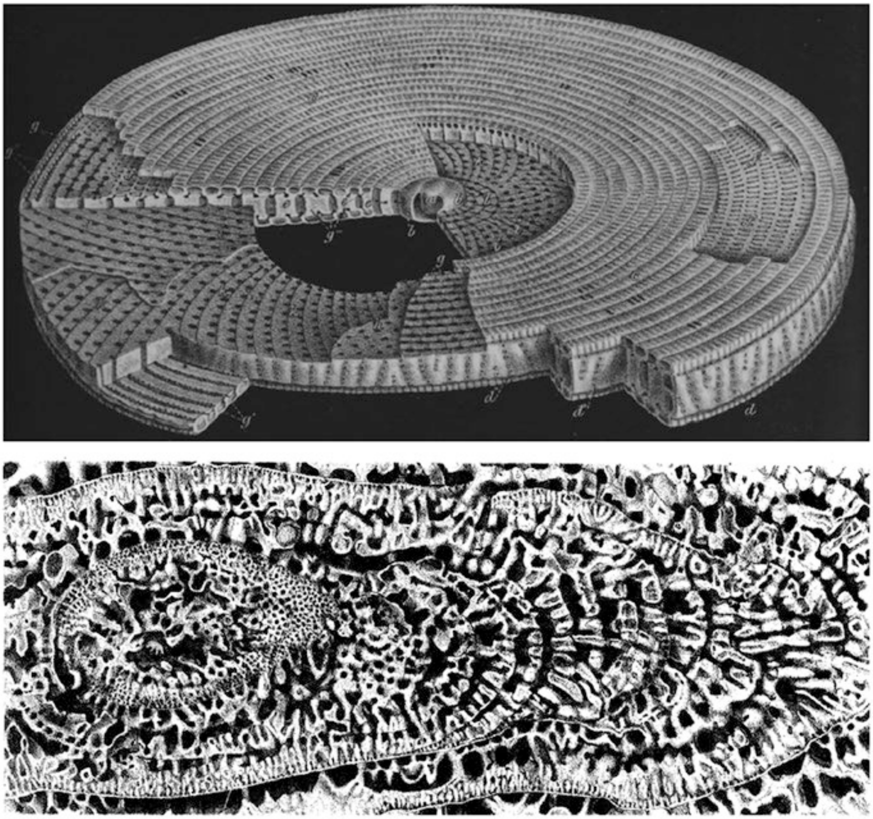

Fig. 1.4 William Benjamin Carpenter's illustrations of the complicated internal architecture of LBF: (top) the equatorial view of a miliolid genus *Orbitolites* and (bottom) axial view of an agglutinated genus *Loftusia*

described the internal structures of nummulitids and alveolinids from Kutch, Saurashtra, and Sind. Another leading British foraminiferologist, William Benjamin Carpenter (1813–1885), who had a medical background, contributed significantly to describing the internal architectures of LBF from the dredged samples of HMS Challenger and other early oceanographic cruises. His extensive observations of the internal structures of *Orbitolites, Orbitoides, Cycloclypeus*, and *Heterostegina* are remarkable for their details and exceptional illustrations (Fig. 1.4). The complexity of the internal structures of LBF revealed in the publications of Carter and Carpenter is impressive, considering the resolutions and magnifications of the microscopes available at those times. Henry Bowman Brady (1835–1891) also studied the Challenger samples for the taxonomy and depth distributions of foraminifers. He reported over 900 species of foraminifers, including those of LBF, and described them in a key reference, "Report on the Foraminifera dredged by HMS Challenger," published in 1884.

1.2.2 Fundamental Works on Systematics

Prolific growth of the systematics of LBF occurred in the twentieth century. Such studies were prompted mainly by the economic value of these foraminifers in oil explorations in North America, Russia, India, and SE Asia. While the overall form and internal features of LBF were revealed in the nineteenth century, scholars added to their systematics, evolutionary connections, and stratigraphic distribution in the twentieth century.

Thomas Wayland Vaughan (1870–1952) was a leading expert on the Cenozoic LBF of North America. He described many species of *Lepidocyclina* and *Discocyclina* from the Eocene of America and established new genera, *Yaberinella* and *Actinosiphon*. W. Storrs Cole (1902–1989) of Cornell University collaborated with Vaughan, and the two workers made numerous contributions to the literature of LBF from this part of the world. Cole and co-workers also reported extensively on foraminiferal assemblages, including LBF, from Pacific islands in the late 1940s through the 1950s. Cole initially combined *Eulepidina* and *Nephrolepidina* as a single subgenus *Eulepidina* and later considered *Eulepidina* as a junior synonym of *Lepidocyclina*, a view not accepted by others in the following years. The Paleozoic genus *Fusulina* was investigated by Lloyd Henbest (1900–1987) and Raymond C. Douglass (1923–2005) of the United States Geological Survey (USGS). The larger foraminiferal collections of all these workers are housed in the National Museum of Natural History, Washington, DC, USA.

VNIGRI, established in 1930 for petroleum exploration, promoted micropaleontologic research in the USSR. The Paleozoic LBF of Urals and Russian Platforms were extensively studied by G.A Dutkevich (1907–1937) and D.M. Rauser-Chernousova (1895–1996). Many significant contributions were made to the systematics and stratigraphic distributions of Fusulinida. The Russian foraminiferologists recognized four subgenera of the characteristic genus *Triticites*: *Montiparus, Triticites, Rauserites,* and *Jigulites*, all of which are now accepted as distinct genera. They also traced the evolutionary sequence of the complexity of the wall texture in *Triticites* that was biostratigraphically significant in establishing the middle-late Carboniferous boundary.

In Europe, the works of d'Archiac in the Alps were carried forward by Hans Schaub (1913–1994), A. Blondeau, and Lukas Hottinger (1935–2011), among others. An extensive study on *Nummulites* and *Assilina* in Paleogene turbidites of the Alps was initiated by Schaub at Basel. That study provided a clear understanding of phylogeny and stratigraphic relationships of species of the two genera. His sustained work resulted in a three-volume monograph in 1981, entitled "*Nummulites et Assilines de la Téthys Paléogène*: *Taxonomie, Phylogenèse et Biostratigraphie*." It is still an essential reference for the systematics of larger foraminifers, and the zonal scheme suggested in this study is generally relevant to biostratigraphy in the Mediterranean area. Blondeau investigated larger foraminifers of the Paris Basin and wrote "*Les Nummulites*" in 1972 on their systematics, ecology, and paleobiogeography. Hottinger worked on the morphometry of *Alveolina* and often on the same samples that Schaub studied for *Nummulites*. An integrated biostratigraphic zonation based on *Nummulites* and *Alveolina* was thus proposed for the Paleogene. Progressively, other genera were also incorporated into it by the other workers, thus developing the Shallow Benthic Zonation of the Tethyan Paleogene. All the rock samples and the prepared specimens of Schaub and Hottinger are preserved in the Museum of Natural History, Basel, Switzerland.

The Dutch foraminiferologists involved in exploration work in the then-Dutch Colonies, Java, Borneo, and Sumatra, greatly advanced our knowledge of the Cenozoic LBF of SE Asia. The Letter Stage Classification by Van der Vlerk (1892–1974) divided the Tertiary into six stages based on nummulitid, alveolinid, and orbitoidal genera assemblages. The stages were named Ta upwards to Tf, and two more divisions, Tg and Th, were added in a later revision. The scheme succeeded in regional biostratigraphic correlation until the planktic foraminiferal zonal scheme was developed in the 1970s. Basel University and Basel's Museum of Natural History actively contributed to research on LBF. August Tobler (1872–1929) and Gottfried Kugler (1893–1986) were involved in the exploration activities in Borneo and elsewhere in SE Asia, while Louis Vonderschmitt (1897–1978) worked in the exploration of tropical islands of the Caribbean and Venezuela. Kugler and Brahmine Caudri (1904–1991) published several papers on Caribbean LBF. Caudri proposed a new genus, *Ranikothalia,* from the Paleocene of Venezuela. She also followed up the preliminary observations of Vaughan and Cole on the larger foraminifers of Trinidad and, in a significant publication, described many new species of *Operculina, Lepidocyclina,* and *Amphistegina*.

The taxonomy and biostratigraphy of LBF of India are known mainly from the works of Ernest Watson Vredenburg (1870–1923) and Gerald de Purcell Cotter (1881–1941) of the Geological Survey of India (GSI), W.L.F Nuttall of the Sedgwick Museum (Cambridge), Yedatore Nagappa (1907–1960) of the Assam Oil Company, and B K Samanta (1937–2016) of the Calcutta University. Vredenburg described many *Nummulites, Discocyclina, Lepidocyclina*, and *Orbitoides* species and noted their stratigraphic ranges. Nuttall reported several new species from Kutch, including *Nummulites stamineus, N. maculatus, Assilina cancellata,* and *Aktinocyclina*