CHARACTERIZATION OF BENTHIC FORAMINIFERA AND ENVIRONMENTAL MAGNETISM OF SOFT SEDIMENTS IN THE OUTER CHANNEL OF CHILIKA LAGOON

Thesis

Submitted in partial fulfilment of the requirement for the degree of

Doctor of Philosophy

By

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2024

যাদবপুর বিশ্ববিদ্যালয়
কলকাতা-৭০০০৩২, ভারত

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CERTIFICATE FROM THE SUPERVISORS

This is to certify that the thesis entitled "**Characterization of Benthic Foraminifera and Environmental Magnetism of soft sediments in the Outer Channel of Chilika Lagoon**" submitted by **Smt. Sucheta Das** who got her name registered on 09.05.2016 for the award of **Ph.D. (Science) degree** of **Jadavpur University**, is absolutely based upon her own work under the supervisions of **Prof. Supriya Mondal** and **Dr. Anupam Ghosh** and that neither this thesis nor any part of it has been submitted for either any degree/ diploma or any other academic award anywhere before.

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ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my supervisors Prof. Supriya Mondal and Dr. Anupam Ghosh for the continuous support of my Ph.D study and related research, for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis.

I would like to thank my parents for supporting me spiritually throughout completing this thesis. This thesis would not have been possible without the encouragement and support of my mother, Smt. Damayanti Das, who stood up for me against the odds.

I am grateful to the Head of Department of Geological Sciences at Jadavpur University for providing me with essential facilities. I would like to pay my special regards to all my respected teachers of the Department of Geological Sciences, Jadavpur University. DST-FIST sponsored the SEM-EDS facility of Jadavpur University, and NCPOR, Goa are also acknowledged for the SEM images.

I would like to express my sincere gratitude to Dr. Mamilla Venkateshwarlu from the Paleomagnetism Laboratory of CSIR-NGRI (Hyderabad) for allowing me to analyses my samples.

I thank my fellow lab mates Dr. Utsha Dasgupta, Dr. Dipankar Buragohain, Dr. Ishita Das, Rohan Subba for the stimulating discussions, for the sleepless nights we were working together before deadlines, and for all the fun we had during this journey. I also appreciate the support of my juniors during fieldwork.

Not to mention, I would like to express my gratitude Dr. Saurodeep Chatterjee, Dr. Debesh Gain, Dr. Rimjhim Maity, Ms. Solanky Das, Ms. Swagata Das and Mr. Rituparna Majumdar from Geophysical Laboratory, Department of Geological Sciences, Jadavpur University who have made significant contributions to this research work of mine.

Lastly, I acknowledge with pleasure the help and support I have always received from Surajit and Amit.

Date: Signature

List of Publications

Journal Papers

- **Das, S.,** Ghosh, A., and Mondal, S., 2024. Foraminiferal biofacies distribution in the outer channel of Chilika Lagoon, Odisha, India. Journal of the Palaeontological Society of India
- **Das, S**., Mondal, S., and Ghosh, A. Study of environmental magnetic characteristics of soft sediments from Chilka Lagoon, Odisha. (Under Review, Geographical Society of India)

Conference Papers

- **Das, S.,** and Ghosh, A., 2020. The study of recent benthic foraminifera in the Chilika Lake, Odisha. 107^{th} Indian Science Congress. 133p
- **Das, S.,** Mondal, S**.,** and Ghosh, A., 2019. Use of Magnetic Susceptibility as a proxy - to determine the pollution rate from Chilika lake sediments. NGRSM. 3p
- **Das, S.,** Ghosh, A., and Mondal, S., 2019. A seasonal study of benthic foraminifera in the Chilika Lagoon, Odisha. 27^{th} ICMS. 100p
- **Das, S.**, Das, I., Dasgupta, U. and Ghosh, A., 2018. Study of marsh foraminifera from Sagar Island(S), 24Parganas, West Bengal. 105^{th} Indian Science Congress. 116p.
- Dasgupta, U., **Das, S.**, Das, I. and Ghosh, A., 2018. The preliminary study of benthic foraminiferal assemblages along the outer channel of Chilika lagoon, east coast of India. Geo-Symposium. 34-35p.
- **Das, S.,** and Ghosh, A., 2017. The study of marsh foraminifera of Sagar Island(S), 24 Parganas, West Bengal - using scanning electron microscopy (SEM). GEOCON.
- **Das, S.**, Mondal, S**.,** Buragohain, D., and Dasgupta, U., 2017. Magnetic susceptibility of road dust from Kolkata-relationship to road traffic. West Bengal state Science & Technology Congress-2017. 56p

Abstract

Environmental monitoring is now critical for coastal areas around the world as a result of continual geomorphologic changes caused by natural events or man-made activity. Benthic foraminiferal assemblages have been used as a proxy for evaluating the health of the coastal environment. Magnetic measurements also provide typical analytical approaches for soil contamination mapping and atmospheric pollution research. The current research aims to (i) characterize foraminiferal biofacies in the Chilika Lagoon's outer channel and central sector, (ii) identify magnetic minerals associated with environmental pollution using magnetic mineral measurements, and (iii) understand the relationship between foraminiferal assemblages and magnetic susceptibility of soft sediments. A micropaleontological study was carried out in the lagoon's outer channel and central sector during the pre- and post-monsoon months. To analyse these microorganisms, surface sediment samples were taken from 56 different places in the lagoon and stained with buffered Rose Bengal solution. During this study, soft-bottom sediments from 54 sites around the Chilika lagoon's outer channel were collected for magnetic mineral examination. For the collected sediments, standard micropaleontological methods were employed. Altogether, thirty-four species of benthic foraminifera are identified, among which *Ammonia* spp. are predominant. Other calcareous taxa include *Elphidium* spp., *Quinqueloculina* sp., *Haynesina* spp., *Pararotalia* sp., *Hanzawaia* sp., *Nonionella* sp. and agglutinated forms such as *Miliammina* sp., *Trochammina* sp. and *Textularina* sp. The current research suggests a reduction in the abundance of live foraminifera in comparison to earlier studies. Three separate biofacies zones have been identified based on total foraminiferal number. The main variables influencing this zonation of foraminifera include low salinity, shallow water depth, low oxygen conditions, and nutrient inflow. All magnetic measurements indicate that ferromagnetic minerals, such as magnetite, are the predominant magnetic carriers in all samples, with certain paramagnetic elements, such as haematite, also present. This study found that agglutinated species (*Miliammina fusca*, *Ammobaculites exiguus*, *Textularia earlandi*) dominate regions with low magnetic susceptibility (MS) ranges, while calcareous hyaline species (*Ammonia beccarii*, *Ammonia parkinsoniana*, *Pararotalia nipponica*) dominate regions with high MS ranges.

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1.1 GENERAL INTRODUCTION

Micropaleontology is a branch of palaeontology that studies microfossils. These microfossils are so tiny that it needs a microscope to study. In this branch of palaeontology, we can study the morphology and classification of the microfossils along with their environmental and stratigraphic significance. Now-a-days these microfossils are widely used to detect and solve different geological problems. Among different group of microfossils, foraminifera are the most important one as it has been increasingly used as environmental bio-indicators. They are among the more abundant and most conspicuous protozoa in most marine and brackish water habitats. Salinity-tolerant coastal and paralic foraminifera have first been used as salinity indicators in the standard estuarine classifications based on their spatial distribution with salinity from oceanic to continental end (e.g., Nichols, 1974), but they are also well adapted for environmental monitoring (Scott et al., 2001). The size and density of the pores are considered as an indicator of the dissolved oxygen concentration (e.g., Sen Gupta and Machain-Castillo, 1993). Compared to other organisms used for environmental survey, foraminifera have the advantage of possessing mineralized tests that are preserved in the sediment. They provide a dataset that can be used to reconstruct environmental changes at different time scales (Cearreta et al., 2000, 2002; Ruiz et al., 2004). Due to these characteristics foraminifera are widely used as a proxy for coastal environmental monitoring along with a wide variety on marginal environment such as estuaries (Alve 1995, Luan & Debenay 2005, Bhattacharjee et al., 2013), marshes (Gehrels & Newman 2004, Horton & Murray 2007) and lagoons (Samir 2000, Martins et al., 2013).

Environmental magnetism is a distinct scientific entity, which studies intrinsic magnetic characteristics of mineral types within non-oriented samples such as magnetic susceptibility (χ), frequency dependent susceptibility (χ_{FD}), anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM). The magnetic properties of sediments are entirely independent of the EMF and are largely a function of mineralogy and grain size that provide insights into the mode of transport, deposition and changes in their properties caused by different processes of iron mineral authigenesis, diagenesis and dissolution.

Environmental magnetism has evolved on three principal objectives: (1) characterizing spatial variability in physical properties of the shallow subsurface (soils, sedimentary sequences) environment, wherein the information is used to model palaeo-climate and palaeo-environment, (2) environmental pollution characterization based on the fact that atmospherically transported magnetic particulate material makes a significant contribution to the iron oxides and iron hydroxides particle content of sedimentary deposits / soils and (3) biomagnetism, where the research programme aims to provide information about the environmental control variables (temperature, rainfall, pH, as well as microbial type and concentration) for the process of Fe^{3+} to Fe^{2+} reduction and challenges posed by environmental magnetic observations of biomineralized nanophase (1–100 nm) materials. The most fascinating examples of investigation come from magnetotactic bacteria found in diverse environments playing a role in fine magnetic particle (submicron size) investigations.

The mineral magnetic variations in sediments, depending on the environmental context, are used as an aid towards elucidation of a diversity of problems. Severeal Indian research groups are working diligently to reconstruct palaeoclimate over the subcontinent, and its contiguous oceanic realm. These type research studies offer considerable potential to correlate marine and terrestrial sequences. However, only a few investigations have used rock magnetic and environmental magnetic properties to extract palaeoclimate and palaeooceanographic information. How stable are Fe-oxides in a given environmental conditions, and modify with a change in chemical and physical ambience are recognised in this research work. The premise is based on the fact that magnetic mineralogy reflects the course of environmental (climate) changes by recording evidence of associated modifications in sedimentation, weathering and pedogenic regimes. So, the magnetic susceptibility is found to be a valuable tool that accurately plays back the original signals entrenched in the soft sediments. Mineral magnetism and Foraminiferal assemblages of Chilika Lagoonal sediments were investigated to reconstruct the depositional environment. These lagoonal sediments are characterised by high biological productivity and abundance of organisms.

1.2 Background Of The Research work

Coastal areas have traditionally been places of human settlement, with the accompanying development of cities, industries and other human-related activities possibly having an impact on the aquatic ecosystems. Today's increased developmental activities change the salinity, temperature and nutrients in the coastal water of eastern India, causing major threats to planktonic and benthic biotic assemblages of marginal marine environments, including lagoons. Lagoons generally are a highly productive ecosystem, due to large nutrient input from their drainage basin, as well as high nutrient cycle and a wide range of habitat supported by the salient gradient. Lagoonal sediment studies became more important in recent years as it shows the most dynamic environments because it acts as the transition zones for mixing of fresh and saline water. Nowadays, there are a series of geological and biological processes to understand the response of these ecosystems with the changes in their environments (Dietl et al., 2015). Previous studies show that often these changes have anthropogenic in origins. Examination of anthropogenic impact to these lagoons can be used to discuss the human effects on the lagoons currently. Benthic micro-organism (foraminifera) become an integral part of past environment reconstruction study. Compared to other organisms used for environmental survey, foraminifera are widely used to reconstruct environmental changes at different time scales (Cearreta et al., 2000, 2002; Ruiz et al., 2004).

Coastal lagoons are highly influenced by the fluvial inputs and tidal variation with wave action, which can affect on foraminiferal assemblages. Foraminiferal diversity can vary seasonally or periodically due to the monsoons and tidal variation of the lagoon. These are the causes of low diversity accumulation of benthic foraminifera in a lagoonal environment. Only euryhaline and stress tolerant species dominate here (Murray,2007). Studies in European waters, e.g., the French Atlantic coast, the Mediterranean and southern Norway, have demonstrated the potential of both living and fossilized benthic foraminiferal assemblages to serve as environmental quality indicators (e.g. Armynot du Châtelet et al., 2004; Alve et al., 2009; Frontalini and Coccioni, 2011; Bouchet et al., 2012; Dolven et al., 2013). Previous studies showed that recent foraminifera aimed at distribution pattern and checklist of species. Modern investigation is mainly focused on the improvement of information about natural ecology of benthic foraminiferal genera and their impact on the surrounding environmental features. Recent foraminiferal studies enriched us with beneficial and everlasting growing knowledge of their ecology and distribution pattern (Murray,2001; 2006) which can be used in environmental monitoring regionally and used as a proxy in palaeoceanography and palaeobathymetry (Atlantic N. America–Culver & Buzas, 1980; New Zealand–Hayward et al., 1999; Gulf of Mexico–Sen Gupta & Smith, 2010). Many studies focussed on benthic foraminifera as bio-indicators of coastal pollution have been carried out (Boltovskoy et al., 1991; Alve, 1995; Yanko et al., 1999; Scott et al., 2001). Thus, benthic foraminifera have been increasingly used as environmental bio-indicators, especially in polluted areas.

Climate change is the biggest issues for present world. The trace of these changes can be detected by different deposition like soil, marine sediments and lagoon sediments. Lagoon sediments are basically good indicators of a sensitive environment as it formed in a closed system as well as has a high depositional rate. The sediments can be originated by natural or regional climatic process (Korsman et al., 1999). The deposition of sediments in the lagoon is not uniform due to energy differences and remoteness from the source (Schrimm et al., 2004). It also gave us a clear thought of anthropogenic stress as well as natural stress in the environment. Different anthropogenic activity inside the catchment area and the lagoon itself may contribute magnetic minerals into this sediment. Industrial effluents, agricultural runoffs, transport, burning of fossil fuels, animal and human excretions, weathering and domestic waste contribute to the heavy metal accumulation in the water bodies (Moore and Ramamoorthy, 1984; Adnano, 1986). Due to change in environmental conditions (pH, sediment redox potential, etc.) the concentration of metals varies in sediments (Forstner, 1989a, Forstner, 1989b, Izquierdo et al., 1997, Zoumis et al., 2001 and Morillo et al., 2002). The magnetic minerals of lagoon sediments are of various types depending on their origin. Some are authigenic, means formed inside the lagoon by chemical or biogenic process, some are digenetic in nature which means transformation of one magnetic or non-magnetic form to a new magnetic one, and some are allogenic that are brought from outside the lagoon. Thompson in 1975 found that in several lagoons, magnetic mineral concentration was high in marginal sediments and areas close to catchments. As bulk Magnetic Susceptibility (MS) measurements show magnetism of all magnetic bearing materials (paramagnetic, ferromagnetic and ferrimagnetic), this makes MS an important source of magnetic information.

Initial work by Locke and Bertine (1986) and Beckwith et al. (1986) identified elevated levels of magnetic oxides present in soils and linked them to magnetic particles in air borne pollution. Subsequent studies confirmed these findings and showed a direct correlation between the magnetic susceptibility (ease of magnetization) of contaminated soils and the presence of hydrocarbons, heavy metals and other combustion-related pollutants (Flanders, 1991; Morris et al.,1995; Kapicka et al.,1999; Petrovsky and Ellwood, 1999). A positive correlation between contaminant concentrations and magnetic oxides has also been identified in lagoon and marine sediments. Morris et al., (1994) and Versteeg et al., (1995, 1997) analysed magnetic properties in core samples from Hamilton Harbour in western Lagoon Ontario. MS logging is frequently measured in lagoon cores for the correlation of overlapping sections from the same core site to create a composite core section (Nowaczyk et al., 2001), for correlation of cores across a lagoon basin (Thompson, 1975; Engstrom et al., 2009), to align and date repeat cores where a location was revisited after an initial palaeo-study (Blumentritt et al., 2013),), or as a marker for erosion within the lagoon catchment (Thompson, 1975; Eriksson and Sandgren 1999; Sandgren and

Snowball 2002). Examination of the levels of magnetic susceptibility within the sediment cores is an easy and efficient way to begin analysis of environmental pollution (Bityukova et al., 1999). Bityukova et al., (1999), discussed regarding magnetic susceptibility as an indicator of pollution in lagoons in Estonia. The anthropogenic materials found in deposition contain magnetic particles, which are reflected by spikes in the magnetic susceptibility (Bityukova et al., 1999). These spikes are useful as points of interest to be analysed in greater detail. The magnetic susceptibility variations recorded on sediments are very useful tool for detecting presence of magnetic minerals in lagoons (Radan et al., 2011). Magnetic susceptibility varies with mineral property and various magnetic domains of the sediment/rock. So different sediments have different magnetic susceptibility values and in a previous study of environmental magnetism, an effect of lithology on these magnetic characteristics had been observed (Sun and Liu, 2000, Ding et al., 2001, Nie et al., 2007, Wang et al., 2017a). As these measurements are rapid, non-polluting, pocket friendly and enable large data set with minimal sample preparation, it is applicable to determine environmental magnetism worldwide.

1.3 Objectives Of The Research Work

The present study focused on recent foraminifera and environmental magnetic characteristics of soft sediments in Chilika lagoon with the following objectives:

- Systematics of benthic foraminiferal assemblages in the study area.
- Understanding the foraminiferal assemblages (live and total), seasonal distribution pattern, diversity, richness and variation in the lagoon and its correlation with abiotic factors.
- To identify the magnetic minerals responsible for environmental pollution from the lagoon by using different Rock Magnetic Analysis.
- Preparation of foraminiferal bio facies map of this lagoonal system and its correlation with magnetic susceptibility of sediments.

1.4 GEOLOGICAL SETTINGS OF CHILIKA LAGOON

1.4.1 **General Features**

Chilika is a well-known largest brackish water lagoon of the world. It is the largest coastal lagoon in India. The coordinates of the lagoon on the Odisha coast are 19° 28′–19° 54′ N and 85° 05′–85° 38′ E and it covers almost 10,0000 ha of land. The lagoon is pear in shape and has a maximum length of 64.3 km with a mean width of 20.1 km. It is connected next to the Bay of Bengal through a long zigzag channel with a wide mouth, commonly known as "Magarmukha". “Palur canal” or “French canal” (man-made canal) connects the southern sector of the lagoon with the Rushikulya estuary and also collects sea water in the water-body. Several numbers of islands are present in the lagoon, among them some important are Krishnaprasad, Nalaban, Kalijai, Somolo and Birds Islands. Over 800 species of fauna were recorded in and around the lagoon in the year 1985-87 in a survey conducted by Zoological Survey of India. More than 710 plant varieties were recorded from here. The lagoon is one of the biodiversity hotspots in the country. Many of the inhabitants of the lagoon are rare, near threatened, vulnerable, endangered and critically endangered species listed in IUCN Red Data List. During winter large number of migratory birds do gather in this lagoon from different parts of the world like, some are from Caspian Sea, Aral Sea, Mongolia, central and southeast Asia, remote places of Russia, Lagoon Baikal and Ladakh, great Himalayas and Rann of Kutchh. Thus, it became the largest wintering ground for the migratory bird of India. The Nalaban island is notified as “Bird Sanctuary” in 1973 under The Wildlife (Protection) Act, 1972. The lagoon was declared as “Ramsar site” (a wetland of international importance) at the Ramsar Convention in 1981. Due to its changing ecological behaviour, the lagoon was listed under the Montreux Record (Threatened list) in 1933. But after its restoration and achievements, Ramsar secretariat removed its name from that record in 2002, which was first in Asian continental history. Chilika is also the natural habitat of highly endangered Irrawady Dolphin (Ghosh et al, 2006). The ecosystem and the environment of the lagoon are maintained according to Coastal Regulation Zone Notification (2011). It has a socio-economic and cultural value to the people of Odisha since its birth and became one of the attractions to poet, philosopher and naturalist worldwide. It also becomes an eco-cultural destination for tourist. The livelihood of the people around the lagoon is dependent on fishing and tourism. Nowadays, the lagoon faced severe problems like heavy siltation, decreases depth and lowers the water mass, drop in salinity, algal blooms, eutrophication and biodiversity loss. The recorded sediment load released throughout the year into the lagoon was at 1.8 million tons in 1998 (Patnaik, 1998), which rises up to 2.94 million tons in 2001 (Annon, 2003). The salinity of the lagoon drops due to poor water circulation and weak tidal influences. To solve these problems, the Department of Forest and Environment and Government of Odisha formed Chilika Development Authority (CDA) to monitor the health of this largest brackish ecosystem.

1.4.2 **Geography and Topography**

Chilika is a superficial bar-built estuary along with large mud flats. Eastern Ghats hill range is situated at the western and southern periphery of the lagoon. A 60 km long beach named Rajhansa separates the lagoon from the adjacent Bay of Bengal in the eastern periphery. The northern periphery is influenced by Mahanadi distributaries (largest river system of Odisha). A ~32 km long zigzag outer channel connects the lagoon with Bay of Bengal at Arakudha village (Panigrahi et al., 2009) with a 100 m width mouth, which is commonly known as the "Magarmukha" (mouth of crocodile). The northern side of the lagoon is the part of Khordha district and western side is in the Ganjam district. The lagoon consists of numerous islands. Among them, six major islands (Parikud, Phulbari, Berahpura, Nuapara, Nalbana, and Tampara.) together constitute the Krishnaprasad revenue Block of Puri district. Chilika drainage basin along with the lagoon spread over 4,300 km^2 of area (Das and Sasmal 1988). Though the width of the lagoon varies and the mouth gets narrower due to heavy siltation. The depth of Chilika bed is getting lower due to the deposition by the river system. Total surface area of the lagoon is estimated at 704 km^2 during the summer (March to June) and 1,020 km^2 in monsoon time respectively (Gupta et al., 2008) which was 905 km^2 and 1,165 km^2 in past (Annandale and Kemp 1915). The depth of this lagoon varies from 0.38 m. to 0.8 m. in the arid season and 1.8 m. to 4.2 m. during monsoon (Panda & Mohanty, 2008). The overall water quality, depth and previously reported biological diversity divided the entire lagoon into four natural ecological sectors (Fig:1.1): Northern (freshwater zone), Central (brackish zone), Southern (marine in nature), and the Outer Channel (marine) (Sahu et al., 2014). Average depth of the northern part is 50 cm while the central part has a depth of 1.5 to 2.5 m. The deepest part i.e., southern part having a depth of 2.5 to 3.5 m (Panigrahi et al., 2009) while the water depth of the outer channel is 1m in average during summer but increases up to 2m during monsoon (Rao et al., 2000). This sector is also influenced by two recently formed natural marine inlets near Gobakunda and Dhalabali (2008 and 2012) and an artificial one that has shifted northward (2000) (Sahu et al., 2014). The central sector covers almost 370 km^2 area of the lagoon, while outer channel only covers 42 km^2 area (Sahu et al., 2014).

The inception of the lagoon is contemplated geologically to be the result of a rise in sea level, approximately between 6000 to 8000 yrs. before. The formation of sea beaches in the southern sector of the lagoon were a result of the sudden halt in the rise of sea level around 7000 yrs. ago.

With the rise of sea level, the beaches continued to grow towards the northeast which is now called as sand splits. Geological studies showed that the seacoast was up to the western border and later moved eastward continuously. The southwestern part of the lagoon dated back between 3500 to 4000 years, which is evidenced by the fossils found there. Due to the deposition of sand, these sand splits changed their shape continuously and thus choked the mouth. So, a constant opening of the mouth needs to be monitored.

1.4.3 **Water Quality**

Chilika is influenced by three hydrological sub systems, in north the areas are affected by river Mahanadi, the west and southwest parts are influenced by Bhargavi River and Rushikulya River along with their streams flowing into Chilika, and in the eastern side there is Bay of Bengal (Ram et al., 1994). Apart from them, the lagoon also collects silt from freshwater flow of 52 channels. Thus, three different types of environments, such as marine, fluvial and terrestrial environment, are found in this lagoon. Marine environment controls the water and sediment exchange between lagoon and sea. It controls the tidal activity along with sand deposition. Fluvial environment contributes high amount of fresh water input with a high sedimentation rate. On the other hand, the terrestrial environment enriched the lagoon bed with pollutants and domestic wastes. The lagoon is influenced by several hydrological activities like (i) unregulated drainage from eroded catchment basins along the western and southern boundaries, (ii) silt enriched freshwater discharges from different watercourses of Mahanadi River and (iii) swapping of lagoon water with the adjacent sea water. These fresh water and sea water intrusion with tidal impact causes the present salinity condition of the lagoon and give it an estuarine characteristic. Mahanadi and its tributaries like Bhargavi, Daya, Nuna, Makra, etc contribute almost 60% of fresh water into the lagoon and 39% of fresh water comes from other channels of the water body. During July–September (Monsoon season) an average rain fall of 1240 mm had been observed in the catchment area (Sahay et al., 2019). There had been influx of fresh water of about 5090 mi. cubic meters annually (1999-2007) was found (Panda & Mohanty, 2008). The hydrography of the lagoon is impacted not only by the precipitation but also by the fresh water contributed by several rivers and rivulets. During pre-monsoon there is high evaporation and less fresh water influx from rivers and rivulets. Fresh water and sea water intrusion affects these sectors severely. Although the southern sector remains brackish water condition due to its stable and undisturbed characteristics. Inflow of sea water take places by two openings; one is through outer channel and other is through the Palur canal. The inflow of tide propagate sea water through the mouth, leads to an increase in salinity of this part of the outer channel (Barik et al., 2019). The salinity increases in the central part and northern sector due to wind mixing, though southern sector remains unchanged. According to Maharana et al. (2019), the outer channel shows the salinity ranges between 23 ppt–29 ppt and pH is in between 8.5-8.7. The pH level at the outer channel remained alkaline due to the presence of salt in the water which accumulates into the lagoon by influx of sea water. This alkaline pH may be the cause of high salinity in the water (Devi and Nagendran, 2017). As per the previous study, the highest temperature recorded at outer channel during summer was 31.1^{o}C and winter was 25 ^{o}C, while the DO level ranged between 6.5 mg /l to 8.5 mg/l. DO level of outer channel is low as compared to other sector of the lagoon due to sea water intrusion from the mouth (Maharana et al., 2019; Nayak et al., 2001). The lagoon experiences high levels of phosphate (0-0.4 ppm), nitrate (10-60 ppm), and silicates (1-8 ppm) due to sediment and nutrient discharge from the north and northwest (Panigrahi et al., 2009). Panigrahi et al. (2009) found that phytoplankton concentrations ranged from 1.95 to 5.75 mg m^{-3} during the post-monsoon, 2.55 to 7.58 mg m^{-3} during the monsoon, and 3.79 to 8.33 mg m^{-3} throughout the summer. The northern sector has greater values except in summer, while the central sector has higher concentrations throughout the summer. Nitrogen-to-phosphorous ratios in the lagoon indicate low primary generation by phytoplankton (Panigrahi et al., 2009). The organic matter percentage of sediment varies from 0.31% to 1.4% in May and 0.4% to 2.0% in December. Sand has low organic matter concentration, while sandy clay and clayey sand have high levels, particularly in December (Kumar et al., 2014).

1.4.4 **Sedimentation**

The lagoon considered as a shallow basin with the highest depth recorded 3.4 m in 1990 (Tripathy, 1995). Though average depth is reduced over time due to sedimentation of fine particles by fresh water influx from different catchments and rivers. Due to its geographical position, the lagoon is blessed by tropical monsoon and collects maximum precipitation of about 1200 mm during southwest monsoon in the months of July- September (Sahu et al., 2014). As a result, the water spread area of the lagoon is maximum throughout the rainy season. During monsoon, the depth of the water's body increases due to the high flow of fresh water and low flush through the mouth. Various studies suggest that the sedimentation rate varies in different sectors of the lagoon due to the inflow from various rivers and rivulets. About 1.5 million metric ton (million MT) sediment load is observed annually at the northern sector of the lagoon contributed by the river Mahanadi and its tributaries whereas, silt load carried by western catchments is 0.3 million MT per year

(Ghosh et al., 2006). High erosion of upstream and sedimentation lowers the depth of the lagoon and is also one of the reasons for blocking the mouth (opening of the lagoon to the sea). As a result the inlet mouth shifted towards the north (Chandramohan and Nayak, 1994). The longshore transport of sediments throughout the coast of Bay of Bengal is ~0.1 million MT year $^{-1}$ (Sarkar et al., 2012). According to Patnaik (1998), the annual sedimentation rate was 1.8 million MT but went up to 2.94 million MT within a span of 3 years (1998-2001) (Annon, 2003). Though the sector wise deposition rate varies. In the northern sector it is 7.6 mm/year whereas 8.0 mm/year is in the central sector and 2.8 mm/year in the southern sector. From the study, it is observed that the sedimentation rate is high in northern and central sector than the southern sector. However, the outer channel showed less amount of deposition due to its active nature and tidal exchange with Bay of Bengal (Sarkar et al., 2012). Barik et al. (2019) observed that lagoon sediments consist primarily of silt near the river mouth, sand near the sea mouth, and silt to sand with a minor quantity of clay in the interior of the lagoon. According to Barik et al. (2019), grain size distribution indicates high energy conditions near the sea outlet, low energy conditions near the river mouth, and medium energy conditions in the lagoon's middle. High rate of evaporation during summer (Mohanty et al. 1996) and large inflow of freshwater from various rivers and canals during the monsoon and post-monsoon seasons are the characteristics of this lagoon. This will also affect the salinity features of the lagoon as well.

1.4.5 **Environmental Status**

As discussed previously in this chapter, Chilika is influenced by several hydrological activities like (i) unregulated drainage from eroded catchment basins along the western and southern boundaries, (ii) silt enriched freshwater discharges from different watercourses of Mahanadi River and (iii) swapping of lagoon water with the adjacent sea water. South-western monsoon (July to October) plays a crucial role in changing the physical parameter of the lagoon. The freshwater flow from the riverine systems and seawater intrusion through tides makes an estuarine ecosystem of the lagoon. But now-a-days waste from agricultural land, aquaculture, and different domestic sources along the water-body increases the pollution load of the lagoon. The average contribution of waste load into the lagoon is about 536 m^3 S^{-1} and 850 m^3 S^{-1} from western catchments, along with the distributaries of Mahanadi (Patnaik, 2002). Furthermore, the prawn culture also contributes a major role in changing the sedimentation pattern and physical character of the lagoon. Use of split bamboo and very fine nets during aquaculture lowers free sediment flow. About 550 million litres per day sewages discharged into the water-body from the villages in and around Chilika. Previous studies reported that this waste water carries roughly 275 mg/l of suspended solid, which is much higher than that of permissible limit (20mg/l) set by Orissa State Pollution Control Board (Panigrahi et al.,2009). Heavy siltation, decrease in salinity and high pollution load helps to grow weeds rapidly and turns the lagoon in to a eutrophic one. The lagoon, in turn, faced severe problems like heavy siltation, which decreases depth and lowers the water mass, drop in salinity, algal blooms, eutrophication and biodiversity loss. The salinity of the lagoon drops due to poor water circulation and weak tidal influences. These changes in the lagoonal environment gave a threat to the local and national governments.

1.5 Organisation Of The Thesis

The present thesis consisting of five chapters. The first chapter gives a general introduction to the research work, background of this study, objectives of the research work and geological settings of Chilika lagoon. Chapter 2 consists of a detailed methodology for both the foraminiferal analysis and mineral magnetic analysis. Chapter 3 provides a documentation of benthic foraminifera (living and total), its seasonal distribution pattern, taxonomy, diversity and richness. Chapter 4 presents the mineral magnetic characteristic of soft sediments. The final chapter, i.e., chapter 5 discuss the suitability of foraminiferal analysis and measurement of magnetic features of soft sediments for determining the present environmental condition of the lagoon.

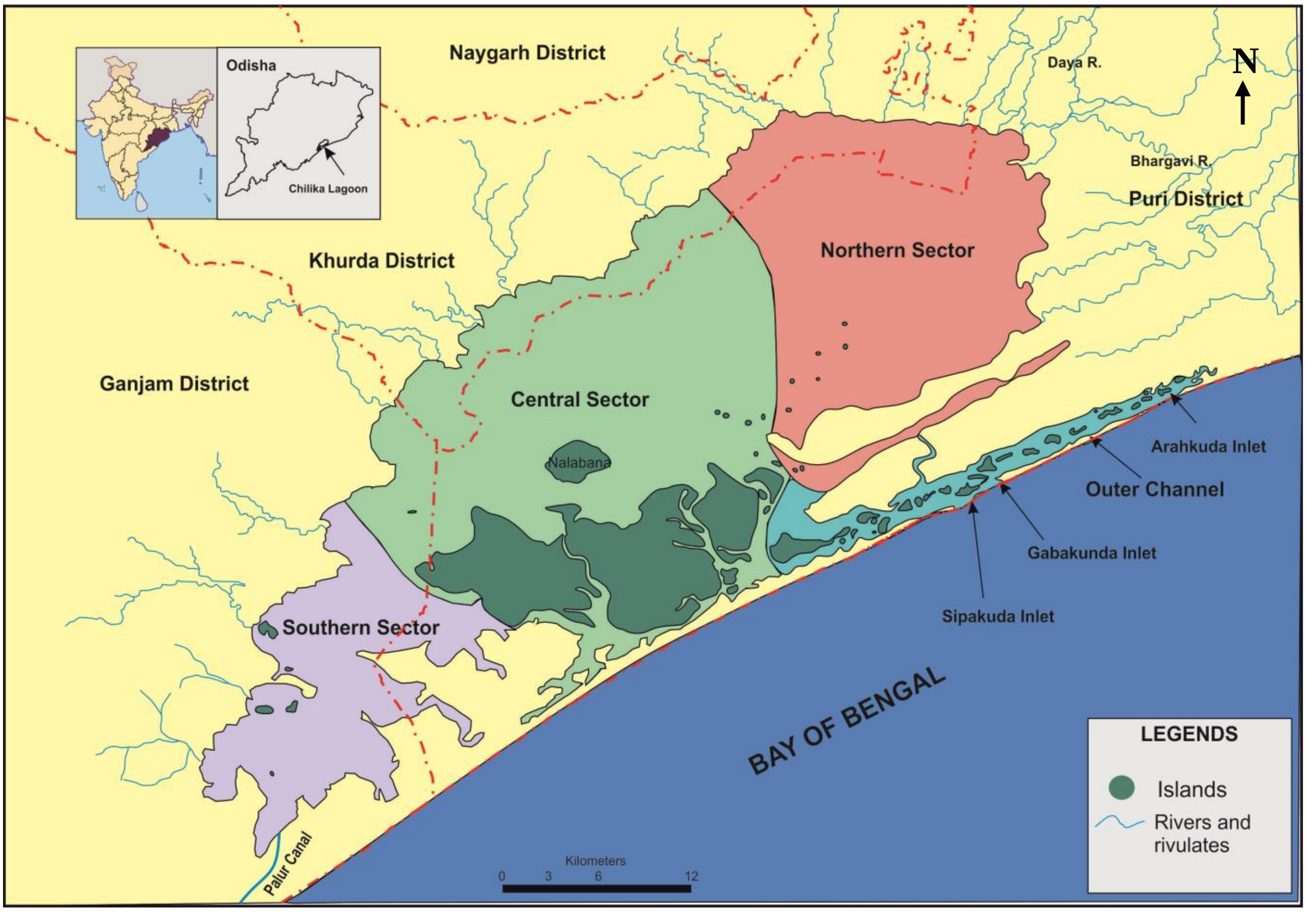

Fig. 1.1 The Chilika lagoon Basin with four sectors.

2.1 FORAMINIFERAL ANALYSIS

2.1.1 **Sample Collection**

Fifty-six stations were selected for sampling, starting from the sea mouth of the outer channel to the central sector of the lagoon (19° 39′–19° 44′ N; 85° 21′–85° 32′ E), by using a portable GPS system (Fig 2.1). The sample was collected from each station of an outer channel during October (2017) representing post-monsoon season and March (2018) representing pre-monsoon period and from the central sector of the lagoon during April (2019) and October (2019) respectively. The undisturbed top (0-1cm) of the lake sediment was scooped by using a trowel and stored in a 250 ml plastic container. Samples were mainly collected from water depths varying from 20 cm to 132 cm (Table 1 and Table 2). Immediately after sampling buffered Rose Bengal Solution (2 grams of Rose Bengal powder in 1 litre ethanol) was added to the sediments as a stain and a preservative. The solution stains the organic part of the protist. Use of the solution first applied by Walton in 1952. Several physiochemical parameters of the water like dissolved oxygen, temperature, pH, salinity as well as depth of the water column were measured at the time of sampling by using a portable multi parameter system (Fig 2.6). Those sampling containers were then correctly labelled and bought to the laboratory for further processing.

2.1.2 **Processing of the sample**

These sampling containers were then kept at room temperature for a few days for proper staining of living mass. 3 weeks later sample was washed with clean water to remove mud-sized sediments and sieved through the 63µm mesh. The wet sediment was completely dehydrated in an oven at 50 ˚C and transferred into a container for sorting and identification was done under stereo zoom microscope. The sand concentration of each sample was calculated from the resultant of the weight of dried unprocessed sediment and the weight of the dried residue left in >63 µm sieve after processing.

2.1.3 **Sorting and Identification**

5 grams of dried sample (outer channel) and 1 gram of dried (central sector) sample were observed with the help of a stereo zoom microscope (model. Nikon SMZ-1000) in the Micropaleontology laboratory at the Department of Geological Sciences, Jadavpur University. Using a spatula, a small portion of these weighed sediments was sprinkled on a gridded black tray for examination under the microscope. The foraminifera with the complete test (excluding broken or reworked

specimens) were then picked by using a fine brush ('000') onto a micropaleontological slide (Fig 2.7). These steps were repeated until all the foraminiferal tests was picked. The living specimen was identified by their bright pink colour. For illustration, the images of the best-preserved species were captured with the help of Carl Zeiss EVO-18 Scanning Electron Microscope at Jadavpur University, India. The genus of observed foraminifera were primarily identified based on the works of Loeblich and Tappan (1974), and for species level identification follows the works of Loeblich and Tappan (1988), Jorissen (1988), Holzmann and Pawlowski (2000), Rao & Srinath, (2002), Kumar et al. (2014), Ghosh et al. (2014), Sen et al. (2018), Barbieri and Vaiani (2018) and Dasgupta and Ghosh (2021). All processed samples are kept in the Micropaleontology Laboratory, Department of Geological Sciences, Jadavpur University.

2.1.4 **Physical Parameters**

Several physiochemical parameters of the water like dissolved oxygen, temperature, pH and salinity of the water were measured at the time of sampling by using a portable multi parameter system (Fig 2.6). The depth of the water column was measured by using a measuring tape (Fig 2.5).

2.1.5 **Statistical Analysis**

By using multivariate statistical analysis, the sorted foraminifera from the study provided insights into the environments during sedimentation. The total foraminiferal number (TFN), including both living and dead forms, has been used for all the analysis. Ternary diagrams were applied to highlight different assemblages into the lagoonal habitat by plotting the percentage of three shell types (porcelaneous, hyaline and agglutinated) present in each sample (Murray 1973, 1991). To find out diversity, it was required to calculate the species richness for each sample and demonstrated it by the Fisher's α index (Fisher et al.1943, Murray 1973). Total foraminiferal number was plotted against the number of species present in study area by using PAST software, which made a comparison in between the foraminiferal diversity (species richness) with their habitat.

The distribution pattern of foraminifera, along with their relative abundance, was calculated by using Pielou's species evenness index and Simpson dominance index. Pielou's species evenness was calculated on the basis of the Shannon-Weiner diversity index. $E= e^{H} /S$, where E, species evenness index; e denotes as the natural log; H is the Shannon-Weiner diversity index; and S is the number of species present in the sediment. Although dominance index was calculated by the ratio of the number of species with the total number of individual present in each sample. Both the indexes were evaluated with the help of PAST Software.

By using Jaccard similarity index, we perform Q-mode clustering technique along with the period group algorithm in order to find the structure in the foraminiferal data set. Detection of structural entities within complex data sets with the help of large-scale analytical procedure is known as cluster analysis. It involves pattern discovery and data mining. The data was entered into PAST software and analysed (Hammer et al., 2001) for the cluster analysis. By this technique, similar foraminiferal assemblages were grouped together and construct a hierarchical dendrogram based on their environmental condition. To group foraminiferal assemblages of similar palaeoecological relevance, unweighted pair group R-mode cluster analysis with arithmetic mean algorithm (UPGMA) was performed on the surface samples from Chilika lagoon. The Bray-Curtis distance method was used for this analysis. Only the corresponding abundances of taxa and the composition of the assemblage are taken into account by this method (Field et al., 1982; Barbieri & Vaiani, 2018).

Location Name	Water Depth (cm)	GPS reading	Location Name	Water Depth (cm)	GPS reading	Location Name	Water Depth (cm)	GPS reading
L1	20	N 19˚41' 40" E 85˚32' 06"	L16	45	N 19˚39' 26" E 85˚29' 59"	L31	43	N 19˚39' 23" E 85˚27' 49"
L2	60	N 19˚40' 25" E 85˚31' 48"	L17	22	N 19˚40.242' E 85˚30.086'	L32	44	N 19˚39' 32" E 85˚27' 08"
L3	65	N 19˚40' 27" E 85˚32' 05"	L18	20	N 19˚39' 40" E 85˚29' 41"	L33	44	N 19˚39' 32" E 85˚27' 08"
L4	60	N 19˚40' 21" E 85˚31' 38"	L19	50	N 19˚39' 14" E 85˚28' 30"	L34	52	N 19˚39' 19" E 85˚27' 28"
L5	70	N 19˚41' 07" E 85˚31' 31"	L20	45	N 19˚39' 01" E 85˚28' 58"	L35	50	N 19˚39' 19" E 85˚27' 28"
L6	60	N 19˚40' 12" E 85˚28' 50"	L21	40	N 19˚39' 01" E 85˚28' 58"	L36	50	N 19˚39' 26" E 85˚28' 21"
L7	60	N 19˚40' 03" E 85˚30' 56"	L22	50	N 19˚39' 01" E 85˚28' 58"	L37	20	N 19˚39' 13" E 85˚25' 57"
L8	70	N 19˚39' 705" E 85˚31' 061"	L23	20	N 19˚39' 41" E 85˚29' 33"	L38	30	N 19˚39' 53" E 85˚26' 33"
L9	80	N 19˚40' 03" E 85˚30' 56"	L24	22	N 19˚39' 40" E 85˚29' 25"	L39	56	N 19˚39.952' E 85˚29.100'
L10	90	N 19˚39' 638" E 85˚30' 774"	L25	25	N 19˚39' 36" E 85˚29' 24"	L40	30	N 19˚40' 05" E 85˚28' 28"
L11	60	N 19˚40' 12" E 85˚28' 50"	L26	45	N 19˚39' 09" E 85˚26' 03"	L41	20	N 19˚39' 41" E 85˚22' 23"
L12	75	N 19˚39' 56" E 85˚30' 42"	L27	47	N 19˚39' 00" E 85˚26' 35"	L42	43	N 19˚36' 35" E 85˚17' 41"
L13	30	N 19˚39' 36" E 85˚30' 24"	L28	40	N 19˚39' 00" E 85˚27' 01"	L43	43	N 19˚36' 13" E 85˚18' 57"
L14	50	N 19˚39' 46" E 85˚30' 16"	L29	50	N 19˚39' 08" E 85˚27' 17"	L44	39	N 19˚36' 04" E 85˚18' 55"
L15	50	N 19˚39' 40" E 85˚29' 54"	L30	55	N 19˚39' 19" E 85˚27' 29"	L45	20	N 19˚38' 48" E 85˚24' 23"

Table 1 Water depth of the sample with GPS location across the outer channel of the lagoon.

Location Name	Water depth (cm)	GPS reading
L1	119	N 19˚45' 32" E 85˚25' 50"
L2	131	N 19˚44' 39" E 85˚26' 23"
L3	121	N 19˚44' 17" E 85˚26' 9"
L4	131	N 19˚44' 7" E 85˚25' 53"
L5	132	N 19˚44' 01" E 85˚25' 37"
L6	131	N 19˚43' 32" E 85˚25' 31"
L7	60	N 19˚41' 32" E 85˚25' 28"
L8	70	N 19˚43' 03" E 85˚23' 15"
L9	80	N 19˚43' 14" E 85˚23' 15"
L10	90	N 19˚42' 49" E 85˚22' 28"
L11	60	N 19˚42' 01" E 85˚21' 55"

Table 2 Water depth of the sample with GPS location across the central sector of the lagoon.

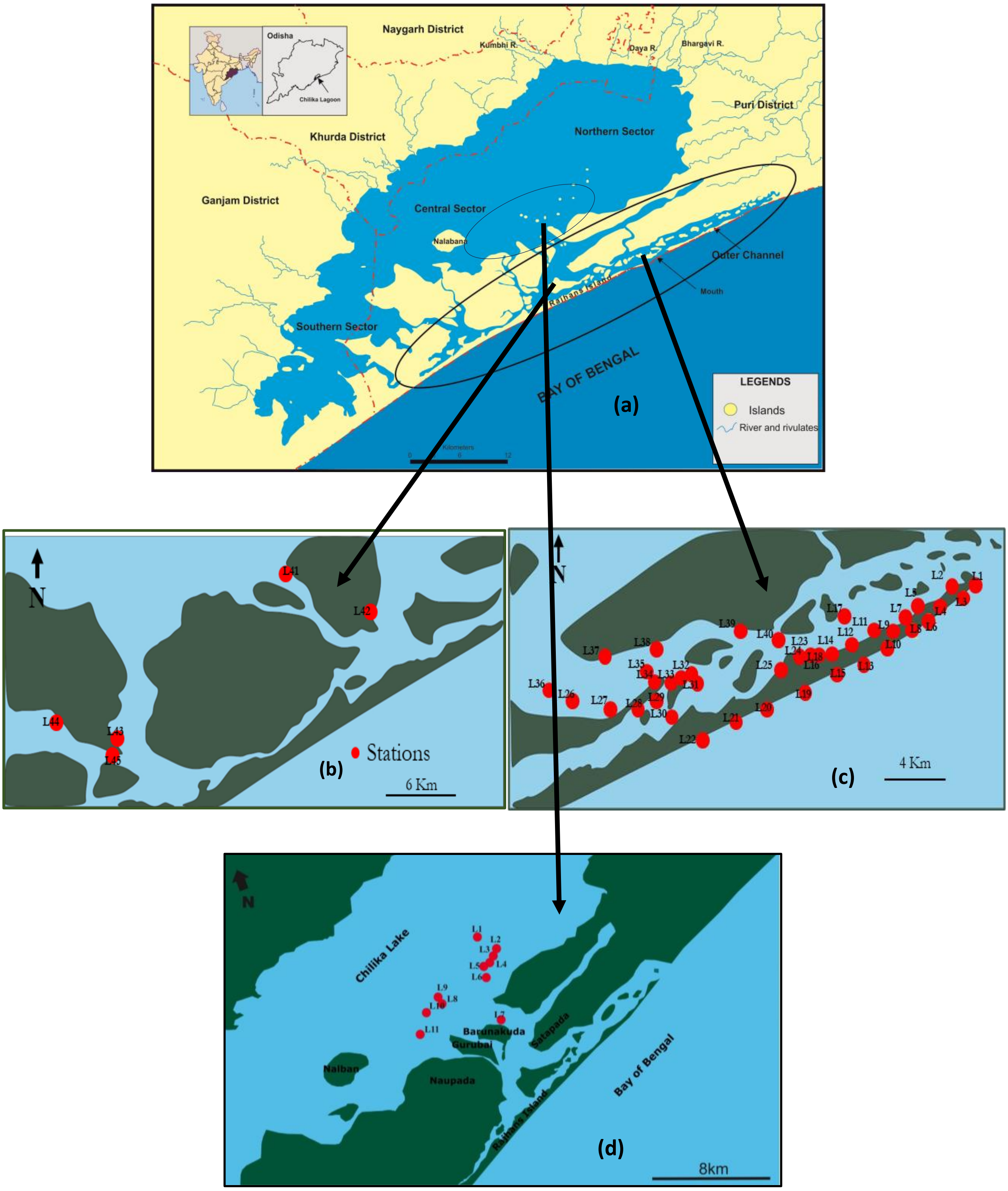

Fig. 2.1 Location map of Chilika Lagoon (a), zoomed view of sampling stations in southern part of outer channel (b), zoomed view of sampling stations in northen part of outer channel (c), and zoomed view of sampling stations in central sector of the lagoon (d).

Fig. 2.2 Sample collection in the outer channel, Chilika Lagoon.

Fig. 2.3 Sample collection in the central sector, Chilika Lagoon.

Fig. 2.4 Mode of transport in sample collection.

Fig. 2.5 Water depth documentation at every sample station.

Fig. 2.6 Measurement of physical parameters, using Portable multi parameter system.

Fig. 2.7 Micropaleontological accessories used in sorting of foraminifera.

2.2 Mineral Magnetic Analysis

2.2.1 **Sample Collection**

Samples were collected from the upper few centimetres of bottom sediments at 54 locations from the outer channel of Chilika Lagoon (Fig. 2.7), using clean and washed PVC spatula and transported to the laboratory in a zip locked plastic pouch to avoid contamination.

2.2.2 **Sample Processing**

Sediment samples were then air dried in the laboratory for few days to avoid moisture content and any chemical reactions. The dried sediments then sieved through normal nylon sieve to get a fine homogenous sample. For magnetic measurements, these sieved samples were again grounded with the help of an agate mortar and screened through a 3 mm sieve mesh. This powdered sample was then stored into a zip-lock plastic pouch for further measurements.

2.2.3 **Magnetic Susceptibility Measurement**

Magnetic susceptibility of a material is about the measurements of its magnetizability against a small magnetic field. If the applied magnetic field is removed, the magnetisation of the material reverts to its initial state. Mathematically, it has been said that volume magnetic susceptibility (κ) is actually the ratio of induced magnetisation of measured sample (M) with the intensity of applied magnetic field (H). As M and H have the same unit, κ is a dimensionless number. When bulk density (ρ) of the material is known, then magnetic susceptibility can also be evaluated in terms of sample mass. The bulk density (ρ) of a sample can be calculated by dividing its mass by volume. To get more accurate magnetic composition, mass specific susceptibility values are more reliable. In our study, we used the Bartington Susceptibility Meter to measure these values of sediment samples. Generally, laboratory sensor MS2B of this meter is used to measure the magnetic susceptibility of soil, rock and sediment samples. This sensor has the ability to make the measurements at two different frequencies. For analysis of our collected soft sediments, the dried powdered sample was put into six identical cylindrical boxes which were perfectly fitted into the adapter of the meter. All six boxes, with known volume content, were weighted with the help of an analytical balance (KERRO BL5002E; Fig. 2.8) before and after filling with sample. Then, the volume susceptibility (κ) values of all the boxes were measured in a weak magnetic field (0.1 mT) at 0.46 kHz (low frequency, lf) and 4.6 kHz (high frequency, hf) on a Bartington MS2B single sample dual frequency sensor with a resolution of 10^{-6} SI units (Fig. 2.9) in the Geophysical Laboratory at the Department of Geological Sciences, Jadavpur

University. From this κ value, mass specific susceptibility value (χ) was calculated and an average χ values of the sample from each station were figured out.

2.2.4 **Mineral Magnetic Parameters**

Different magnetic mineral parameters such as Isothermal Remanent Magnetization (IRM) curves, Thermomagnetic curve, and Hysteresis Loops were established by using the Advanced Variable Field Translation Balance (AVFTB) at the Palaeomagnetism Laboratory, CSIR-National Geophysical Research Institute (NGRI), Hyderabad (Fig. 2.10). Around 300-500 mg of dried powdered samples from each location were used for these measurements. A ‘zero’ magnetic quartz glass container with a sample along with quartz wool was used into the AVFTB instrument. IRM and back field demagnetization curves were evaluated to find out the saturation field in terms of coercivity. Isothermal Remanent Magnetization (IRM) curves were obtained in a 10000 Oe steady induced field. Thermomagnetic studies can help to identify the Curie temperature and thermal changes in magnetic minerals throughout heating and cooling cycle. On the other hand, hysteresis loops were obtained by applying magnetic fields until their saturation point. Different hysteresis parameters like the saturation remanence (Mrs), the saturation magnetization (Ms), coercive force (Hc), and the coercivity of remanence (Hcr) were evaluated by plotting them into Day diagram (Day et al. 1977) for identifying grain size and domain state of different magnetic minerals.

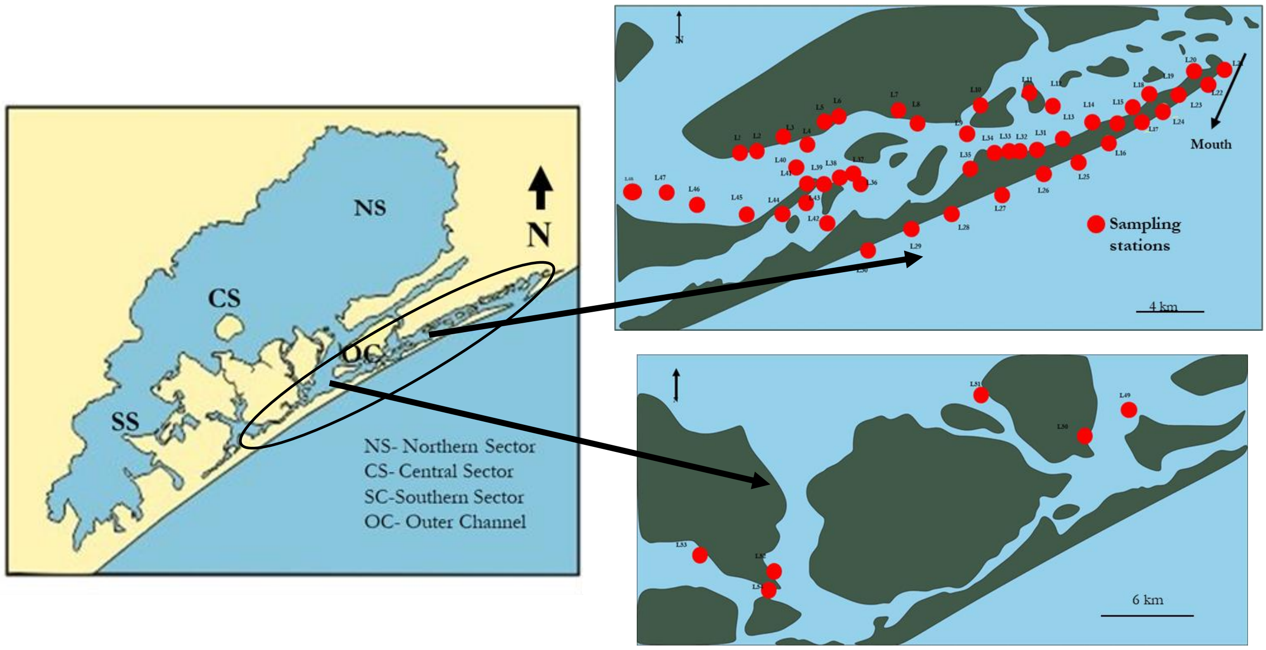

Fig. 2.7 Map of Chilika lagoon showing locations of 54 sampling sites.

Fig. 2.8 Bartington Susceptibility Meter (MS-2).

Fig. 2.9 KERRO BL5002E Weighing Machine.

Fig. 2.10 Advanced Variable Field Translation Balance (AVFTB) Instrument.

3.1 INTRODUCTION

Chilika, Asia's largest lagoon, is situated on the north-east coast of the India. Based on its wealth of diversity and significant socio-economic condition, Chilika was labelled as the Ramsar site by Government of India in 1981. Like all other coastal ecosystem, Chilika is threatened too by increasing anthropogenic disturbances. In 2011, it was found that approximately 300 square kilometres of the lagoon was covered with weeds (Sahu et al., 2014) which became a major threat to health of the lake. Study of benthic indicator, like foraminifera, will help to evaluate the lagoon's health since it provides information about various environmental condition such as fluctuations of salinity, dissolved oxygen concentration, variation in pH along with the effect of both natural and anthropogenic effects. Sector wise detailed information about foraminiferal diversity of the Chilika lake (there are four ecological sectors in the lake) is very little. The information about the presence of foraminifera in the lagoon had been recorded earlier by Rajan (1965), Patnaik (1971) and Sarma and Rao (1980). Rao in 1987 identified 7 species of these microorganisms from this shallow water-body. Later in the year 2000, Rao et al., recorded a total of 69 species of this fauna from the collected sediments samples of the lagoon. The outer channel of the lagoon recorded a high number of species and genera of foraminifera. Though arenaceous forms of the microorganism were low in this sector of the lake. These types of forms are increases within the lagoon, especially in the central sector, but in the northern sector the number is less (Rao et al., 2000). During months of rain the faunal species were poor than the dry season which is due to the fact that marine organism can easily tolerate low salinity at high temperature and the source of food is more there than the near shore (Jayalakshmy and Rao, 2001). A multivariate statistical study of foraminifera from the lagoon was recorded by Jayalakshmy and Rao in the year of 2003. Few years from this study, fifteen agglutinated species of foraminifera were identified from the Chilika lagoon by Kumar et al. (2014). Sen and Bhadury in 2016 worked on the seasonal variation of living benthic foraminiferal assemblages to understand its dynamics in a stressed condition of lake. Sen et al. (2018) also documented benthic foraminiferal diversity from the marginal environment of the lagoon whereas, the study of Rao et al. (2000) covers marine influenced part of the water body. Workers such as Mishra et al. (2019) stated that the Chilika lagoon has a low diverse foraminiferal assemblage and dominance of *Ammonia* sp. and agglutinated forms. The effect of low saline brackish water conditions due to the restricted inflow of seawater in the lagoon supports the dominance of *Ammonia* sp. (Barik et al., 2020). The total organic carbon, salinity and water depth are controlling factors for agglutinated forms (De & Gupta, 2010). Dasgupta and Ghosh (2021) identified four different *Ammonia* spp. and two morphotypes of *Ammonia* spp. It is also observed from the literature survey that several studies on water quality, ecology, metal pollution, salinity structure and geochemical parameters of sediment of Chilika lagoon have been performed before and after the artificial opening (Panda et al., 1995, 2006; Nayak and Behera, 2004; Panigrahi et al., 2007, 2009).

This current study reports the seasonal distribution of foraminifera and its diversity from 45 sediment samples in the outer channel and 11 sediment samples in the central sector of the lagoon.

3.2 MICROFOSSIL ASSEMBLAGES

The samples were collected during March - April (pre-monsoon) and October (post-monsoon). During the study, a total of thirty-four species of benthic foraminifera are documented, of which 18 are hyaline, 14 are agglutinated, and 2 are the porcelaneous test (Plate I, II & III). *Ammonia* spp. (*Ammonia beccarii, Ammonia parkinsoniana, Ammonia tepida, Ammonia sobrina*) is the most dominant taxa among all. The other hyaline forms are *Pararotalia nipponica, Elphidium advenum, Elphidium hispidulum, Elphidium williamsoni, Elphidium excavatum, Haynesina germanica, Haynesina depressula, Hanzawaia sp., Elphidium* sp.*, Nonion sp., Nonionellina labradorica, Heterolepa* sp*, Cocoarota* sp. *Rotalidium annctens. Miliammina fusca, Ammobaculites exigus, Textularia earlandi, Textularia agglutinans, Textularia* sp.*, Ammobaculites agglutinans, Ammotium salsum, Milliammina obliqua, Trochamina inflata, Entzia* sp.*, Haplophragmoides* sp.*, Trochammina advena, Milliammina* sp.*, Ammotium fragile* are agglutinated forms and *Quinqueloculina seminulum, Quinqueloculina* sp. are two observed porcelaneous taxa.

3.3 SYSTEMATICS

The species identified from the Chilika lagoon has been described as follows:

Superfamily RZEHAKINACEA Cushman, 1933

Family Rzehakinidae Cushman, 1933

Genus *Miliammina* Heron-Allen and Earland, 1930

Miliammina fusca

(Plate I, fig.7)

Quinqueloculina fusca Brady, 1870, p. 286, pl. 11, figs. 2–3.

Miliammina fusca (Brady) Phleger and Walton 1950, p. 280, pl. 1, figs. 19a–b.

Miliammina fusca (Brady) Scott and Medioli 1980a, p. 40–41, pl. 2, figs. 1–3

Distribution: *Miliammina fusca* is quite common in all hyposaline marshes environment (Murray, 1971). In the previous study, this species is found in the outer channel of the lagoon at temp 4˚ to 28˚C and (Kumar et al., 2014).

Miliammina obliqua

(Plate I, fig.8)

Miliammina obliqua - Heron-Allen & Earland,1930, p. 42, pl. 1, figs 7, 12.
Miliammina cf. obliqua Heron-Allen & Earland, 1994, p. 210, pl. 3, figs 9-10.
Miliammina obliqua Heron-Allen & Earland - Hayward et al. 1999, p. 82, pl. 1, figs 7-8

Distribution: They mostly found in estuaries, marshes, coastal lagoons. These species are found in the outer channel of the lagoon and can tolerate salinity in between 1 to 35 (De & Gupta, 2010).

Miliammina sp

(Plate I, fig. 9)

Remarks: In the present study, this species of *Miliammina* also recorded from the high saline and temperate condition of the lagoon and it was found in limited at the outer channel as well as central sector of the lagoon.

Superfamily LITUOLOIDEA de Blainville, 1827

Family Lituolidae de Blainville, 1827

Subfamily Ammomarginulininae Podobina,1978

Genus *Ammobaculites* Cushman, 1910

Ammobaculites agglutinans (d'Orbigny, 1846)

(Plate I, fig. 1)

Spirolina agglutinans d'Orbigny 1846, p. 137, pl. 7, figs. 10-12.
Ammobaculites agglutinans (d'Orbigny) Panchang and Nigam 2014, pl. 1, figs. 21-24.

Distribution: *Ammobaculites agglutinans* preferred to live in a clayey sediment with an organic rich environment (Setty & Nigam, 1982). The species was reported at relatively high temperature and salinity at the outer channel of Chilika lagoon (Kumar et al., 2014)

Ammobaculites exiguus Cushman & Brönnimann, 1948

(Plate I, fig. 2)

Ammobaculites exiguus Cushman & Brönnimann 1948, p. 38, pl. 7, figs. 7-8.

Ammobaculites exiguus (Cushman & Brönnimann) Debenay 2012, p. 74.

Distribution: *Ammobaculites exiguus*, infaunal form lives in brackish marshes and lagoons, can tolerate salinity from 0 to 25 ppt and temperature 0–27˚C (Ellison & Murray, 1987). This is one of the most abundant taxa observed in the lagoon tolerating higher salinity and temperature (Kumar et al., 2014).

Family: Lituolidae de Blainville, 1827

Subfamily: Ammomarginulininae Podobina, 1978

Genus: *Ammotium* Loeblich and Tappan, 1953

Ammotium fragile Warren 1957

(Plate I, fig. 3)

Ammotium fragile Warren 1957, p.32, pl. 3, figs. 14,15.

Ammotium fragile (Warren) Hayward and Hollis 1994, pl 2, figs. 1-3

Distribution: This species is one of the common agglutinated species of Chilika lagoon, which can withstand higher salinity and temperature (Kumar et al., 2014; Rao et al., 2000).

Ammotium salsum Cushman & Bronnimann, 1948a

(Plate I, fig.4)

Ammobaculites salsus Cushman & Bronnimann, 1948a, p.16, pl. 3, figs. 7-9.

Ammobaculites salsum (Cushman & Bronnimann, 1948a) Rao & Rao 1974, pl.1, fig. 6.

Distribution: This infaunal foraminifera is common in marshes, intertidal mudflats and brackish lagoons (Phleger, 1967) and can tolerate salinities up to 60ppt (Debenay and Page`s, 1987). Presence of this species also noticed in the lagoon in the present day (Sen & Bhadury,2016).

Family Haplophragmoididae Maync, 1952

Genus Haplophragmoides Cushman, 1910

Haplophragmoides sp

(Plate I, fig.6)

Remarks: In the present study, *Haplophragmoides* sp are generally found in temperate and high saline muddy substrate with low oxygenic conditions of the lagoon.

Superfamily TEXTULARIACEA Ehrenberg, 1838

Family Textulariidae Ehrenberg, 1838

Genus Textularia De france, 1824

Textularia agglutinans d‘ Orbigny, 1839

(Plate I, fig.14)

Textularia agglutinans d‘ Orbigny, 1839, p. 144, pl. 1, figs. 17-18, 32-34.

Textularia agglutinans (d‘ Orbigny) Fiorini & Vaiani 2001, p. 369, pl. 1, figs. 1-4.

Distribution: *Texularia agglutinans* can tolerate relatively low oxygenic conditions at sea bottom (Bernhard et al., 1997; Fiorni and Vaiani, 2001) and dominated nearshore vegetated environments (Murray & Alve 2000, Horton et al., 2003, 2005). From the recent studies it is also recorded from the inner part of Chilika lagoon (Jayalakshmy & Rao, 2001; Sen & Bhadury, 2016).

Textularia earlandi Parker 1952

(Plate I, fig.15)

Textularia earlandi Parker 1952b, p. 458.

Textularia earlandi (Parker) Murray 1971b, p. 33, pl. 9, figs 1-5

Distribution: It is a shallow infaunal species who can tolerate dysoxia (Bernhard et al., 1997). The live assemblage of this species also found in the outer channel of Chilika lagoon in a sandy to silty sandy sediment and sometimes in clayey sand, relatively in higher salinity and low organic matter (Kumar et al., 2014).

Textularia sp

(Plate I, fig.16)

Remarks: In the present study, this species of *Textularia* also recorded from high saline and low oxygenic condition of the lagoon and it was found in limited at the outer channel.

Superfamily: TROCHAMMINACEA Schwager,1877

Family: Trochamminidae Schwager, 1877

Subfamily: Trochammininae Schwager, 1877

Genus: Trochammina Parker and Jones, 1859

Trochammina advena Cushman, 1922

(Plate I, figs. 10,11)

Trochammina advena Cushman, 1922, pl. 1, figs. 2-4

Distribution: The presence of this agglutinated species is only noticed in the outer channel of the Chilika lagoon, and its presence is limited to the outer channel (Rao et al., 2000).

Trochammina inflata

(Plate I, figs. 12,13)

Nautilus inflatus Montagu, 1808, p. 81, pl. 18, Fig. 3.4.

Trochammina inflata (Montagu), De Rijk, 1995a, p. 31, pl. 2, figs. 1–3.

Distribution: This species is observed from a brackish environment worldwide. It is also one of the identified agglutinated species of Chilika lagoon (Sen & Bhadury, 2016)

Subfamily: Jadammininae Saidova, 1981

Genus: Entzia Daday, 1883

Entzia macrescens (Brady, 1870) - p. 84

(Plate I, fig.5)

Trochammina inflata (Montagu) var. *macrescens* - Brady, 1870, p. 290; pl. 11, fig. 5.

Trochammina macrescens Brady - Scott & Medioli, 1980, p. 44; pl. 3, figs 1-12.
Jadammina macrescens (Brady) - Hayward et al., 1999, p. 83; pl. 1, figs 27-29.
Jadammina macrescens (Brady) - Debenay & Luan; 2006, pl. 1, figs 30, 31.

Distribution: This species is mostly found in high marsh areas. This agglutinated species is also observed in the Chilika Lagoon (Rao et al., 2000).

Superfamily ROTALIACEA Ehrenberg, 1839

Family Rotaliidae Ehrenberg, 1839

Subfamily Ammoniinae Saidova, 1981

Genus *Ammonia* Brünnich, 1772

Ammonia sobrina Shupack, 1934

(Plate II, figs. 7,8)

Rotalia beccarii (Linn6) var. *parkinsoniana* Cole 1931, p. 49, pl. III, figs. 5, 6.
Ammonia sobrina (Shupack) *Rotalia beccarii* (Linné) var. *sobrina* Shupack, 1934, p.8, figs. 4 a, b, c *Ammonia sobrina* (Shupack) Setty & Nigam 1984, pl. 32, figs. 9-10.

Distribution: *Ammonia* is the most dominant genus within the living foraminiferal assemblage at Chilika. This species is mainly confined to the inner part of the lagoon, but their presence is also notified from the outer channel (Rao et al., 2000).

Ammonia parkinsoniana (d'Orbigny, 1839)

(Plate II, figs. 3,4)

Rosalina parkinsoniana d'Orbigny 1839, p. 99, pl. 4, figs. 25–27.
Ammonia parkinsoniana var. *parkinsoniana* morphotype 5 (d'Orbigny) Jorissen 1988, p. 46, pl. 9, figs. 1–2.
Ammonia parkinsoniana (d'Orbigny) Fiorini and Vaiani 2001, p. 384, pl. 6, figs. 14–15.

Distribution: *Ammonia* is widespread in marginal marine environments worldwide. Dominancy of *Ammonia* is observed in several lagoonal environments worldwide such as Venice lagoon, Italy (Donnici et al. 1997), Ria de Aveiro lagoon, Portugal (Martins et al. 2013), Araruama lagoon, Brazil (Debenay et al. 2001). *A. parkinsoniana* is dominated in the outer channel of Chilika lagoon (Rao et al., 2000).

Ammonia tepida (Cushman, 1926)

(Plate II, figs 5,6)

Rotalia beccarii (Linné) var. *tepida* Cushman 1926, p. 79, pl. 1.

Ammonia beccarii tepida (Cushman); Jorissen 1987, p. 38, pl. 2, fig. 8.

Ammonia parkinsoniana (d'Orbigny) var. *tepida* Cushman, morphotypes 1, 2, 3; Jorissen 1988, p. 46, pl. 7, figs. 1–4, pl. 10, fig. 1.

Ammonia tepida (Cushman); Fiorini and Vaiani 2001, p. 384, pl. 6, figs. 7–8.

Distribution: This species is mostly recorded in estuaries, lagoons, and deltaic environments (Debenay et al., 2000; Murray, 2006). *A. tepida* is one of the most abundant species in the lagoon (Jayalakshmy & Rao, 2001).

Ammonia beccarii (Linné, 1758)

(Plate II, figs 1,2)

Nautilus beccarii Linné, 1758, p. 710.

Ammonia beccarii (Linné), Mouanga, 2017, pl. 16, figs. 1a–c

Ammonia beccarii forma beccarii (Linné), Jorissen 1988, pl. 5, figs. 1–4

Ammonia beccarii (Linnaeus), Cimerman and Langer, 1991, p. 76, pl. 87, figs. 3–4

Ammonia papillosa (d'Orbigny), Morigi et al., 2005, pl. 1, figs. 4a–b.

Ammonia beccarii, Serandrei Barbero et al., 2008, pl. 33.

Ammonia beccarii (Linné 1758), Hayward et al., 2021, 153–154, pl. 17, figs. 7–12; pl. 18, figs7–12; pl. 19, figs. 5–10; text-fig. 31.

Distribution: *Ammonia beccarii* is observed in low salinity and high sandy sediment (Maria et al., 2019). *Ammonia beccarii* is also reported in brackish water of Lake Varano, a Mediterranean lagoon in Italy (Frontalini et al.,2014). This species is most abundant and widely distributed in the outer channel of Chilika lagoon (Rao et al., 2000).

Genus *Rotalidium* Asano, 1936

Rotalidium annectens Parker and Jones, 1865

(Plate III, figs. 8,9)

Rotalia beccarii (Linnaeus) var. annectens Parker and Jones, 1865, pp. 387, 422, pl.19, fig.11a-c.

Rotalidium annectens (Parker and Jones); Panchang, 2008, p. 246, pl. 37, figs. 4a-c, 5a-c.

Remarks: This species of *Rotalidium* reported from the western Bay of Bengal (S.M. Saalim et al., 2022). In our study, it is found in the sediments of Chilka lagoon.

Subfamily Pararotaliinae Reiss, 1963

Genus Pararotalia Le Calvez, 1949

Pararotalia nipponica TAsano, 1936

(Plate III, fig. 6)

Rotalia nipponica - Asano, 1936, p. 614; pl. 31, figs 2a-c.

Rotalia nipponica Asano - Asano, 1951c, p. 15, text figs 112-114.

Pararotalia nipponica (Asano) - Haig, 1997, p. 278; fig. 7, nos 19, 20.

Pararotalia nipponica (Asano) - Parker, 2009, p. 682; figs 480a-f, 481a-i

Distribution: *Pararotalia nipponica* can sustain extensive saline conditions (Nigam et al., 2006). This species was found abundantly at the outer channel of the Chilika lagoon (Anil kumar et al., 2013). In the study, it is also recorded from some places of the central sector of the lagoon.

Family Elphidiidae Galloway, 1933

Subfamily Elphidiinae Galloway, 1933

Genus Elphidium Montfort, 1808

Elpidium hispidulum Cushman, 1936

(Plate II, fig 10)

Elphidium hispidulum Cushman, 1936, p.83, pl.14, figs 13 a-b.

Elphidium hispidulum Narayan & Pandolfi 2010, pl. 1, figs. 21,22.

Remarks: *Elphidium hispidulum* and *Cribroelphidium hispidulum* both show similar morphological characters.

Distribution: This species reported in the sandy mud environment (Narayan & Pandolfi, 2010). It is also observed in the sediment of the Chilika lagoon (Jayalakshmy & Rao, 2001).

Elphidium advenum (Cushman, 1922)

(Plate II, fig. 11)

Polystomella advena Cushman 1922: p. 56, pl. 9, figs. 11, 12.

Elphidium advenum (Cushman); Cushman 1930, p. 25, pl. 10, figs. 1–2.

Elphidium advenum (Cushman); Fiorini & Vaiani 2001, p. 388, pl. 7, figs. 10, 12–13.

Distribution: *Elphidium advenum* is commonly recorded in the Adriatic Sea, and it is considered tolerant to low salinity (Jorissen, 1988). It is also found in the sandy substrate of Chilika lagoon (Jayalakshmy & Rao, 2001).

Elphidium williamsoni Haynes, 1973

(Plate II, fig. 12)

Elphidium williamsoni - Haynes, 1973, p. 207, pl. 24, fig. 7; pl. 25, figs 6, 9; pl. 27, figs 1-3.

Elphidium williamsoni Haynes - Hottinger et al., 1993, p. 150; pl. 215, figs 1-5.

Elphidium excavatum williamsoni Haynes - Hayward et al., 1997, p. 78; pl. 10, figs 1-8.

Elphidium cf. *E. williamsoni* Haynes - Parker, 2009, p. 591; figs 418a-l, 419a-e.

Distribution: This species is mostly observed in substrates of lagoons (Debenay, 2012). In our study, it is recorded from the central sector and outer channel areas of the Chilika lagoon.

Elphidium sp.

(Plate II fig. 9)

Remarks: This form of *Elphidium* is observed in the sediments of the Chilika lagoon.

Family Nonionidae Schultze, 1854

Subfamily Nonioninae Schultze, 1854

Genus *Haynesina* Banner and Culver, 1978

Haynesina depressula (Walker and Jacob, 1798)

(Plate III, fig.2)

Nautilus depressulus Walker and Jacob 1798, p. 641, pl. 14, fig. 33.

Nonion depressulum Jorissen 1988, p. 23, pl. 2, fig. 7.
Haynesina depressula (Walker and Jacob) Milker & Schmiedl 2012, p. 112, fig. 25, 17–18.
Haynesina depressula (Walker and Jacob) Barbieri & Vaiani 2018, p. 207, pl. 1, figs. 17–18

Distribution: This species of *Haynesina* can tolerate low saline condition. It indicates fresh water impact on the water body. This species is mainly recorded in coastal lagoons, coastal bays, shrimp Ponds (Debenay, 2012). It is also recorded from the outer channel of the Chilika lagoon (Jayalakshmy & Rao, 2001).

Haynesina germanica (Ehrenberg, 1840)
(Plate III, fig. 3)

Distribution: This species is typically found in fine sediment and well documented in a stressed environment (Alve, 1995; Yanko et al., 1999). It was recorded from the outer channel of the Chilika lagoon (Jayalakshmy & Rao, 2001).

Genus *Nonionellina* Voloshinova, 1958
Nonionellina labradorica (Dawson, 1860)
(Plate III, fig. 5)

Nonionina labradorica Dawson, 1860, p. 191, fig. 4.
Nonionellina labradorica (Dawson); Riveiros and Patterson, 2008, p. 29, fig. 12.7a-c.
Nonionellina labradorica (Dawson); Margreth, 2010, p. 123, pl. 36, fig. 4.
2014 *Nonionellina labradorica* (Dawson); Panchang and Nigam, pl. 34, figs. 8a-c, 9a-c.

Distribution: It was recorded in the sediments from the outer channel and central sector of the Chilika Lagoon (Jayalakshmy & Rao, 2001).

Genus *Nonion* de Montfort, 1808
Nonion sp
(Plate III, fig. 4)

Remarks: This species of *Nonion* are recorded from the substrate of the central sector and outer channel of the Chilika lagoon.

Superfamily CHILOSTOMELLACEA Brady, 1881

Family Heterolepidae Gonzáles-Donoso, 1969

Genus *Heterolepa* Franzenau, 1884

Heterolepa sp

(Plate III, fig.12)

Remarks: This species of *Heterolepa* observed in the sediments of the Chilika lagoon.

Superfamily CHILOSTOMELLACEA Brady, 1881

Family Gavelinellidae Hofker, 1951

Subfamily Gavelinellinae Hofker, 1956

Genus *Hanzawaia* Asano, 1944

Hanzawaia sp.

(Plate III, fig. 1)

Remarks: This species are found in the sediments of the Chilika lagoon (Jayalakshmy & Rao, 2001).

Genus *Cocoarota* Loeblich and Tappan, 1986

Cocoarota sp.

(Plate III, fig. 11)

Remarks: This species of *Cocoarota* observed in the sediments of the Chilika lagoon.

Superfamily MILIOLACEA Ehrenberg, 1839

Family Miliolidae Ehrenberg, 1839

Subfamily Hauerinidae Schwager, 1876

Genus *Quinqueloculina* d'Orbigny, 1826

Quinqueloculina seminulum (Linnaeus, 1758)

(Plate III, fig. 7)

Serpula seminulum Linnaeus, 1758, p. 786, pl. 2, fig. 1a-c.

Quinqueloculina seminulum (Linnaeus); Murray, 2003, p. 17, pl. 4, figs. 11-12.

Quinqueloculina seminulum (Linnaeus); Talib and Farooqui, 2007, p. 18, pl.1, fig. 9 a-b.

Quinqueloculina seminula (Linnaeus); Margreth, 2010, p. 101, pl. 7, fig. 8a-c.
Quinqueloculina seminula (Linnaeus); Milker and Schmiedl, 2012, p. 57, fig. 15.30-31.
Quinqueloculina seminula (Linnaeus); Debenay, 2012, p. 126.

Distribution: *Quinqueloculina seminulum* mostly recorded from the sediments of coastal lagoons, marshes, estuaries, bays. These Species are recorded from the sediments of the Chilika lagoon (Jayalakshmy & Rao, 2001).

Quinqueloculina sp.
(Plate III, fig. 10)

Distribution: This species is found in the sediments of Chilika lagoon.

3.4 RESULTS

3.4.1 Foraminiferal assemblages from outer channel of the Chilika lagoon

The seasonal distribution of total foraminiferal number (TFN) observed in all stations of the outer channel of the lagoon are plotted for both pre (March) and post-monsoon (October) seasons (Figure-3.1). Twenty-eight species of benthic foraminifera are documented from the surface sampling, of which 13 are hyaline, 14 are agglutinated, and one species of porcelaneous test (Plate I, II, & III). spp. (*Ammonia beccarii*, *Ammonia parkinsoniana*, *Ammonia tepida*) is the most dominant taxa among all. The other calcareous taxa are *Pararotalia nipponica*, *Elphidium advenum, Cribroelphidium hispidulum, Elphidium williamsoni, Haynesina germanica Rotalidium annectens, Hanzawaia* sp., *Elphidium* sp., *Nonion* sp., *Nonionellina labradorica* and *Quinqueloculina seminulum.* The identified agglutinated forms are *Miliammina fusca Ammobaculites exiguus, Textularia earlandi, Textularia agglutinans, Textularia* sp., *Ammobaculites agglutinans, Ammotium salsum, Milliammina obliqua, Trochammina inflata, Entzia* sp., *Haplophragmoides* sp., *Trochammina advena, Milliammina* sp. and *Ammotium fragile.* The abundance of total foraminifera was high during pre-monsoon and recorded from the mouth part of the outer channel. The abundance of living foraminifera is also high along the same (Fig. 3.2).

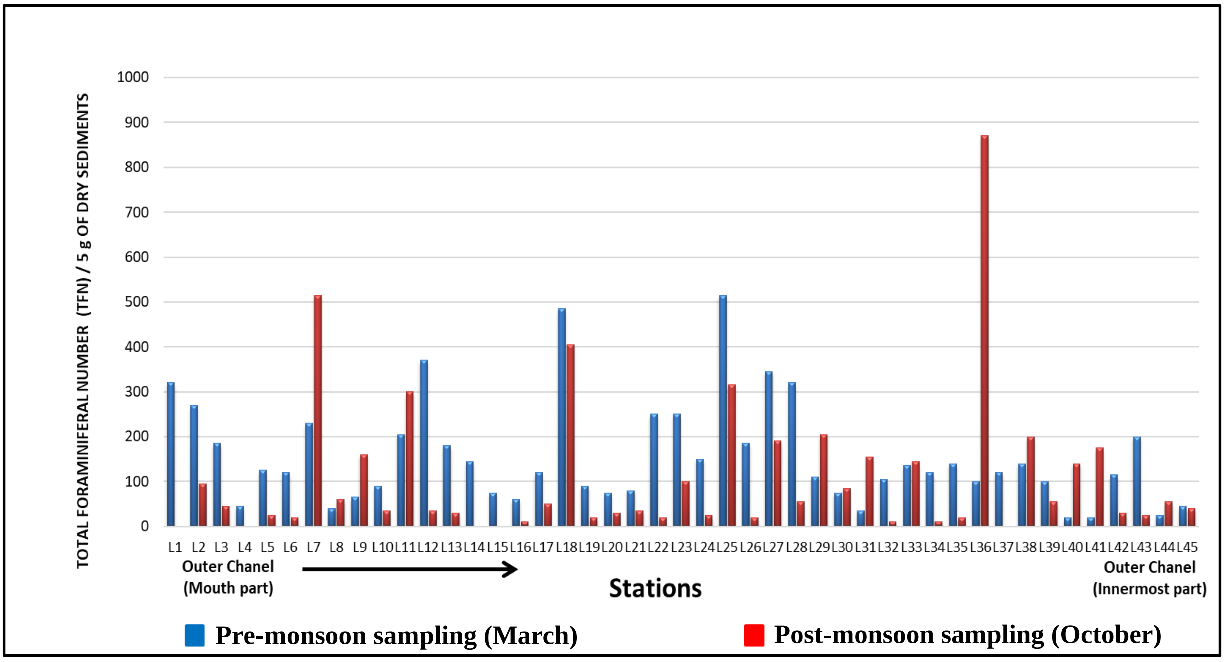

Fig. 3.1 Seasonal distribution of the total number of foraminifera in the outer channel region.

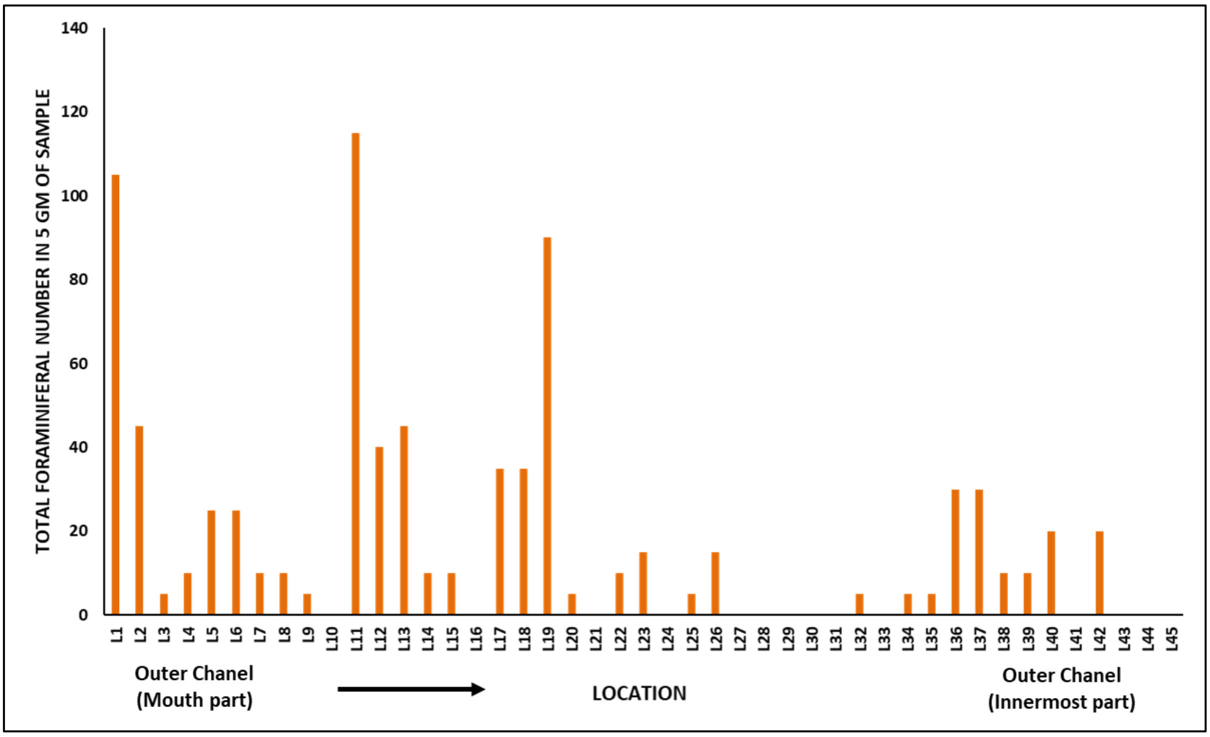

Fig. 3.2 Variation of the living foraminifera across the sampling locations in the outer channel (Pre-monsoon).

The outer channel shows an overall high sand percentage varying between 70 to 100 (Fig. 3.3). As we move away from its mouth, the assemblages of agglutinated foraminiferal forms were high (Fig 3.4). Murray's Ternary diagram of pre- and post-monsoon shows two clusters (A and B) of foraminiferal populations (Fig 3.5). Cluster A represents the stations nearer to the mouth of the Chilika lagoon dominated by calcareous tests. Cluster B includes the station away from the mouth, represented by the agglutinated tests. Fisher's alpha species diversity value ranged between 1 to 4 for all the sampling stations (Fig 3.6). The Evenness index ranges between 0.70 and 1 with an average of 0.83 (Fig 3.11), and the Dominance index ranges from 0.09 to 0.62 with an average of 0.22 (Fig 3.12). Seasonal variations of dominated calcareous taxa such as *Ammonia beccarii* and *Ammonia parkinsoniana*, and dominated agglutinated forms such as *Miliammina fusca* and *Ammobaculites exiguus* are plotted in Fig.3.7 to 3.10. It is observed from the study that the abundance of calcareous taxa is high along the mouth part of the outer channel, whereas inner most part is dominated by agglutinated forms.

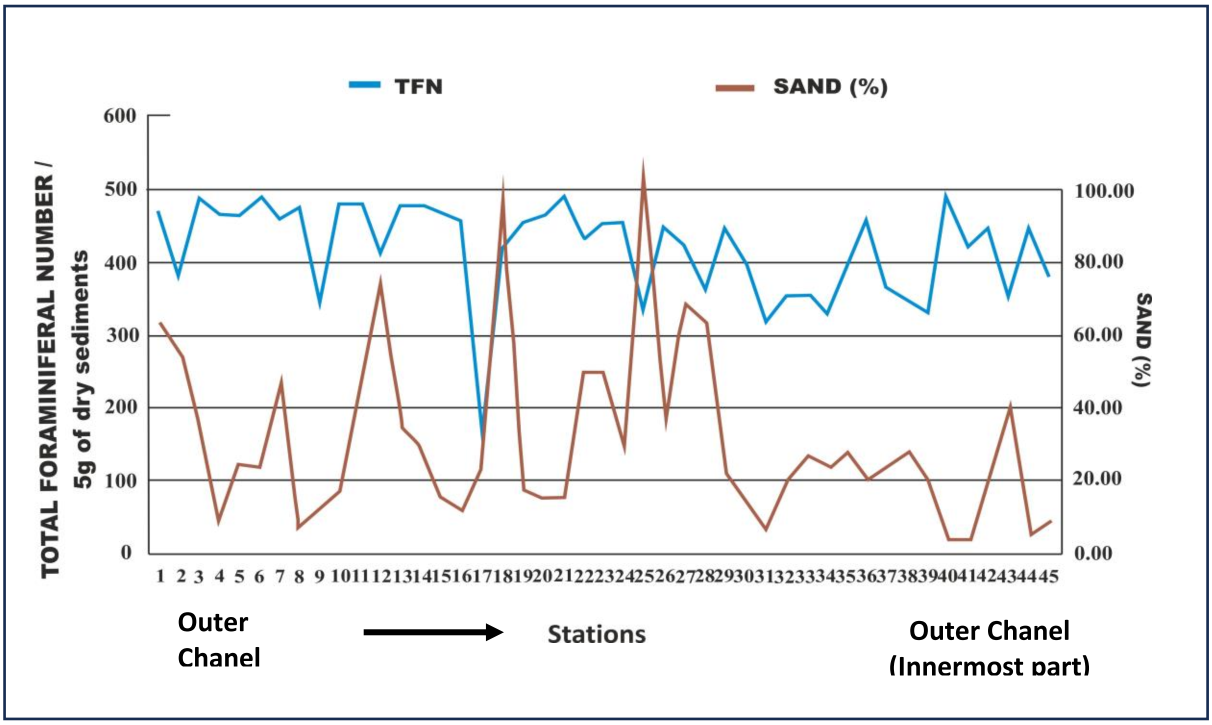

Fig. 3.3 Correlation of Sand (%) and Total Foraminiferal Number in the outer channel.

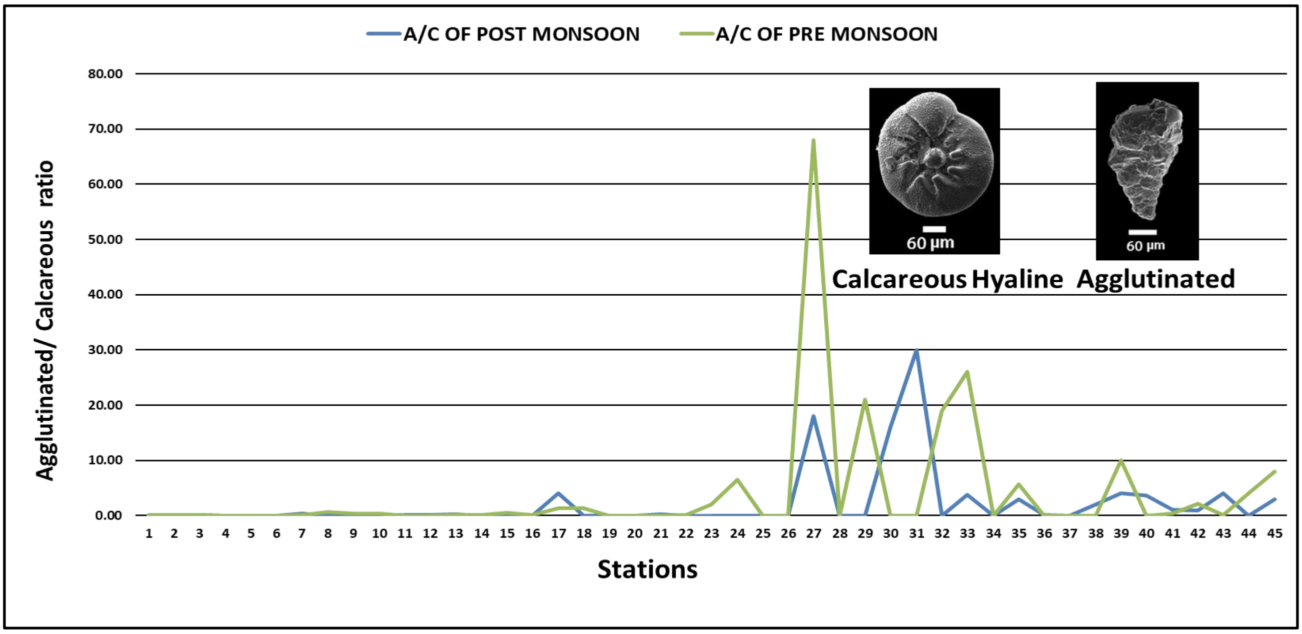

Fig. 3.4 Agglutinated/calcareous foraminiferal ratio (A/C) in the outer channel.

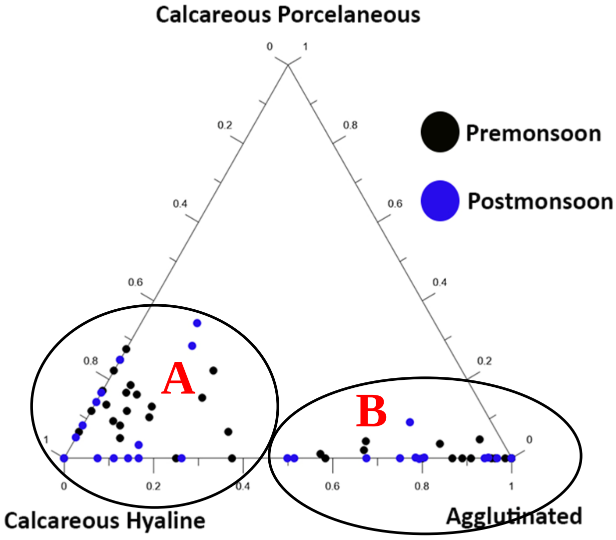

Fig. 3.5 Murray's Ternary Diagram of pre- and post-monsoon along the outer channel.

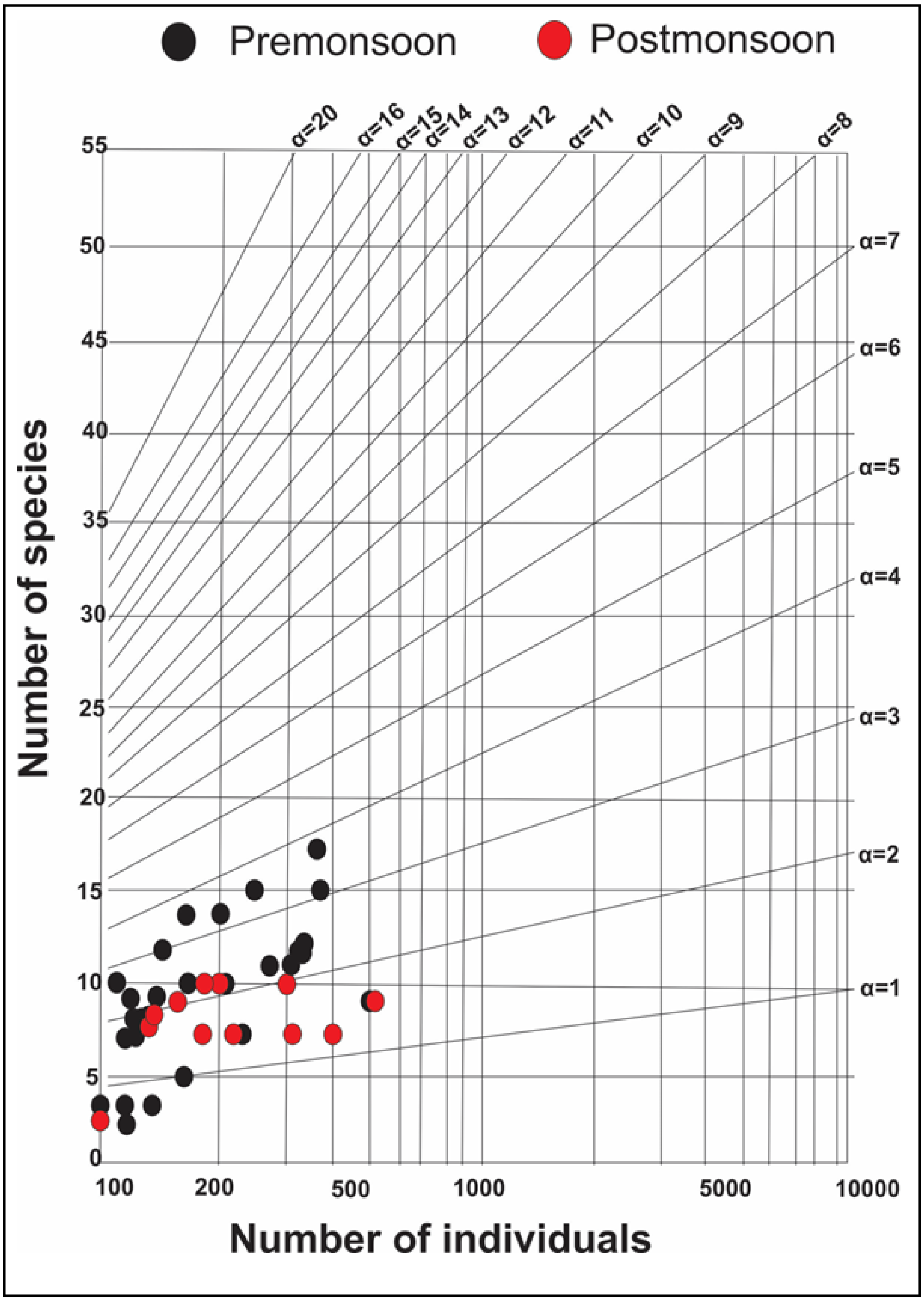

Fig. 3.6 Fisher-α Diversity Index.

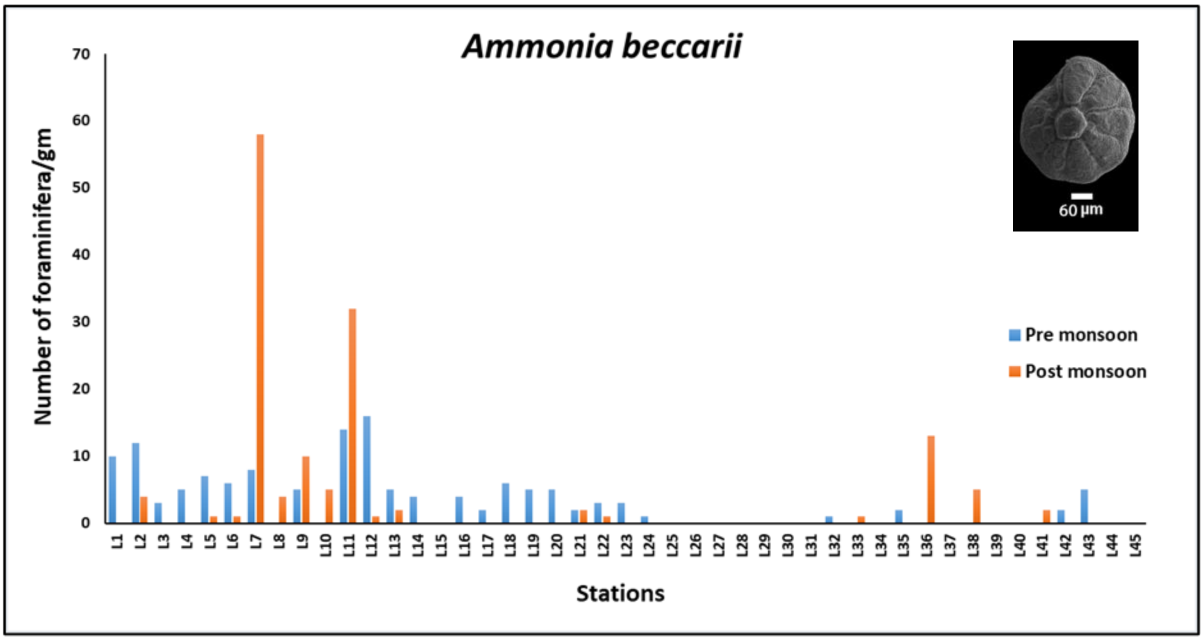

Fig. 3.7 Seasonal variations of *Ammonia beccarii* across the sampling stations.

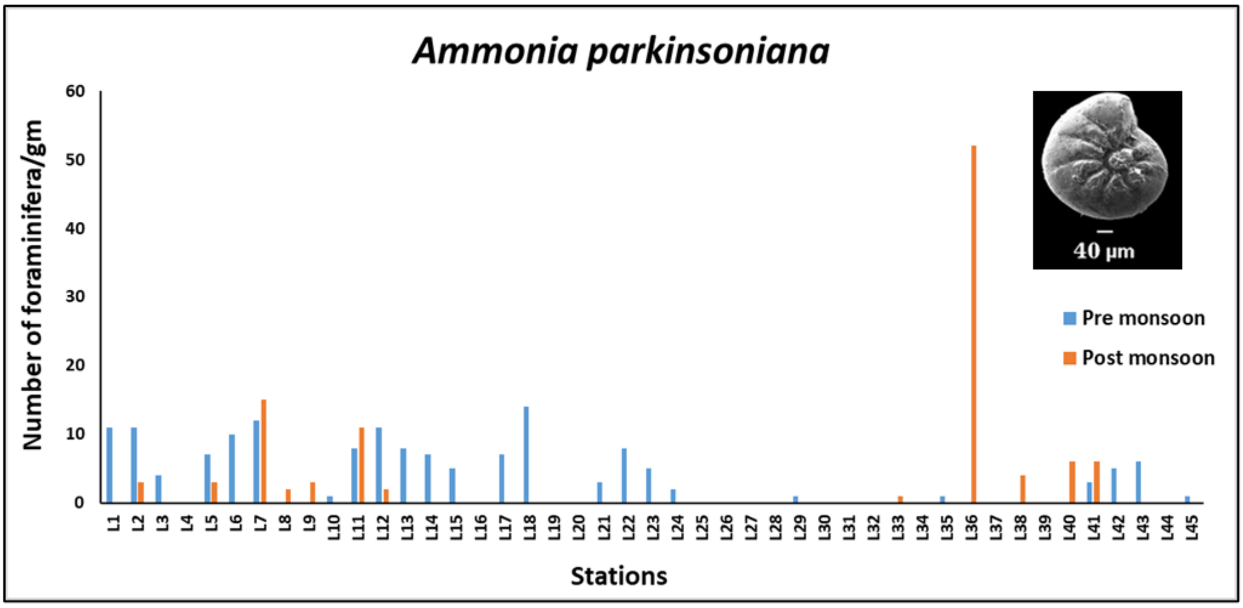

Fig. 3.8 Seasonal variations of *Ammonia parkinsoniana* across the sampling stations.

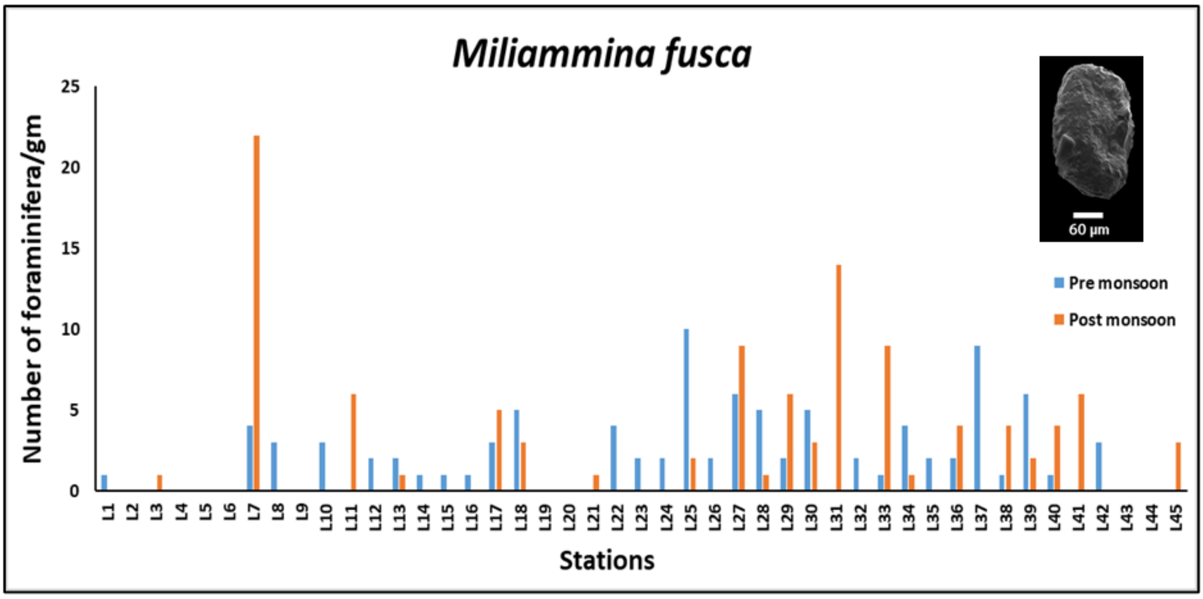

Fig. 3.9 Seasonal variations of *Miliammina fusca* across the sampling stations.

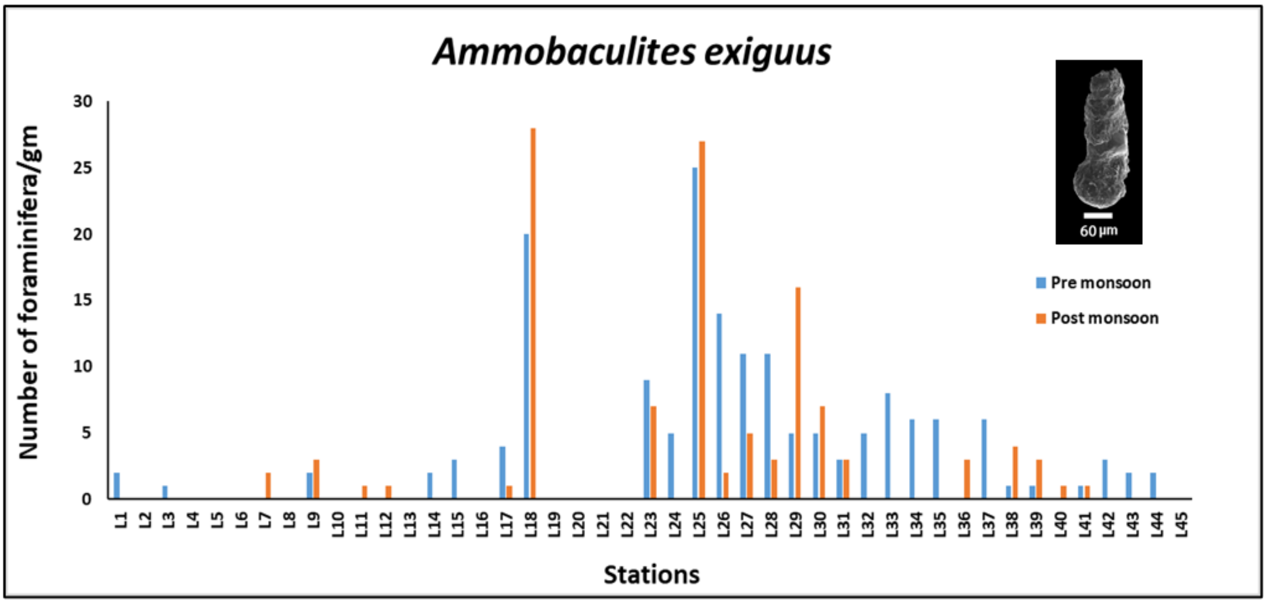

Fig. 3.10 Seasonal variations of *Ammobaculites exiguus* across the sampling stations.

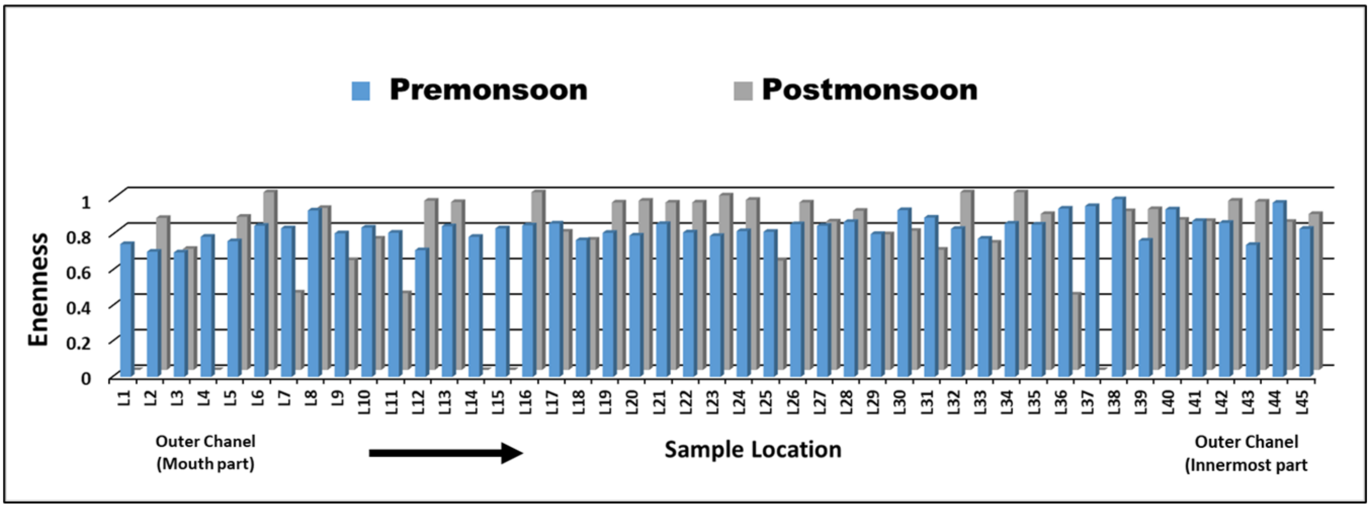

Fig. 3.11 Graph of Evenness Index.

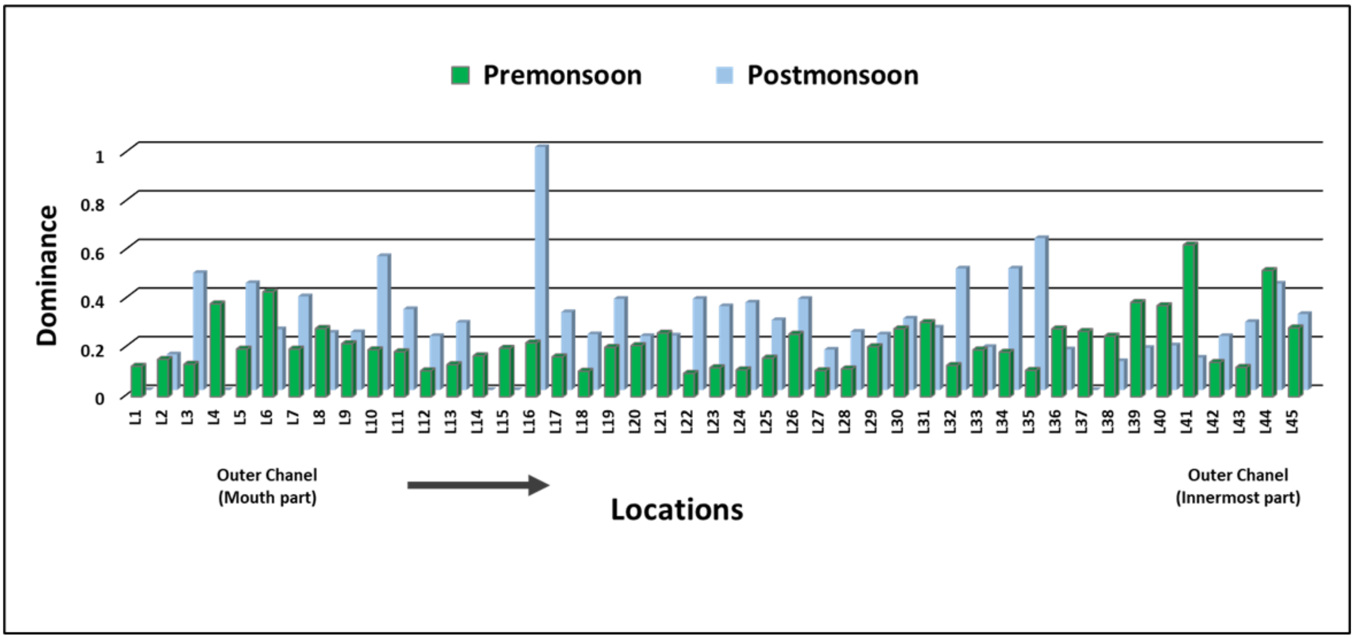

Fig. 3.12 Graph of Dominance Index.

A multivariate clustering (Q-Mode) was performed with 28 species of foraminifera recorded from the sampling site to ascertain any grouping of taxa based on the stations, composition or seasons (Fig 3.13). Jaccard similarity index clustered them into two groups. The sampling station from the inner part of the outer channel constitutes Group A, while Group B represents the sampling stations near the lagoonal mouth.

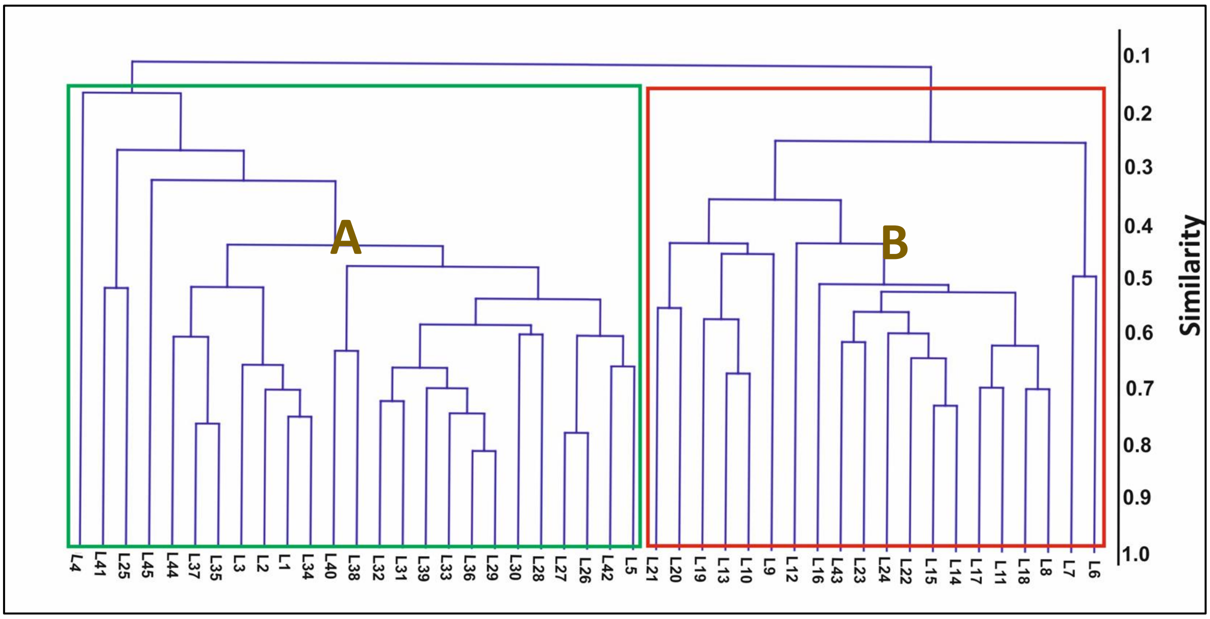

Fig. 3.13 A Multivariate cluster analysis (UPGMA paired group, Jaccard similarity index) based on species composition values.

3.4.2 Foraminiferal assemblages from the central sector of the Chilika lagoon

The surface sampling of this sector of the lagoon states that the total foraminiferal number (TFN) in the post-monsoonal (October) month is greater than pre-monsoonal (April) abundance in almost all the stations (Fig. 3.14). Total thirty foraminiferal species are documented from this sector of the lagoon, of which 17 are hyaline, 11 are agglutinated, and 2 are the porcelaneous test. The most dominant taxa is *Ammonia* spp. (*Ammonia sobrina, Ammonia parkinsoniana, Ammonia tepida, Ammonia beccarii*), followed by *Pararotalia nipponica, Haynesina germanica, Haynesina depressula, Hanzawaia* sp., *Elphidium advenum, Elphidium hispidulum, Elphidium williamsoni, Elphidium excavatum, Elphidium* sp., *Cocoarota* sp., *Heterolepa* sp., *Nonionellina labradorica, Cibicides* sp., *Miliammina fusca Ammobaculites exiguus, Textularia earlandi,* *Textularia agglutinans, Ammobaculites agglutinans, Ammotium salsum, Milliammina obliqua, Trochammina inflata, Entzia* sp.*, Haplophragmoides* sp.*, Trochammina advena,* and *Quinqueloculina seminulum* and *Quinqueloculina* sp. are two porcelaneous taxa. A similar trend is observed in Figure 3.15, where the abundance of living forms is higher in the post-monsoonal samples than in the pre-monsoonal months.

As seen in Figure 3.16, the central sector has an overall high sand percentage that varies from 0.4 to 48 and is inversely related to the TFN. Like the outer channel, all the central sector sample stations had a Fisher's alpha species diversity value between 1 and 4 (Fig. 3.17). *Ammonia tepida, Ammonia parkinsoniana, Ammonia sobrina,* and *Pararotalia nipponica* are the four dominant species whose variations along stations are seen in Figures 3.18 to 3.21. According to the study, these calcareous hyaline forms are abundant at almost every station during the post-monsoon period.

Utilizing Bray-Curtis R-mode analysis and the paired group (UPGMA), the similarity of the foraminiferal assemblages was evaluated. In this study, only species with an abundance of 5% or higher among all specimens from the one sampling station are chosen. Two separate clusters are observed in Figure 3.22. *Ammonia* spp. (*A. tepida- A. parkinsoniana-A. sobrina*) predominates in Group A and *Pararotalia nipponica–Hanzawaia* sp.–*Haynesina* sp., dominate the second cluster, Group B.

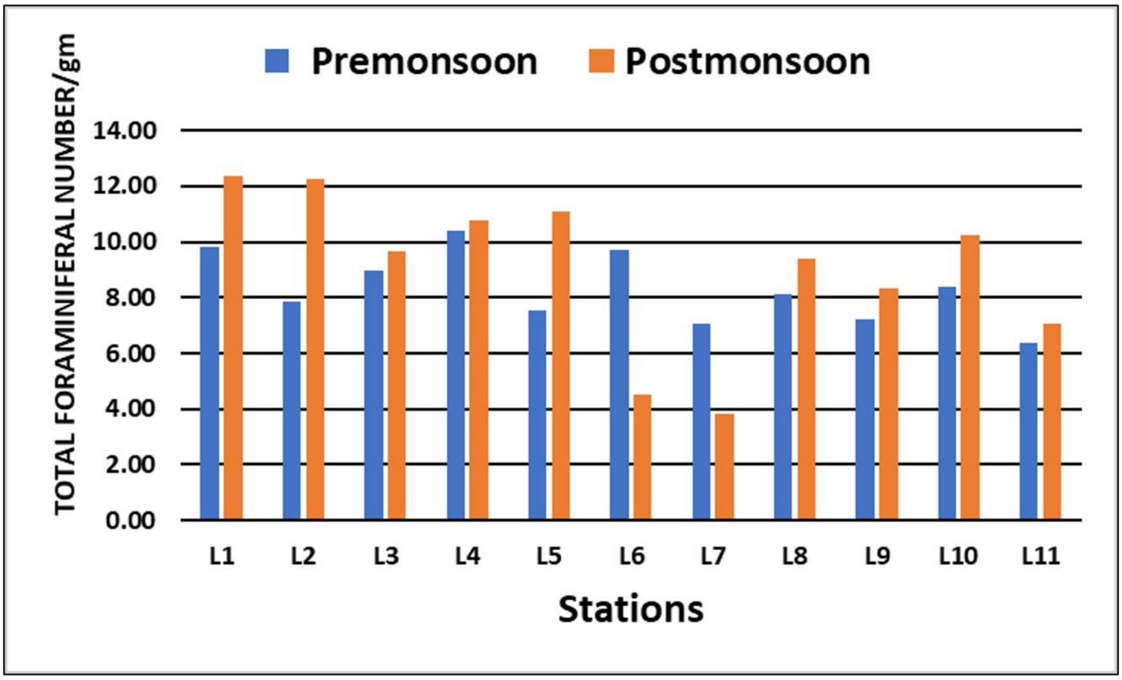

Fig. 3.14 Total Foraminiferal Number (TFN) in log scale along the sampling stations in the central sector of the Chilika Lagoon.

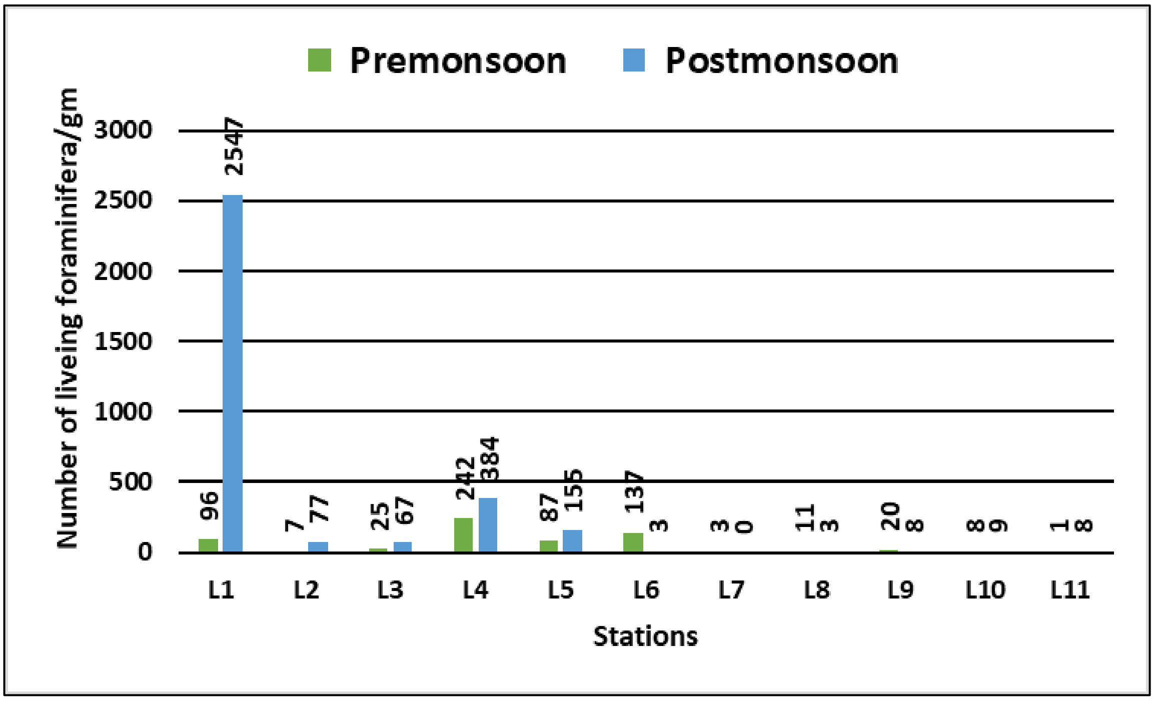

Fig. 3.15 Variations of the living foraminifera across the sampling stations in the central sector of the Chilika Lagoon.

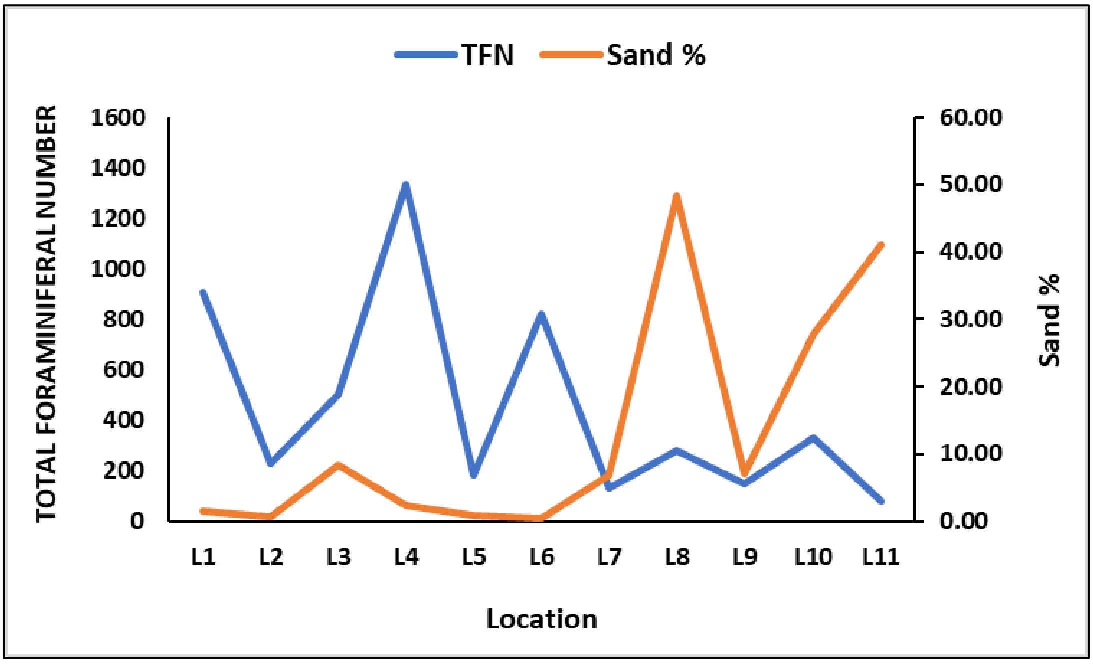

Fig. 3.16 Variation of Sand (%) and Total Foraminiferal Number in the central sector.

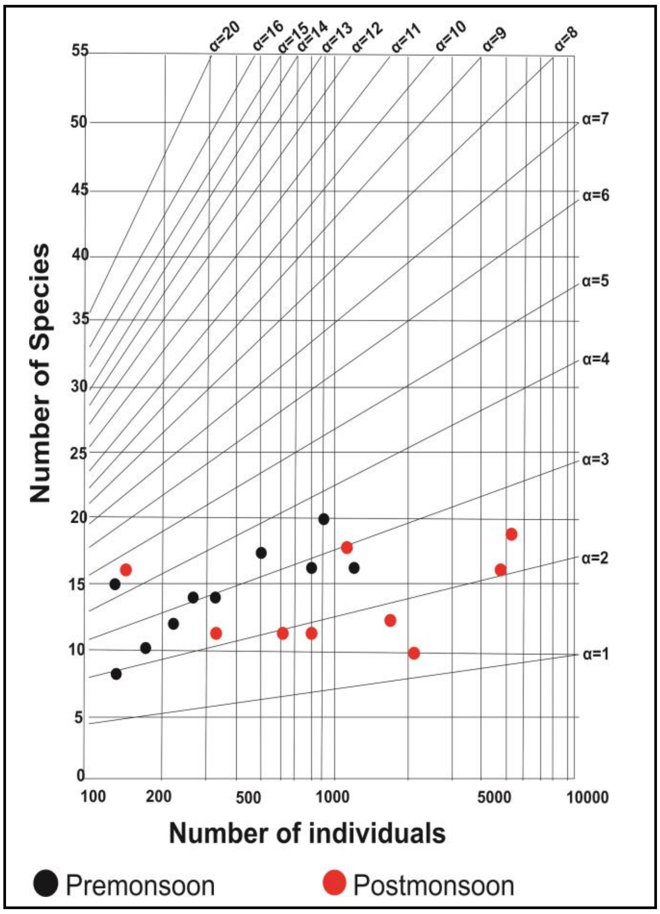

Fig. 3.17 Fisher-α Diversity Index.

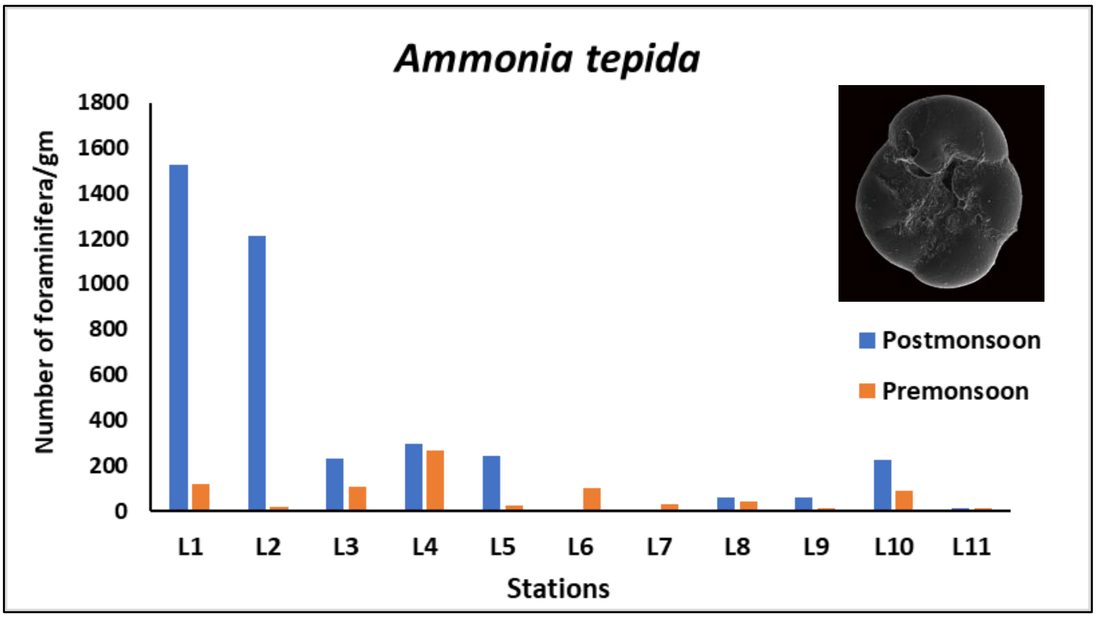

Fig. 3.18 Seasonal variations of *Ammonia tepida* across the sampling stations of central sector.

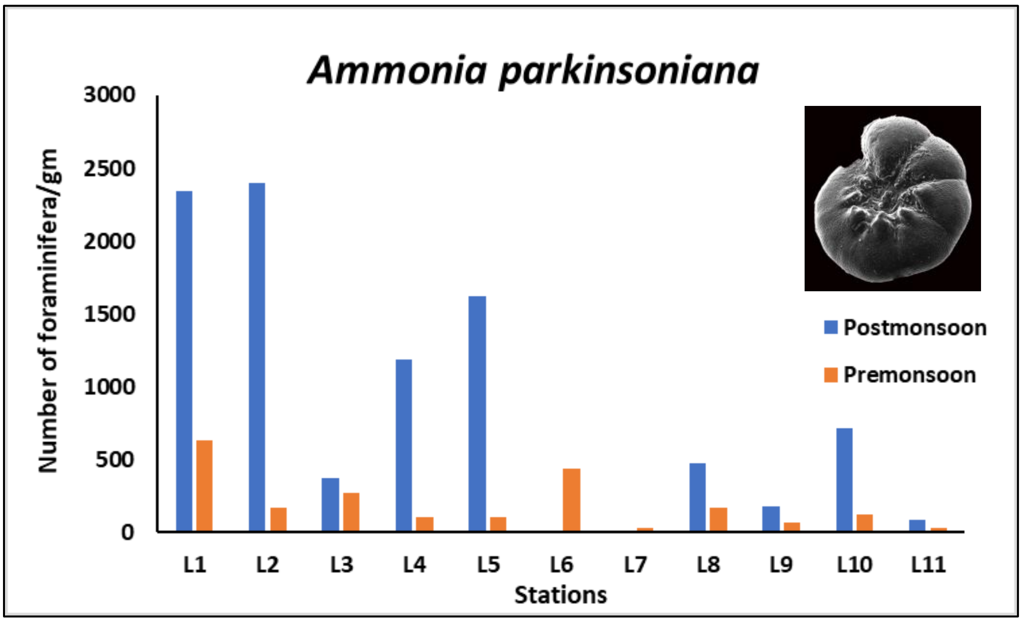

Fig. 3.19 Seasonal variations of *Ammonia parkinsoniana* across the sampling stations of central sector.

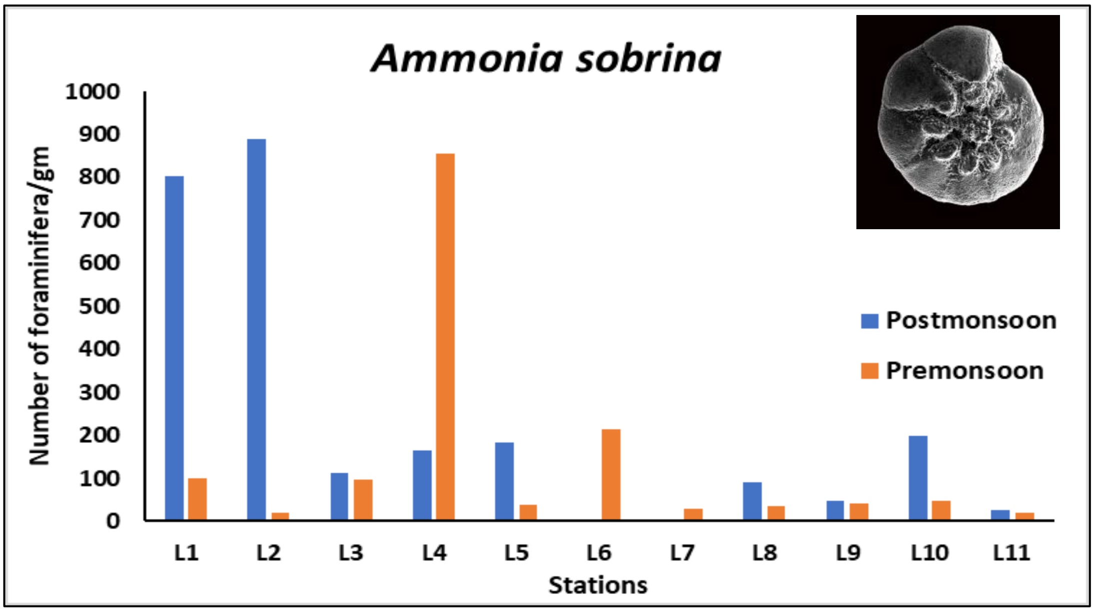

Fig. 3.20 Seasonal variations of *Ammonia sobrina* across the sampling stations of central sector.

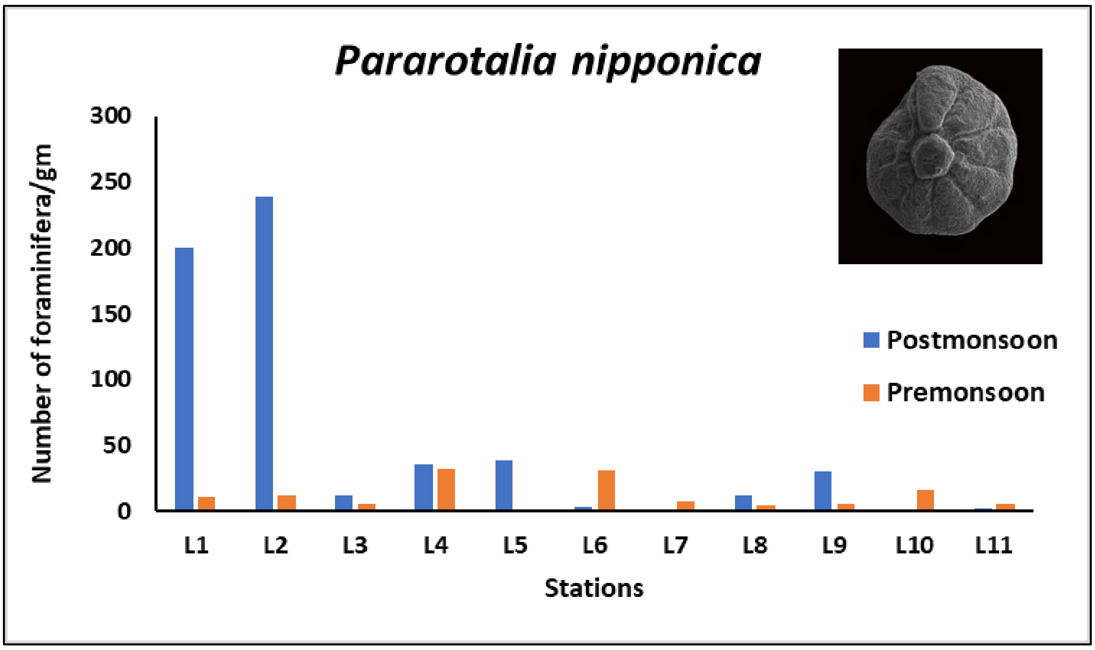

Fig. 3.21 Seasonal variations of *Pararotalia nipponica* across the sampling stations of central sector.

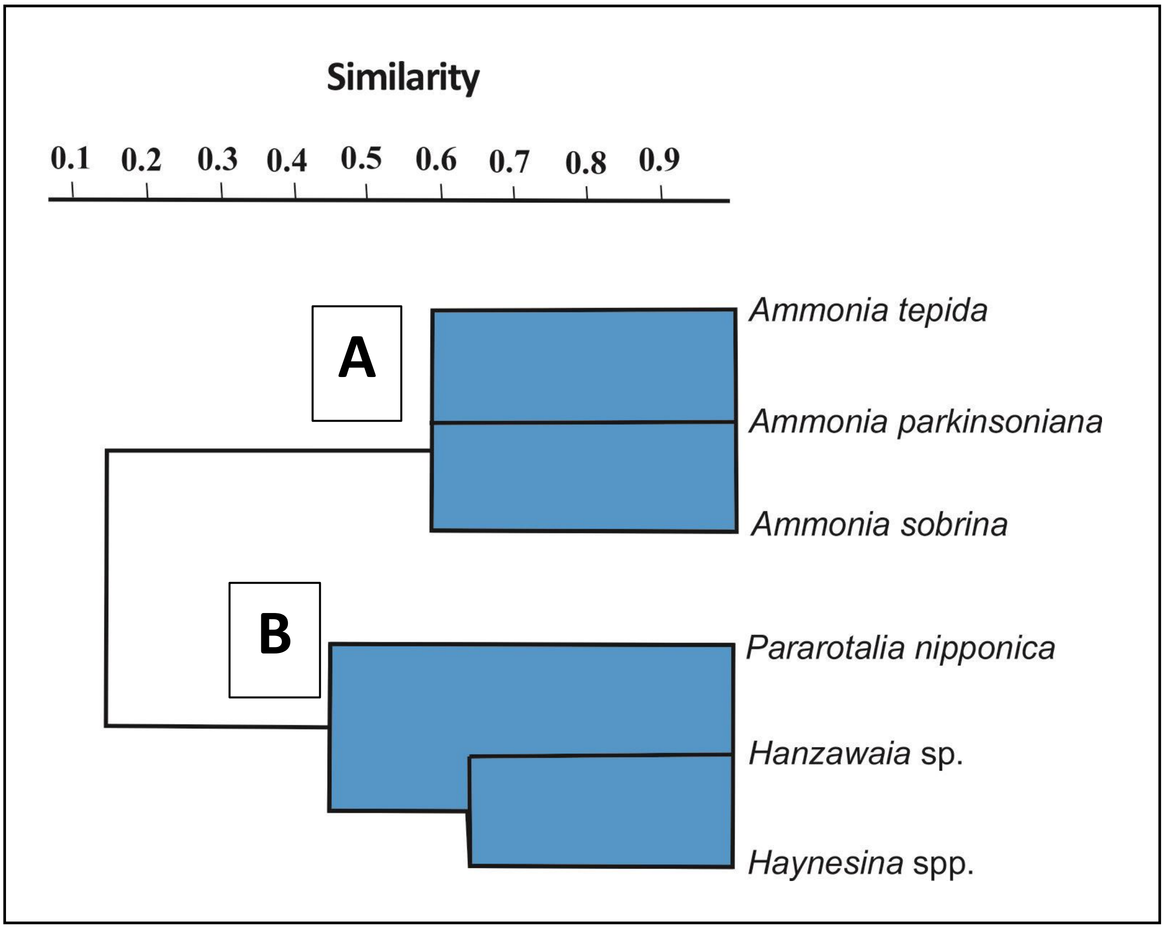

Fig. 3.22 Paired group (UPGMA) and Bray-Curtis R-mode cluster analysis based on the similar foraminiferal assemblages.

PLATE I

Scanning electron micrographs of calcareous taxa of benthic foraminifera, Chilika lagoon.

Legend: Si–Side view; S–Spiral view; U–Umbilical view.

1. *Ammonia beccarii* (S)

2. *Ammonia beccarii* (U)

3. *Ammonia parkinsoniana* (U)

4. *Ammonia parkinsoniana* (S)

5. *Ammonia tepida* (U),

6. *Ammonia tepida* (S)

7. *Ammonia sobrina* (U)

8. *Ammonia sobrina* (S)

9. *Elphidium* sp. (Si)

10. *Cribroelphidium hispidulum* (Si)

11. *Elphidium advenum* (Si)

12. *Elphidium williamsoni* (Si)

PLATE I

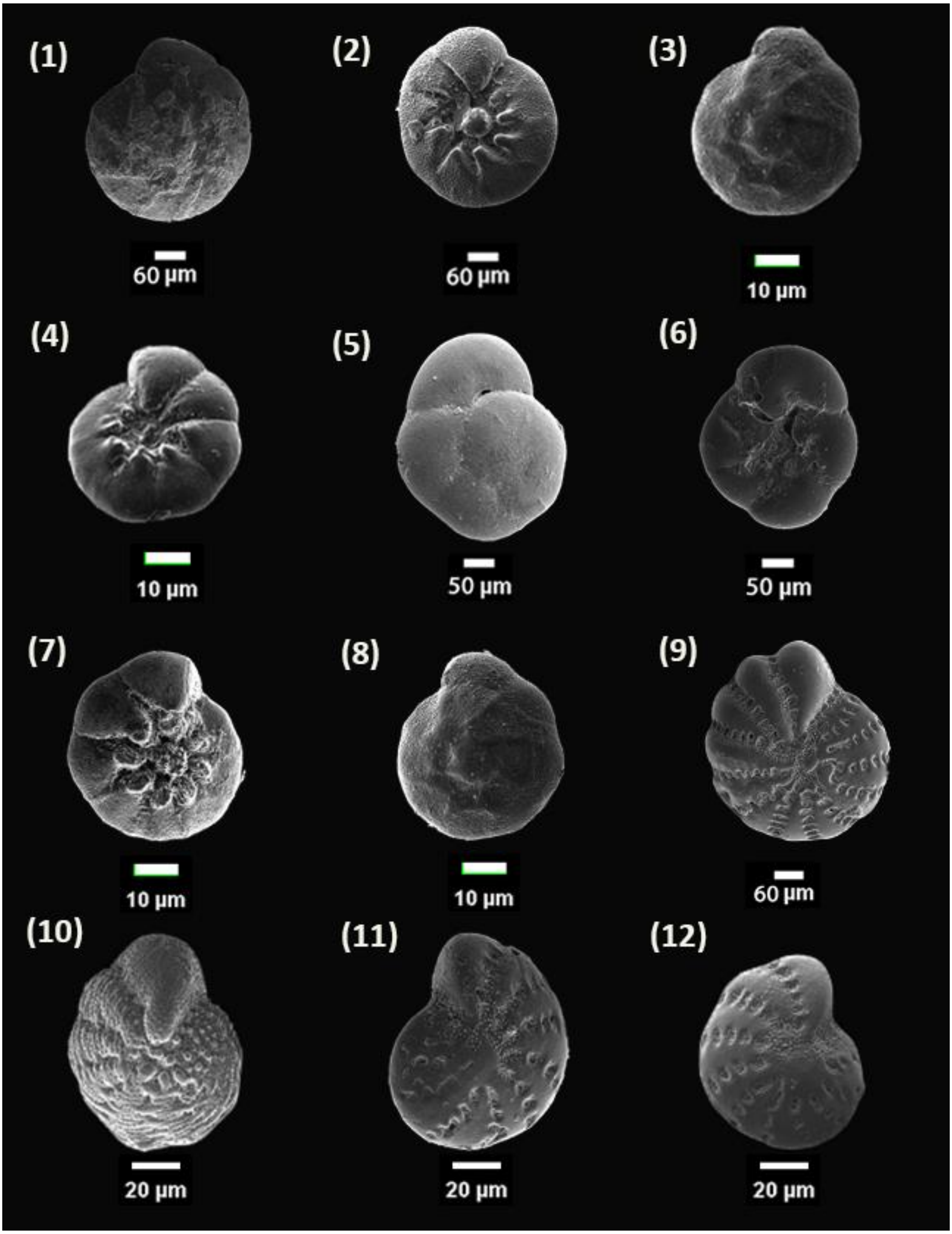
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PLATE II

Scanning electron micrographs of calcareous taxa of benthic foraminifera, Chilika lagoon.

Legend: Si–Side view; S–Spiral view; U–Umbilical view.

1. *Hanzawaia* sp.(U)

2. *Haynesina depressula* (Si)

3. *Haynesina germanica* (Si)

4. *Nonion* sp. (Si)

5. *Nonionellina labradorica* (Si)

6. *Pararotalia nipponica* (U)

7. *Quinqueloculina seminulum* (Si)

8. *Rotalidium annctens* (S)

9. *Rotalidium annctens* (U)

10. *Quinqueloculina* sp. (Si)

11. *Cocoarota* sp. (S)

12. *Heterolepa* sp. (U)

PLATE II

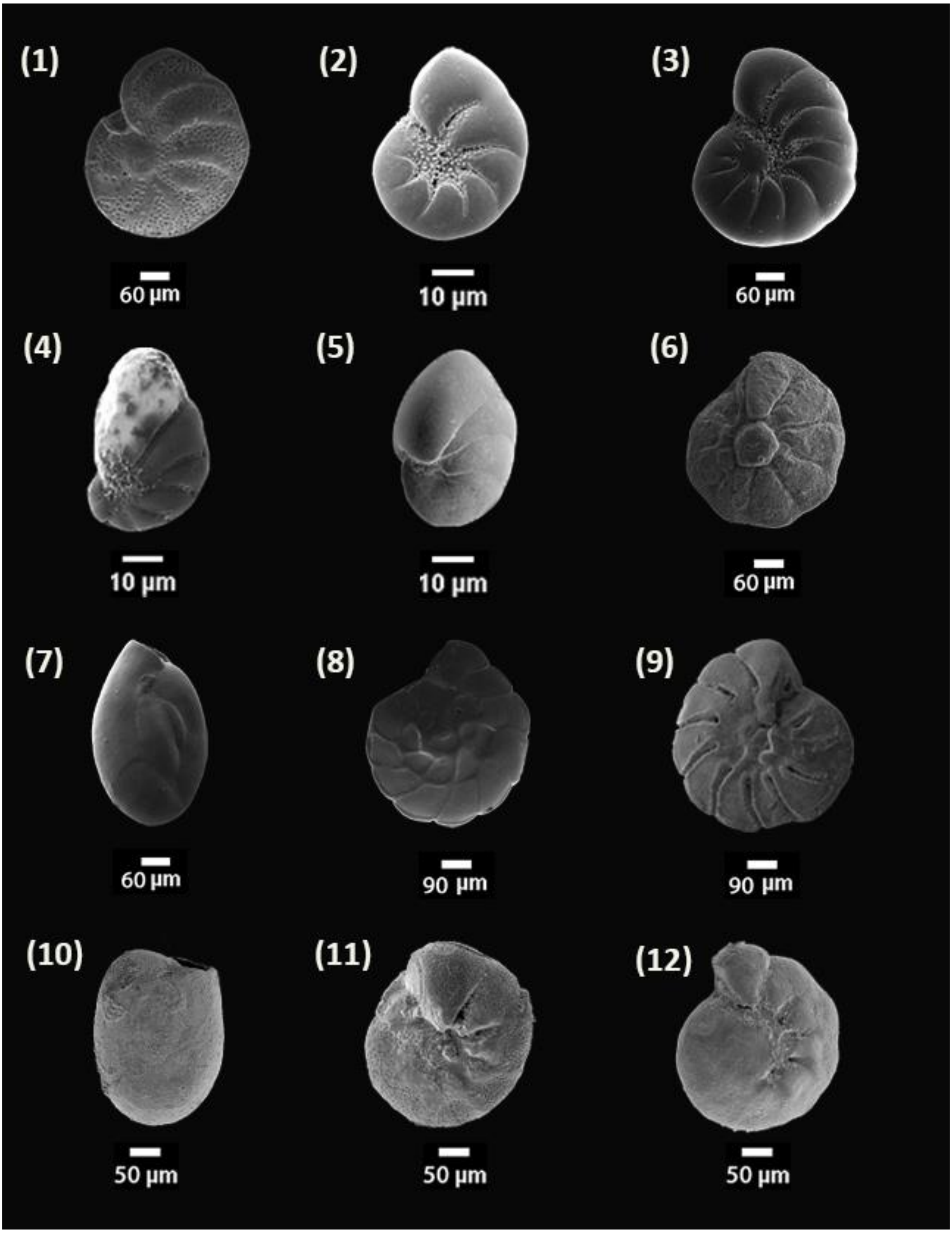
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PLATE III

Scanning electron micrographs of agglutinated taxa of benthic foraminifera, Chilika lagoon.

Legend: Si–Side view; S–Spiral view; U–Umbilical view.

1 *Ammobaculites agglutinans* (Si)

2 *Ammobaculites exiguus* (Si)

3 *Ammotium fragile* (Si)

4 *Ammotium salsum* (Si)

5 *Entzia sp.* (Si)

6 *Haplophragmoides* sp. (Si)

7 *Miliammina fusca* (Si)

8. *Miliammina obliqua* (Si)

9. *Miliammina* sp. (Si)

10. *Trochammina advena* (U)

11. *Trochammina advena* (S)

12. *Trochammina inflata* (S)

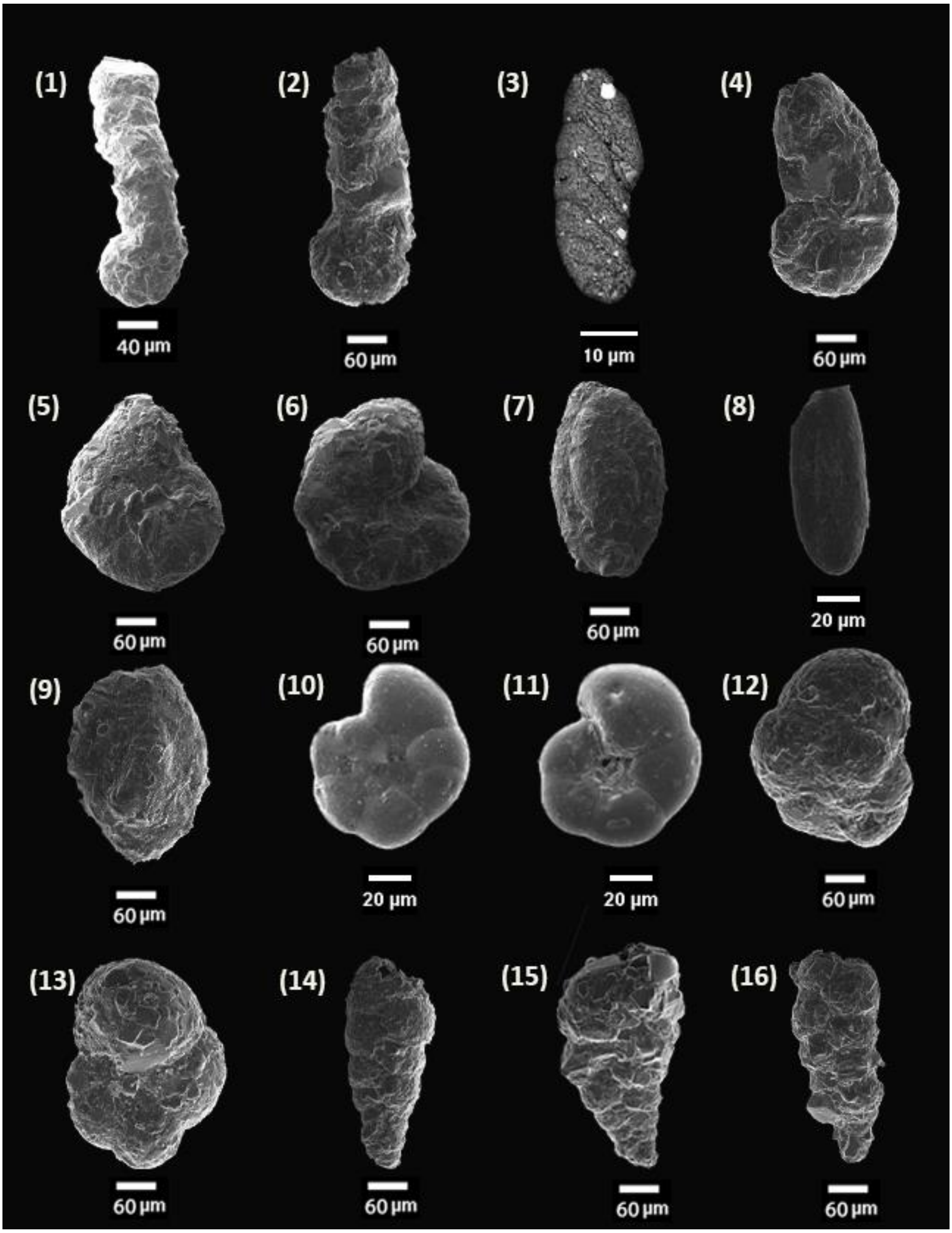
13. *Trochammina. inflata* (U)

14. *Textularia agglutinans* (Si)

15. *Textularia earlandi* (Si)

16. *Textularia* sp. (Si)

PLATE III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4.1 MAGNETIC SUSCEPTIBILITY STUDY

The (initial) apparent reversible magnetic susceptibility (hereafter referred to as susceptibility) is a constant of proportionality between a weak applied field and the induced magnetisation. More simply, it is a measure of a sample's 'magnetisability' or its degree of attraction to a magnet, and is most easily visualised as a function of the volume of ferrimagnetic minerals, e.g., magnetite, titanomagnetite and maghemite in the sample although in reality it is a complex parameter highly dependent upon the intrinsic susceptibility of individual 'magnetic' minerals in the sample, their grain size and shape, and the sample shape (Thompson & Morton, 1979; Mullins, 1977).

Actually, when materials placed within an external magnetic field that material acquire a magnetic moment. This is the magnetic susceptibility and is a measure of the ability of a material to acquire magnetization. A positive value of susceptibility is achieved by materials which become magnetized parallel to the direction of the applied field. Anti-parallel magnetization results a negative value of susceptibility. The volume magnetization, M induced within a material of susceptibility, K, is related linearly to the applied field, H by the equation

$$\mathbf{K = M / H.}$$

The susceptibility of a soft sediment sample does not actually depend upon the percentage of iron oxides present, but depends on how much of the iron oxides are ferrimagnetic. Higher magnetization in sediments is due to the presence of ferrimagnetic materials, chiefly among them being magnetite and members of the titanomagnetite series.

In the present study single samples of dried (80°C) materials were measured in Bartington Susceptibility Meter. Data from the Fig. 4.1 shows that sample from location-1(L1) indicates high value of bulk susceptibility i.e. 113.29 x 10^{-6} SI unit, on the other hand L16 shows low range of susceptibility value i.e., 3.08 x 10^{-6} SI unit. Data shows the large ranges of Magnetic Susceptibility (MS) values throughout the outer channel of the lagoon. Based on the apparent bulk density for each sample location, the topsoil's apparent mass specific magnetic susceptibility was calculated. From the result it is evident that the samples that are collected from outer part of the outer channel show high MS values in respect to the areas that are in the inner part of the outer channel (Table 3).

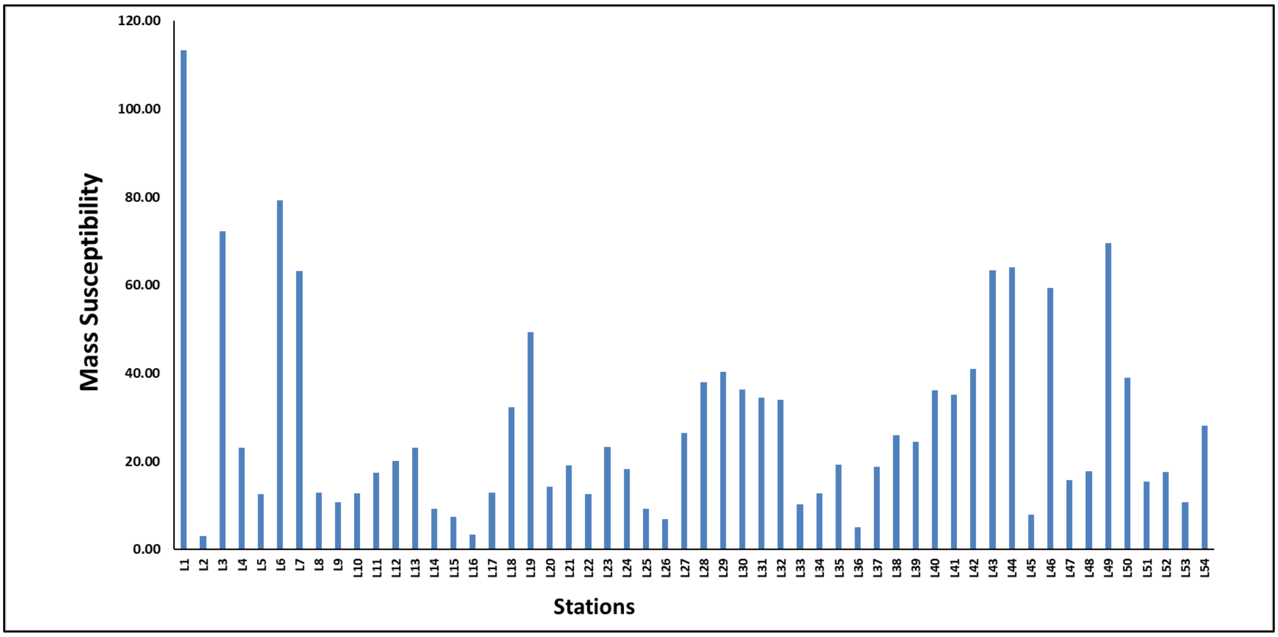

Fig. 4.1 Mass Susceptibility values of 54 Locations.

Location Name	**Latitude** (in degrees)	**Longitude** (in degrees)	**Mass in SI**	**Density in SI**	**Average volume Susceptibility in SI (k x 10^{-6})**	**Mass Susceptibility in SI (X x 10^{-6})**
L1	19.6625	85.4413	20.65	0.46	51.50	113.29
L2	19.6614	85.4424	17.11	0.38	1.17	3.08
L3	19.6594	85.4459	17.57	0.39	28.08	72.14
L4	19.6590	85.4473	19.14	0.42	9.83	21.69
L5	19.6594	85.4495	19.23	0.43	5.33	1.12
L6	19.6606	85.4521	17.37	0.38	30.42	79.17
L7	19.6616	85.4555	16.22	0.36	22.92	63.16
L8	19.6634	85.4604	15.38	0.34	4.33	12.87
L9	19.6639	85.4641	14.99	0.33	3.58	10.79
L10	19.6659	85.4978	16.22	0.36	4.58	12.78
L11	19.6664	85.4812	16.33	0.36	6.17	17.40
L12	19.6670	85.4795	14.91	0.33	6.67	20.11
L13	19.6671	85.4764	15.13	0.33	7.67	23.03
L14	19.6774	85.4991	14.96	0.33	3.08	9.23
L15	19.6710	85.4991	15.29	0.34	2.50	7.44
L16	19.6707	85.5014	13.51	0.30	1.00	3.32
L17	19.6606	85.5129	14.38	0.32	4.08	12.91
L18	19.6618	85.5177	13.76	0.30	9.83	32.30
L19	19.6661	85.5164	17.08	0.38	18.58	49.38
L20	19.6646	85.5141	16.35	0.36	5.17	14.24
L21	19.6636	85.5115	16.30	0.36	6.83	19.08
L22	19.6656	85.5117	18.55	0.41	5.17	12.59
L23	19.6700	85.4806	17.18	0.38	8.83	23.26
L24	19.6725	85.5272	18.04	0.40	7.33	18.30
L25	19.6736	85.5300	17.42	0.39	3.58	9.32
L26	19.6944	85.5350	16.27	0.36	2.50	6.87
L27	19.6600	85.5067	15.88	0.35	9.25	26.48
L28	19.6572	85.4997	15.49	0.34	13.00	37.92
L29	19.6539	85.4750	14.58	0.32	13.00	40.37
L30	19.6503	85.4828	15.78	0.35	12.67	36.25
L31	19.6472	85.4753	14.92	0.33	11.33	34.40
L32	19.6444	85.4664	14.82	0.33	11.08	33.92
L33	19.6627	85.5044	18.18	0.40	4.08	10.21
L34	19.6612	85.4983	17.87	0.40	5.08	12.82
L35	19.6611	85.4947	14.07	0.31	6.00	19.20
L36	19.6613	85.4926	16.70	0.37	1.67	5.12
L37	19.6611	85.4903	14.27	0.32	5.92	18.76
L38	19.6599	85.4900	12.40	0.27	7.08	25.89
L39	19.6525	85.4342	13.84	0.31	7.50	24.39
L40	19.6500	85.4431	15.88	0.35	12.75	36.15
L41	19.6500	85.4503	16.15	0.36	12.58	35.18
L42	19.6522	85.4547	17.90	0.40	16.17	40.95
L43	19.6553	85.4581	16.77	0.37	23.50	63.39
L44	19.6564	85.4636	16.76	0.37	23.75	64.10
L45	19.6589	85.4522	16.22	0.36	2.83	7.90
L46	19.6563	85.4579	15.12	0.33	19.83	59.36
L47	19.6553	85.4578	17.69	0.39	6.17	15.77
L48	19.6572	85.4725	16.67	0.37	6.58	17.83
L49	19.6536	85.4325	15.25	0.34	23.42	69.52
L50	19.6614	85.3729	17.35	0.38	14.92	38.89
L51	19.6098	85.2948	12.52	0.28	4.25	15.34
L52	19.6036	85.3157	16.21	0.36	6.25	17.60
L53	19.6011	85.3152	17.69	0.39	4.17	10.73
L54	19.6467	85.4064	14.55	0.32	9.08	28.18

Table 3. Magnetic Susceptibility values (Mass Susceptibility and Volume Susceptibility) for corresponding sampling sites.

Spatial variations of the mass susceptibility values are mapped by 2D and 3D contour diagrams (Figures 4.2 and 4.3). On the 2D map, regions with very high density of contour lines indicates the locations with high susceptibility values and those low values of susceptibility are represented by largely spaced contours. This 2D map of the study area shows a high range of susceptibility values towards the inner part of lagoon. On the other hand, in the 3D susceptibility contour maps, locations with higher values are represented by isolated peaks on the map but the rest of the topography indicates low susceptibility ranges.

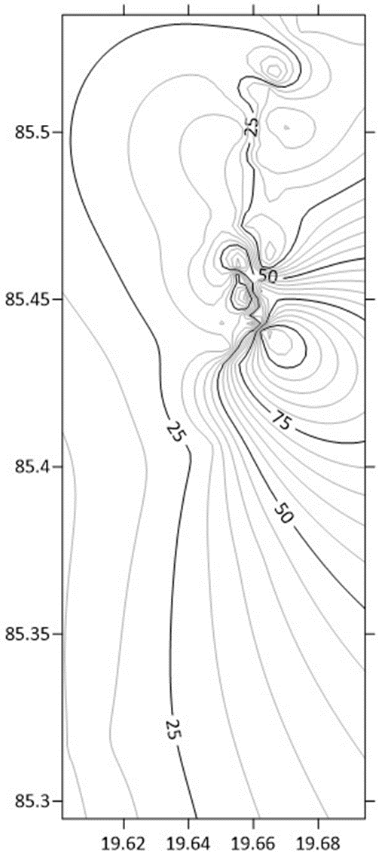

Fig.4.2 2D Susceptibility Map of Study Area.

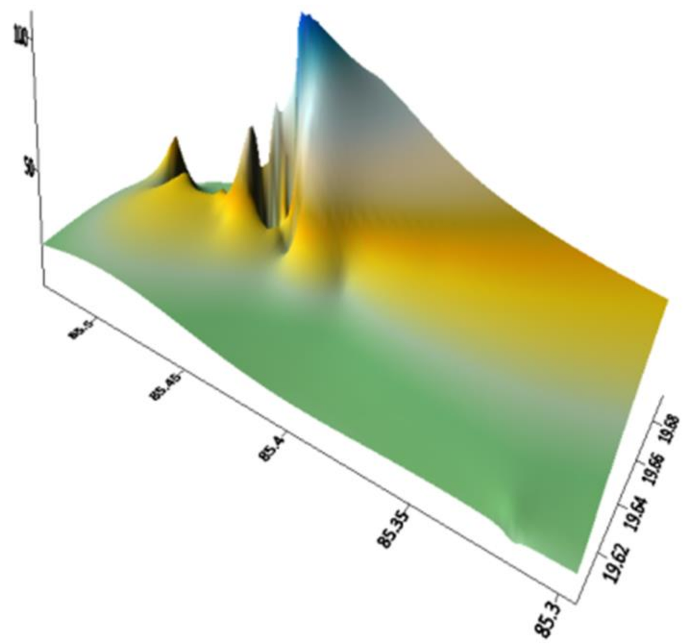

Fig.4.3 3D Susceptibility Map of Study Area.

4.2 THERMOMAGNETIC STUDY

The temperature above which some materials permanently lose their magnetic properties is known as the Curie temperature (T_C), sometimes known as the Curie point. However, induced magnetism can (almost always) replace the T_C. The most popular technique for calculating T_C is to measure the temperature-dependent high-field induced magnetization, or Mi, and produce thermomagnetic curves (e.g. Housden et al., 1988). During the heating and cooling process, variations in Mi can also provide information concerning magneto-mineralogical transformations.

Very minute amount of powder of soft sediments were placed into a movable container and heated upto 700°C in a saturating magnetic field. The decreasing saturation remanence is monitored by a computer controlled horizontal Curie Balance as the temperature increases, until it falls to zero. The corresponding value of temperature for zero saturation remanence is known as the Curie Temperature, T_c, of the magnetic minerals within the sample. As the sample was cooled to 100°C, a saturation magnetization was acquired by the sample resulting in a cooling curve. Similar heating and cooling curves are observed for samples which have undergone little alteration during the heating phase. However, changes in magnetic mineral may occur yielding contrasting curves.

In the present, the thermomagnetic study was carried out for the soft sediments of outer channel of Chilika Lagoon. In figures 4.5 - 4.8 show the variations in thermomagnetic curves for representative soft sediment samples. Representative samples display both reversible and irreversible curie curve behaviour. Based on the thermomagnetic results, it is clear that multi-component magnetic minerals are present in the sample L1,which is evident in the heating curve. According to the study, the soft sediment samples contain both ferromagnetic and paramagnetic materials. Haematite, a paramagnetic mineral with a T_c of 680 ^oC, and magnetite, a ferromagnetic mineral with a T_c of 580 ^oC, are both present. In this case, the heating and cooling curves have nearly identical characteristics, which is reversible in nature acquiring a relatively stable magnetic behaviour. The thermomagnetic curves, from the following samples such as L6, L10, L11, L12, L15, L16, L20, L28, L31, L34, L36, L43, L44, L46 and L51, also exhibit a similar feature.

However, in the case of sample L17, it is clear from the thermomagnetic curve that the sample exhibits the Curie temperature is about 570 ^oC, indicating the existence of magnetite. This type of sample can acquire stable magnetization, and samples L22, L30, and L50 exhibit comparable characteristics. The natures of these curves are also reversible.

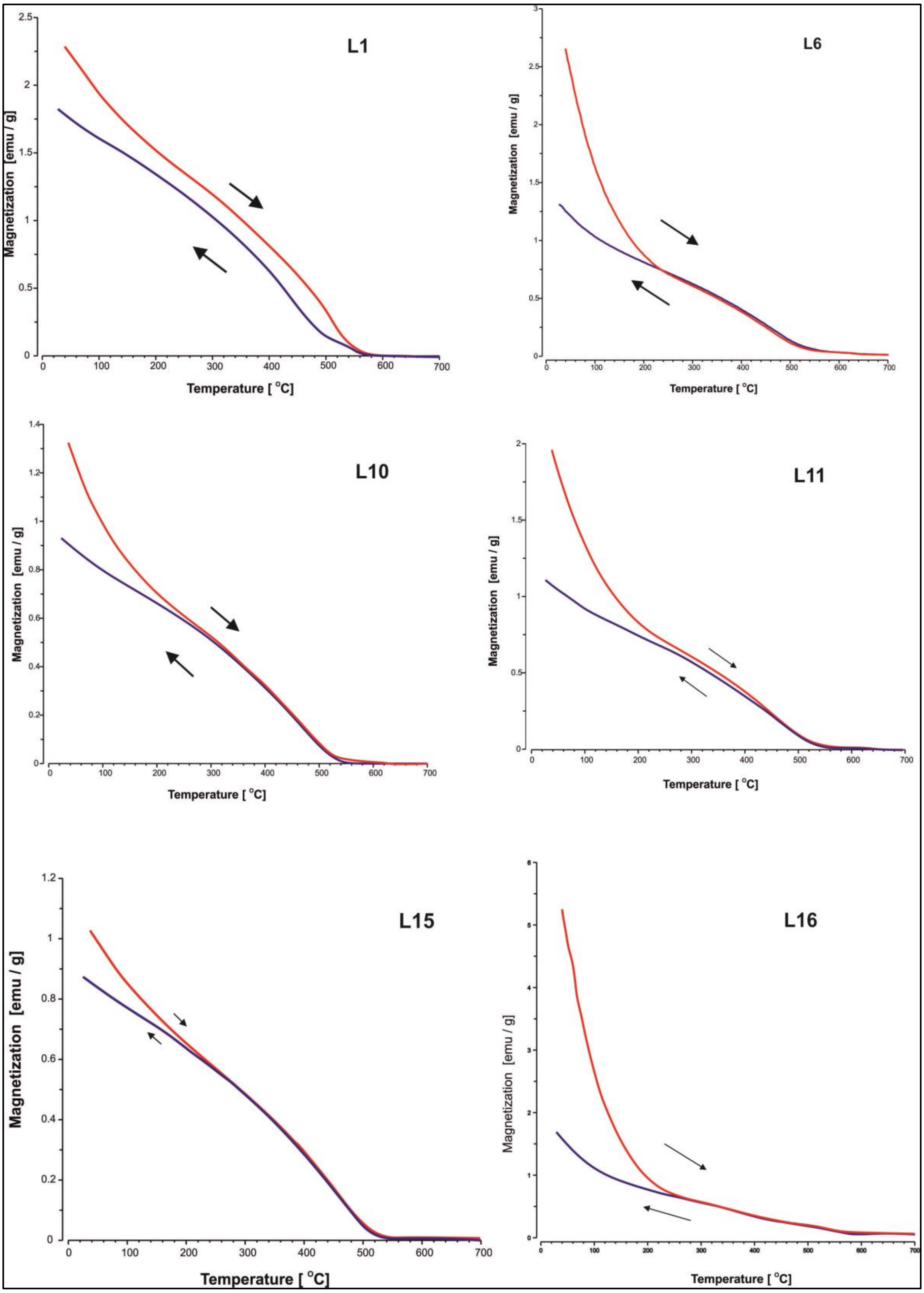

Fig. 4.4 Thermomagnetic curves for representative samples. Heating (Cooling) curves are shown in Red (Blue) colour with arrows, denoting curve progression.

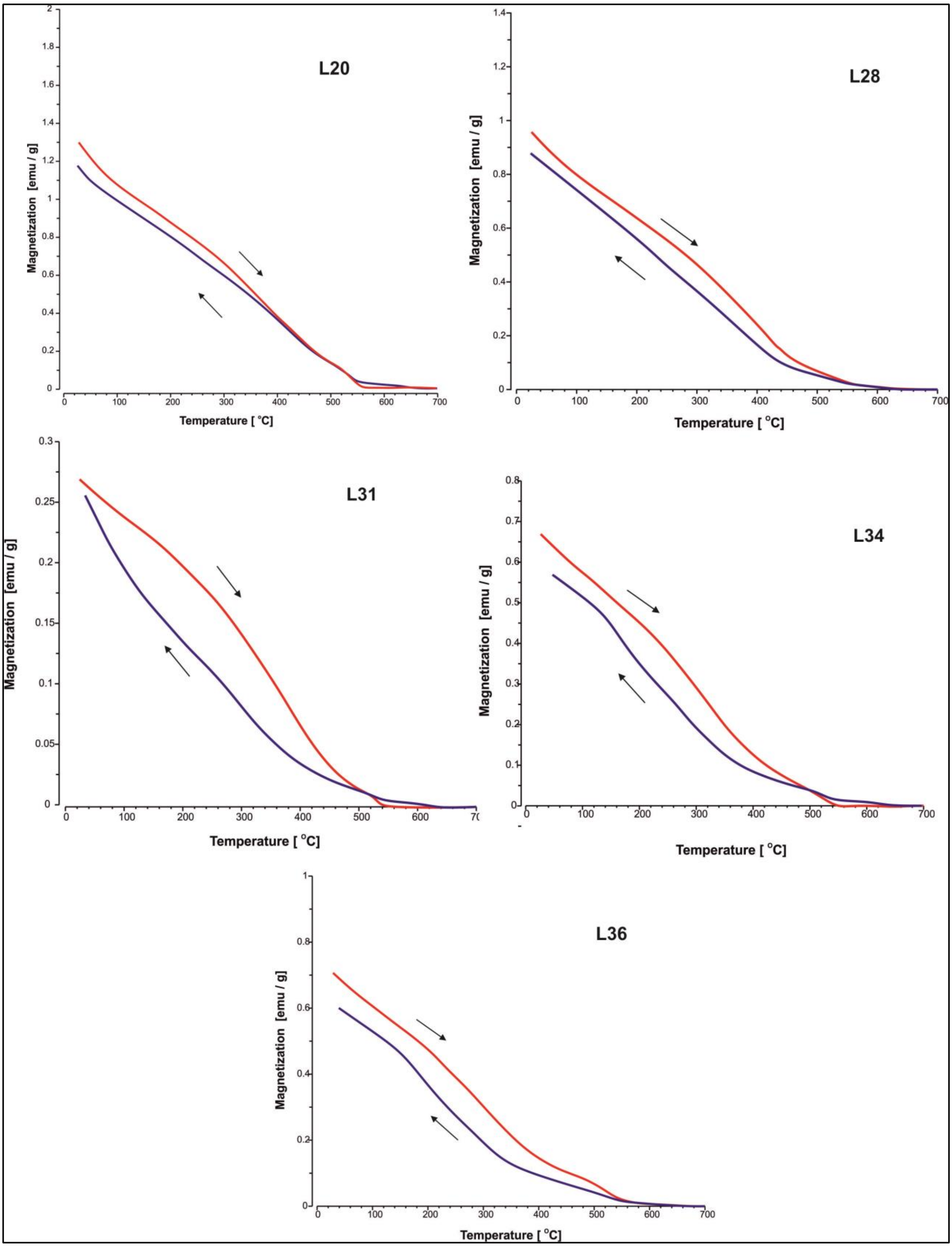

Fig. 4.5 Thermomagnetic curves for representative samples. Heating (Cooling) curves are shown in Red (Blue) colour with arrows, denoting curve progression.

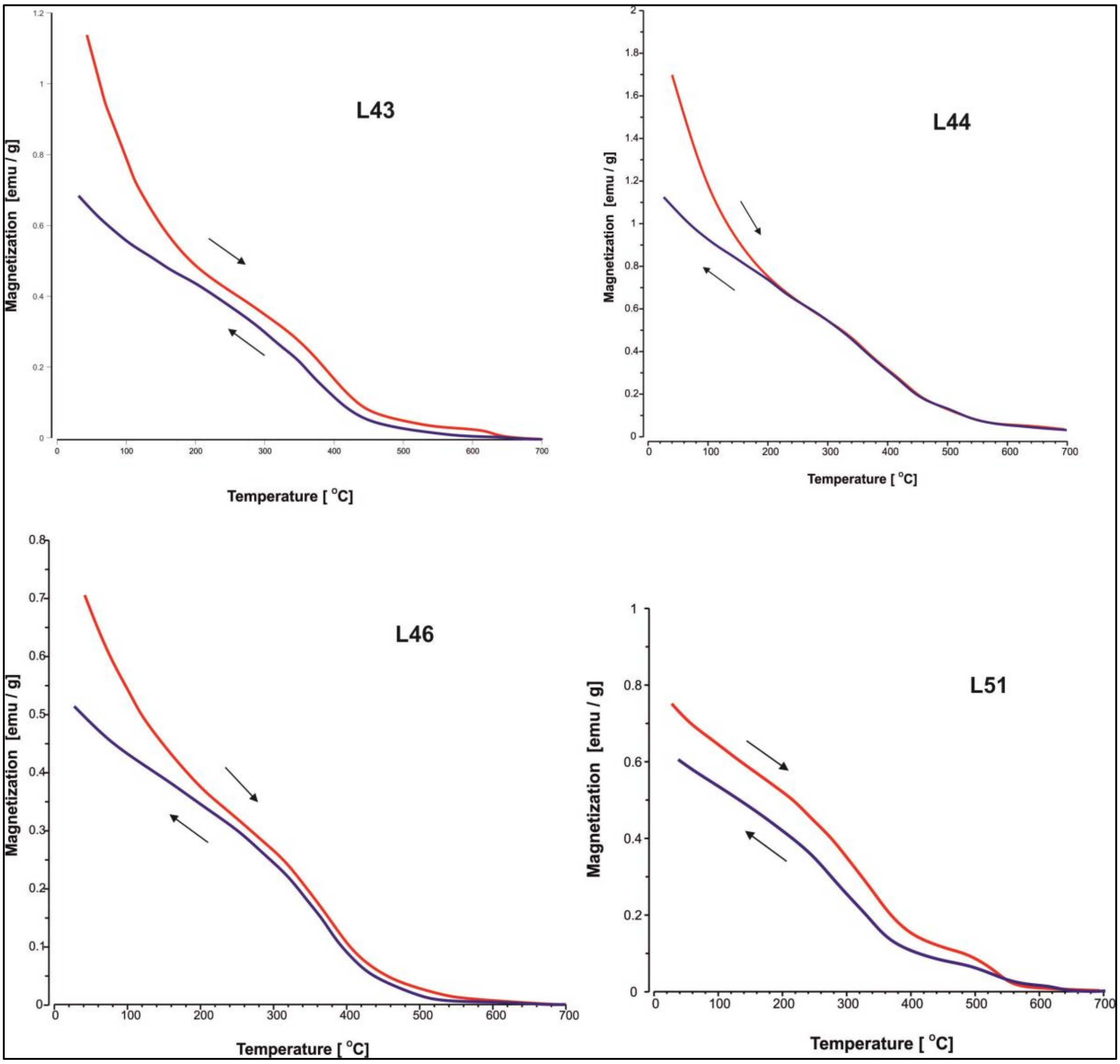

Fig. 4.6 Thermomagnetic curves for representative samples. Heating (Cooling) curves are shown in Red (Blue) colour with arrows, denoting curve progression.

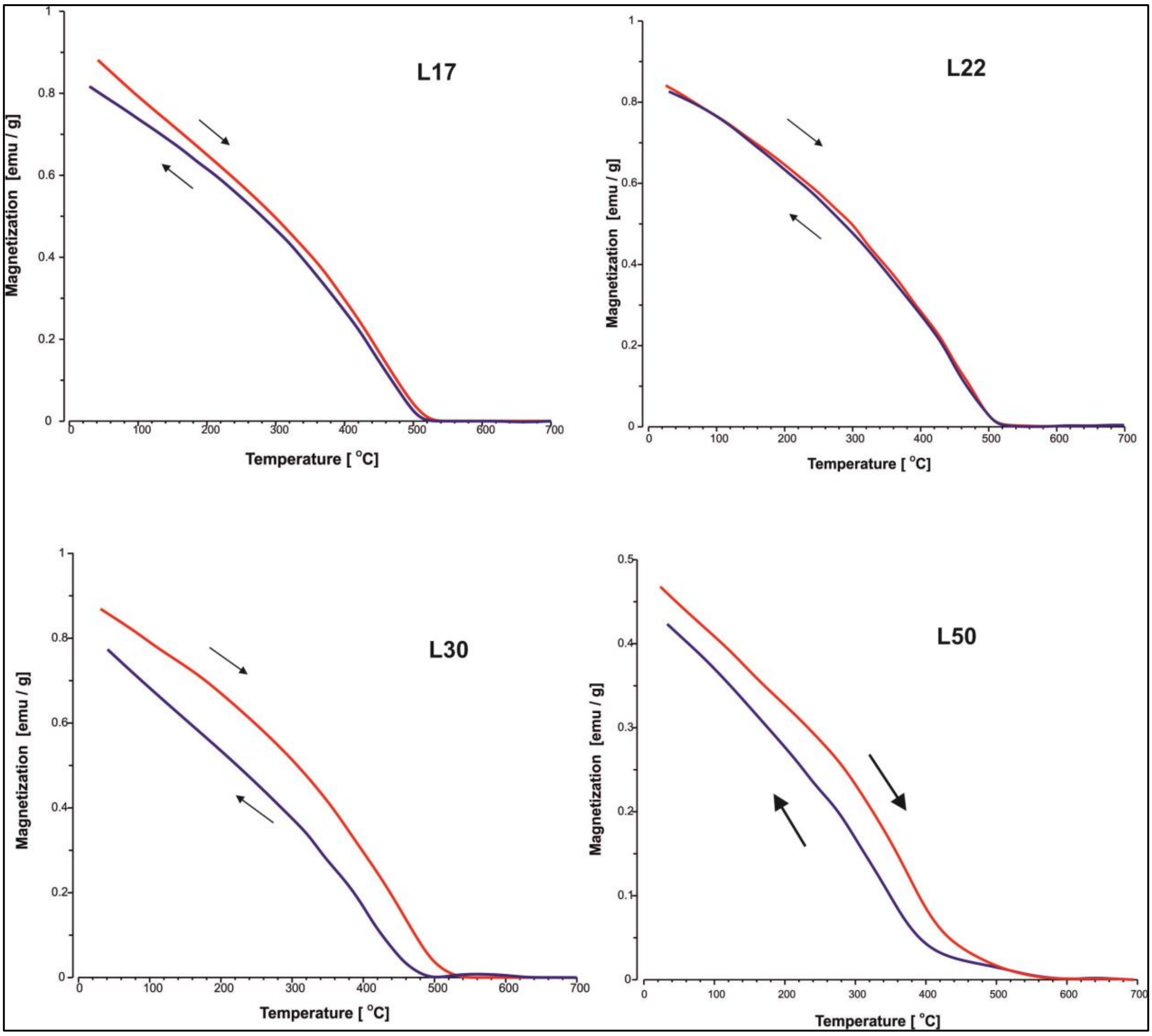

Fig. 4.7 Thermomagnetic curves for representative samples. Heating (Cooling) curves are shown in Red (Blue) colour with arrows, denoting curve progression.

4.3 HYSTERESIS STUDY

Dust samples of soft sediment were subjected to cycled magnetic field in a Advanced Variable Field Translation Balance (AVFTB). A resulting hysteresis loop indicates the presence of ferromagnetic minerals and can be expressed in terms of saturation magnetization and coercivity. Each sample was weighed to allow mass correction to be made, prior to being exposed to the magnetic field, from an initial magnitude of 1000 mT. The area enclosed by the resulting loop was a measure of the work done in taking a unit measure of the mineral around the cycle once. Values of saturation magnetization M_s, residual saturation M_{rs} and coercivity H were recorded and compared to identify the domain state of the ferro-magnetic minerals present. A ratio of $M_{rs} / M_s < 0.1$ indicates a predominant presence of MD grains, whereas, $M_{rs} / M_s > 0.1$ implies that a significant fraction of SD grains is present. The coercivity can provide information on the type of magnetic minerals contained within the soft sediment sample. It is an especially good indicator of haematite which has a value of H above 5 mT and is therefore characterized by an increasing curve above the applied field.

The size as well as the hardness of magnetic minerals can be determined by using the magnetic hysteresis curve, which is the identical probability of the rock's magnetic property. During this research study, hysteresis measurements have been carried out by Advanced Variable Field Translation Balance (AVFTB). On the basis of hysteresis loops, it is evident that the studied soft sediment samples are consisting of both ferro- and para-magnetic minerals. In Figures 4.8 to 4.11, it is abundantly evident that hysteresis loop shapes range from thinner to wider. Generally thinner loops indicate the predominance of low-coercive components, i.e., presence of ferromagnetic minerals, whereas, widely open loops indicate the presence of a medium leading to a relatively high-coercive magnetic-mineral, i.e., the presence of paramagnetic minerals.

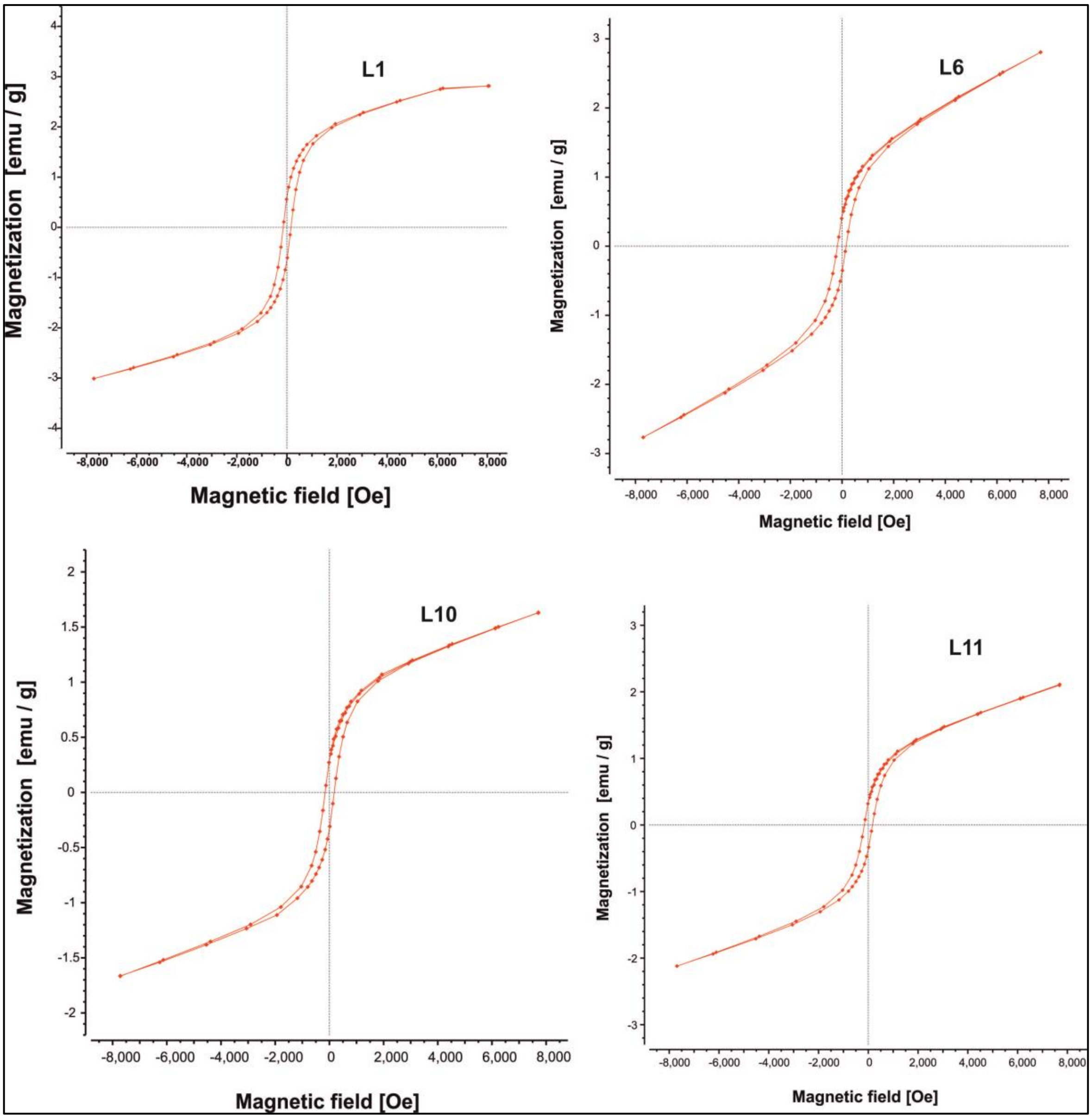

Fig. 4.8 Magnetic Hysteresis Loops for representative samples of outer channel of Chilika.Lagoon.

Based on the hysteresis loop of L1 sample, it is clear that the studied sample contains both ferro and para magneticminerals. The ferromagnetic minerals have a very low coercive force, while the other unsaturated paramagnetic minerals are also present. The soft sediments of L6, L10, L11, L12, L15, L16, L20, L28, L31, L34, L36, L43, L44, L46, and L51 all also exhibit the similar features. However, sample L17 has the characteristics of a ferromagnetic hysteresis loop with stable, saturated, low-coercive magnetic-minerals. The following samples like L22, L 30, and L50, also exhibit similar nature of ferromagnetic mineral.

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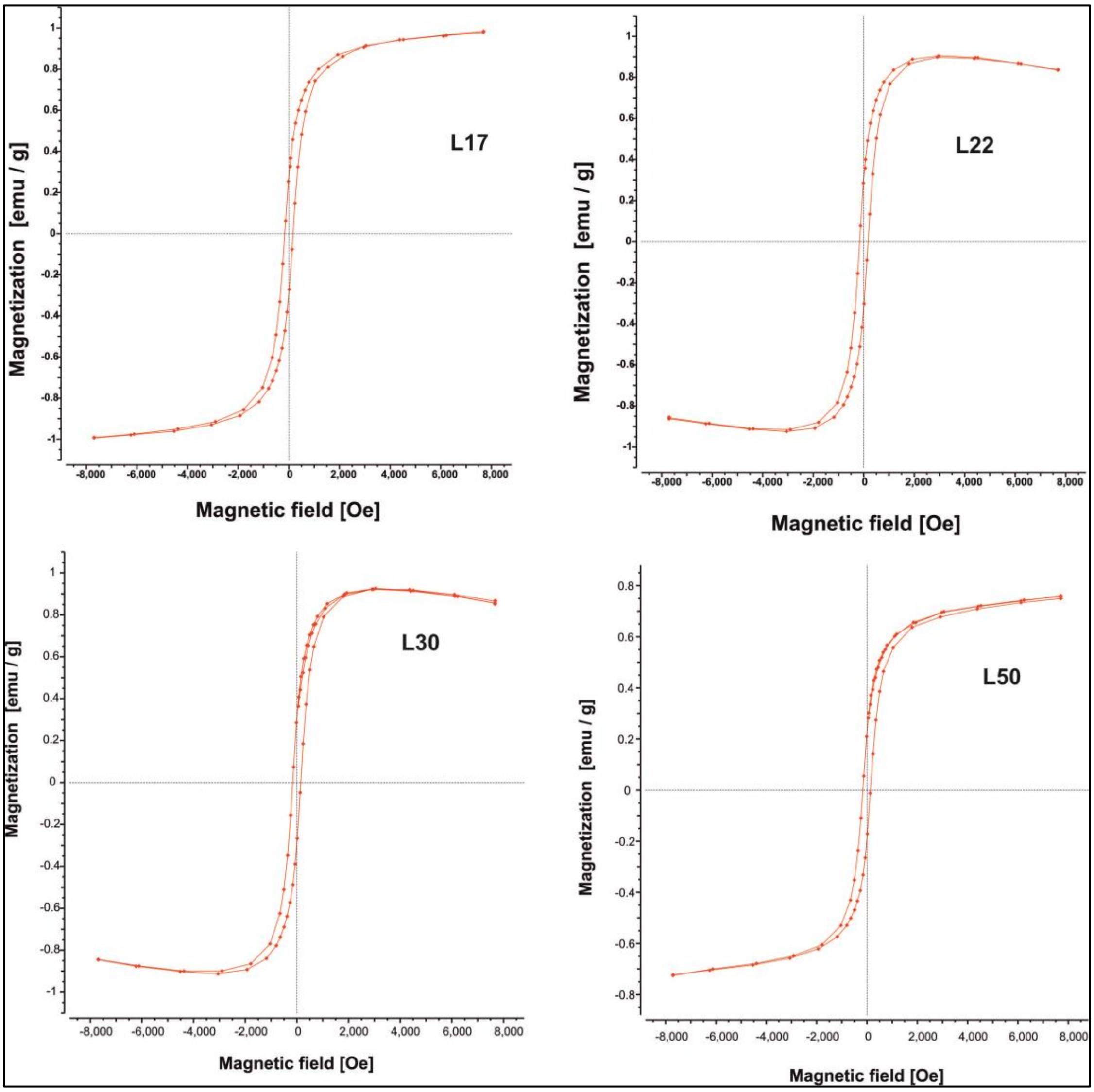

Fig. 4.9 Magnetic Hysteresis Loops for representative samples of outer channel of Chilika Lagoon.

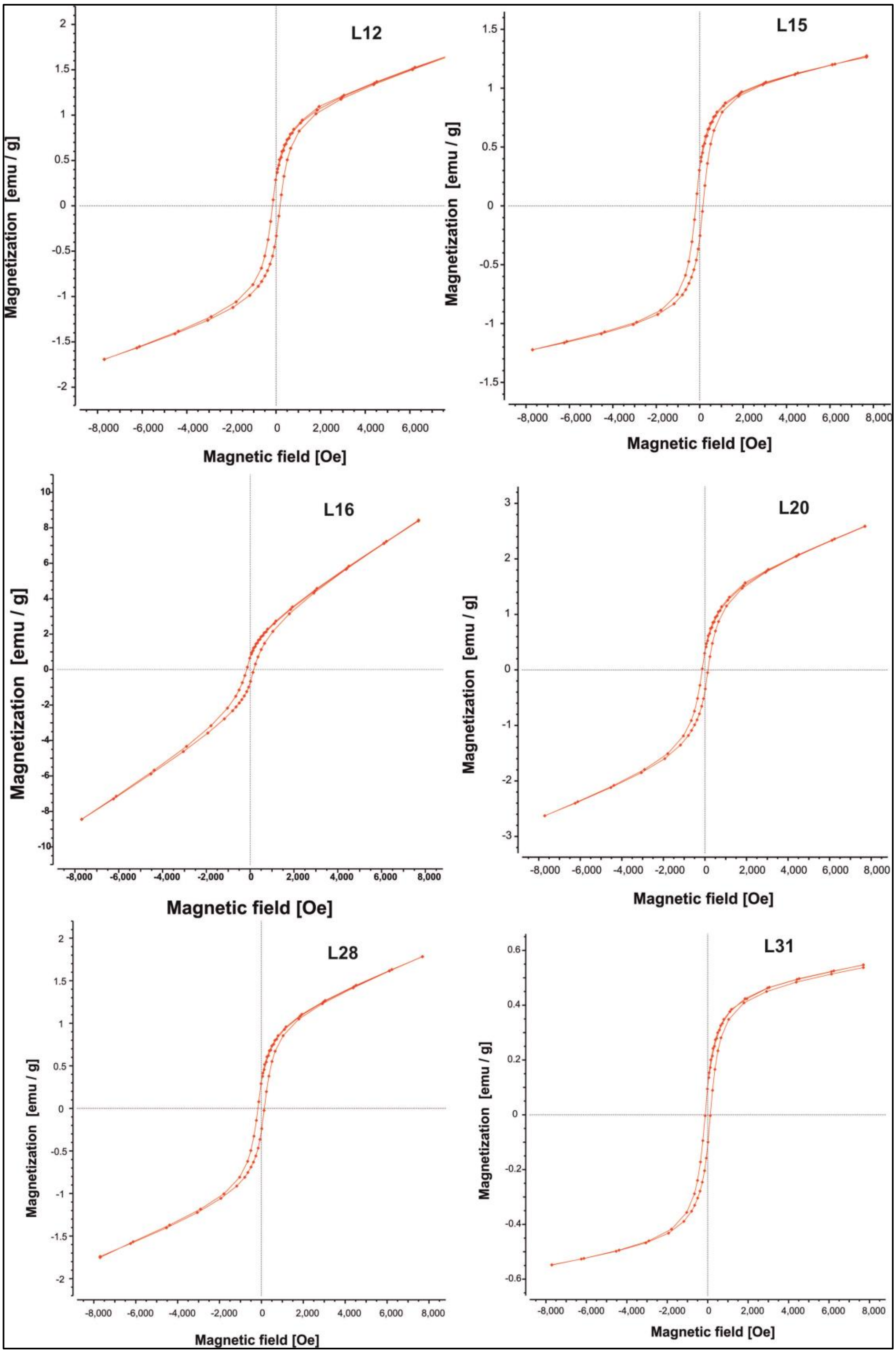

Fig. 4.10 Magnetic Hysteresis Loops for representative samples of outer channel of Chilika Lagoon.

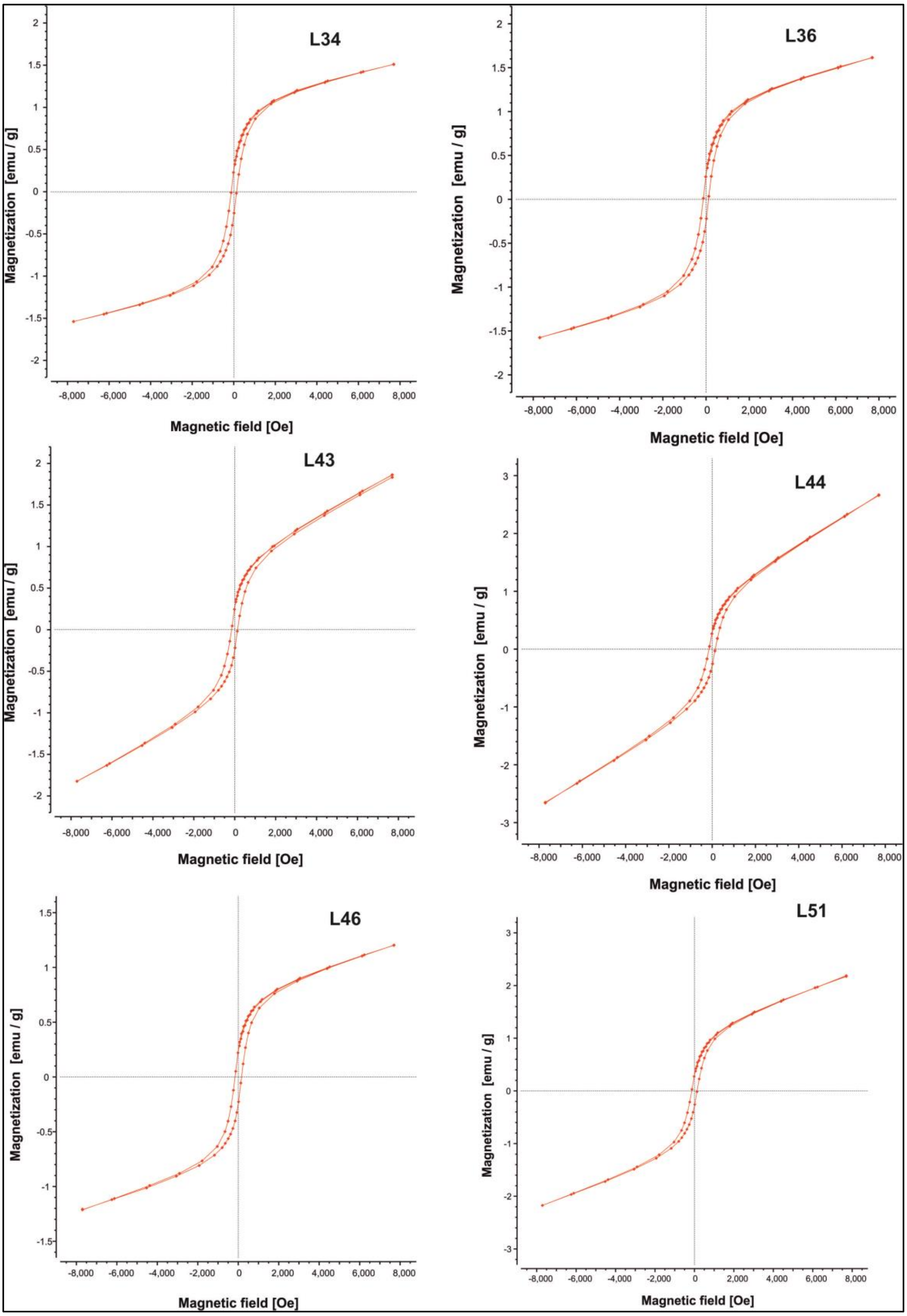

Fig. 4.11 Magnetic Hysteresis Loops for representative samples of outer channel of Chilika Lagoon.

4.4 Isothermal remanent magnetization (IRM) study

An isothermal remanent magnetization (IRM) is produced when a rock experiences a large saturating magnetic field over a short period of time at constant temperature. In the laboratory, isothermal remanent magnetizations are applied by subjecting the samples to an applied field in one constant direction using a Pulse Magnetizer. The acquired magnetization was measured by Spinner Magnetometer for each magnitude of the applied field progressively increased to 2500 mT. The saturation value of the IRM was indicated by the maximum value of intensity attained by the sample. The orientation of the sample was kept constant to avoid an opposing field partially cancelling out the acquired magnetization.

IRM can be used to detect very small amounts of magnetic material and is especially proficient at distinguishing between the magnetite-ulvospinel series and the haematite-ilmenite series. Minerals belonging to the former of the two series have typically low coercivities and saturate in low applied fields less than 500 mT. Conversely, members of the haematite-ilmenite series require high applied fields to reach saturation and are recognisable in laboratory studies by the continuing rise in the IRM acquisition curve to the maximum fields (~2500 mT) obtainable in the laboratory. The acquisition curves provide a more comprehensive method of distinguishing haematite within the samples from much stronger carriers of remanent magnetization, such as magnetite, than the studies of thermomagnetic behaviour because stronger saturating fields can be used than with the VSM. The weak-field IRM only affects the lowest part of the coercivity spectrum in which magnetite falls producing a characteristic IRM saturation at ~300 mT for this mineral. The isothermal remanent magnetization has been plotted against the magnetizing field for the samples (Figs. 4.12; 4.13; 4.14; 4.15 and 4.16).

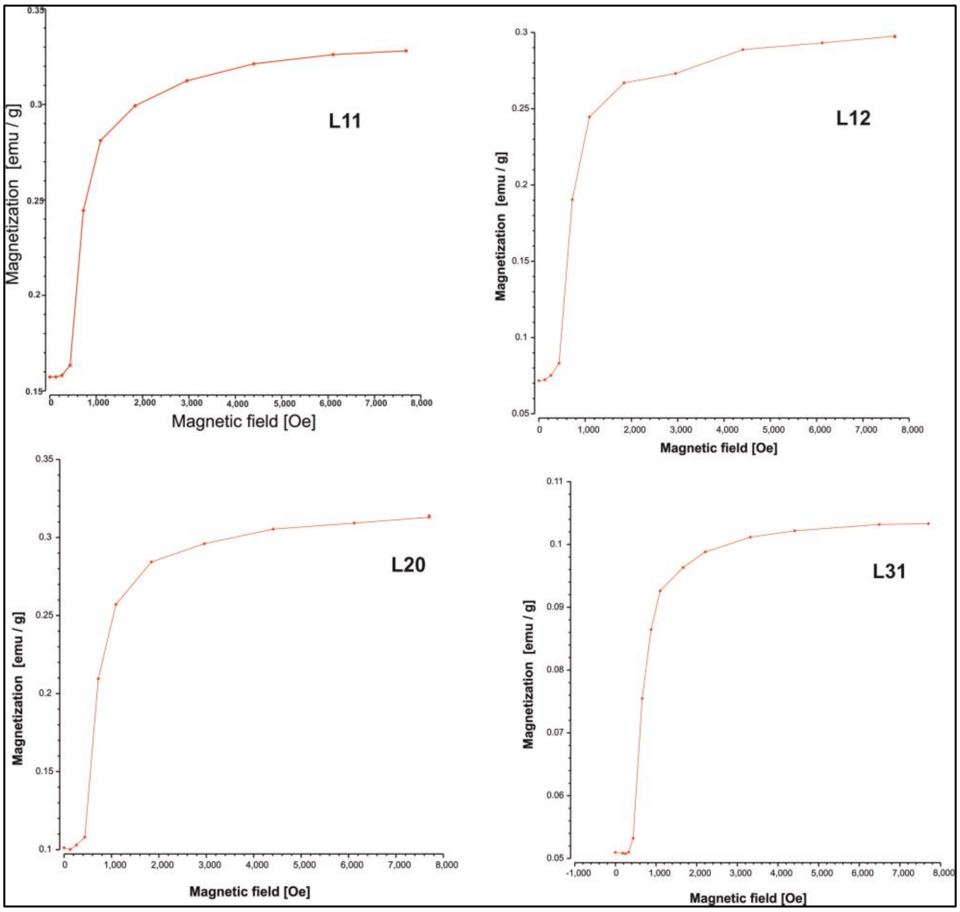

Fig. 4.12 Isothermal Remanent Magnetization (IRM) curves for some representative samples of outer channel of Chilika Lagoon.

In this study, the L1 sample shows a continuous steep magnetization trend that tends to saturate at roughly around 1000 Oe, suggesting that, the presence of ferromagnetic minerals, and eventually saturates at about >4000 Oe, suggesting the existence of paramagnetic minerals. In the samples like L10, L11, L12, L20, L31,L34, L36, and L43 all the samples exhibit similar characteristics (Fig 4.12 and 4.13). So, from the IRM curves of these above-mentioned samples, it is evident that the presence of both ferro- and para-magnetic minerals in the studied soft sediments.

An IRM curve exhibiting a typical paramagnetic character is obtained for L6, and similar characteristics are also observed in case of following samples like L15, L16, L20, L28, L44, L46, and L51 (Fig 4.14 and 4.15). On the other hand, the IRM curve for L17 shows a typical ferromagnetic character, with saturation at roughly about1000 Oe. The similar nature of IRM curve is also evident in the following samples like L22, L30 and L50 (Fig 4.16).

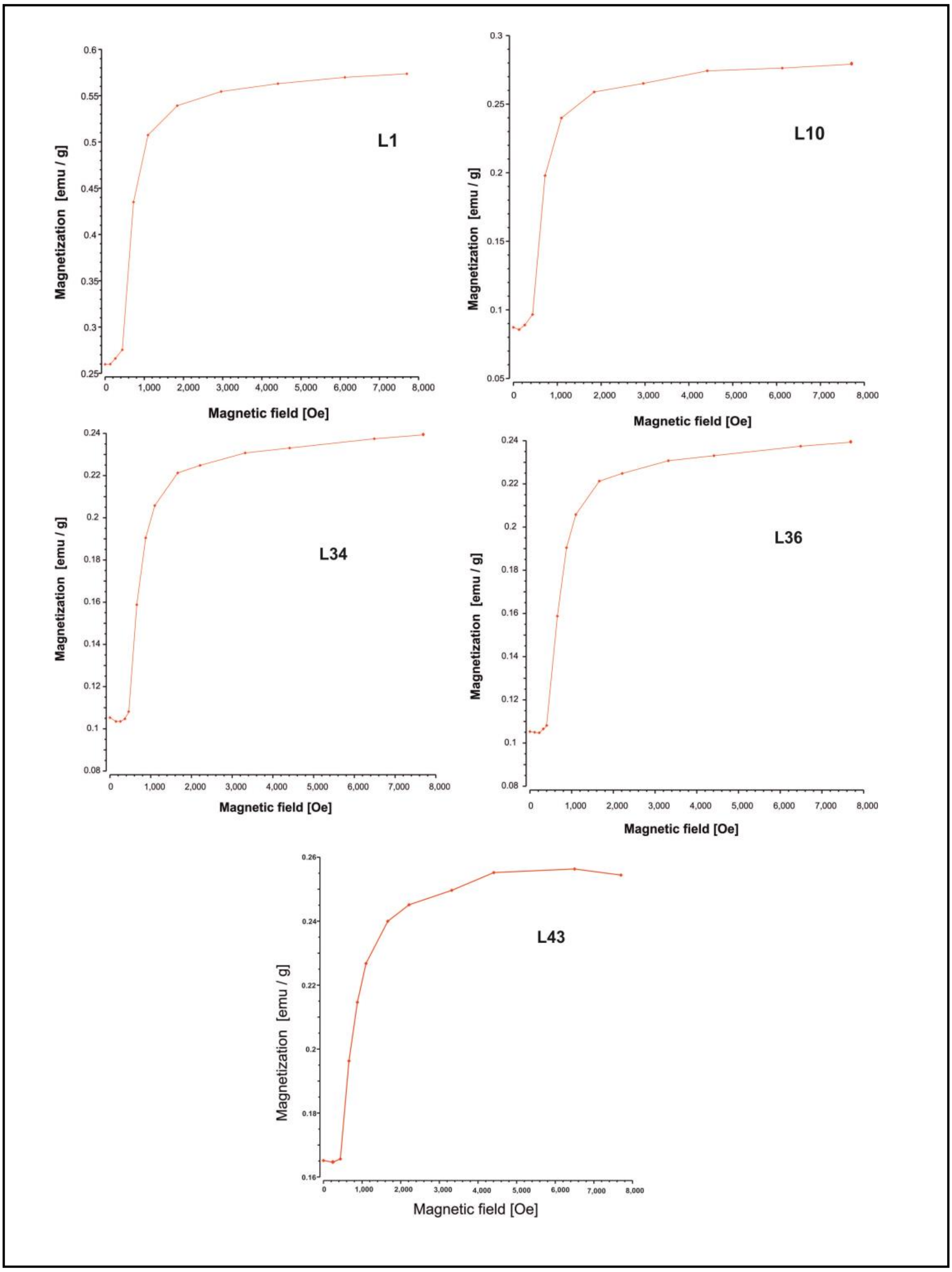

Fig. 4.13 Isothermal Remanent Magnetization (IRM) curves for some representative samples of outer channel of Chilika Lagoon.

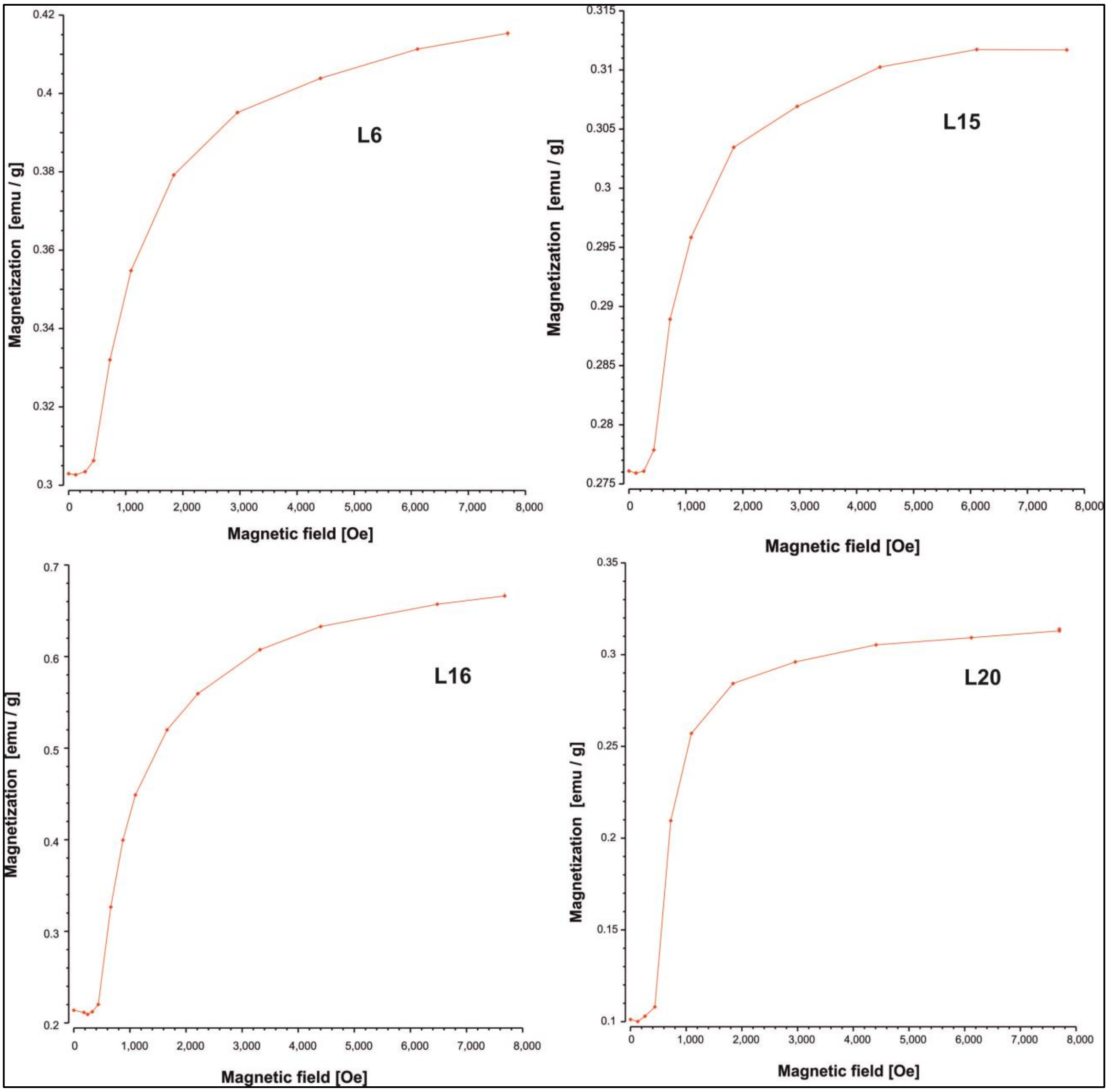

Fig. 4.14 Isothermal Remanent Magnetization (IRM) curves for some representative samples of outer channel of Chilika Lagoon.

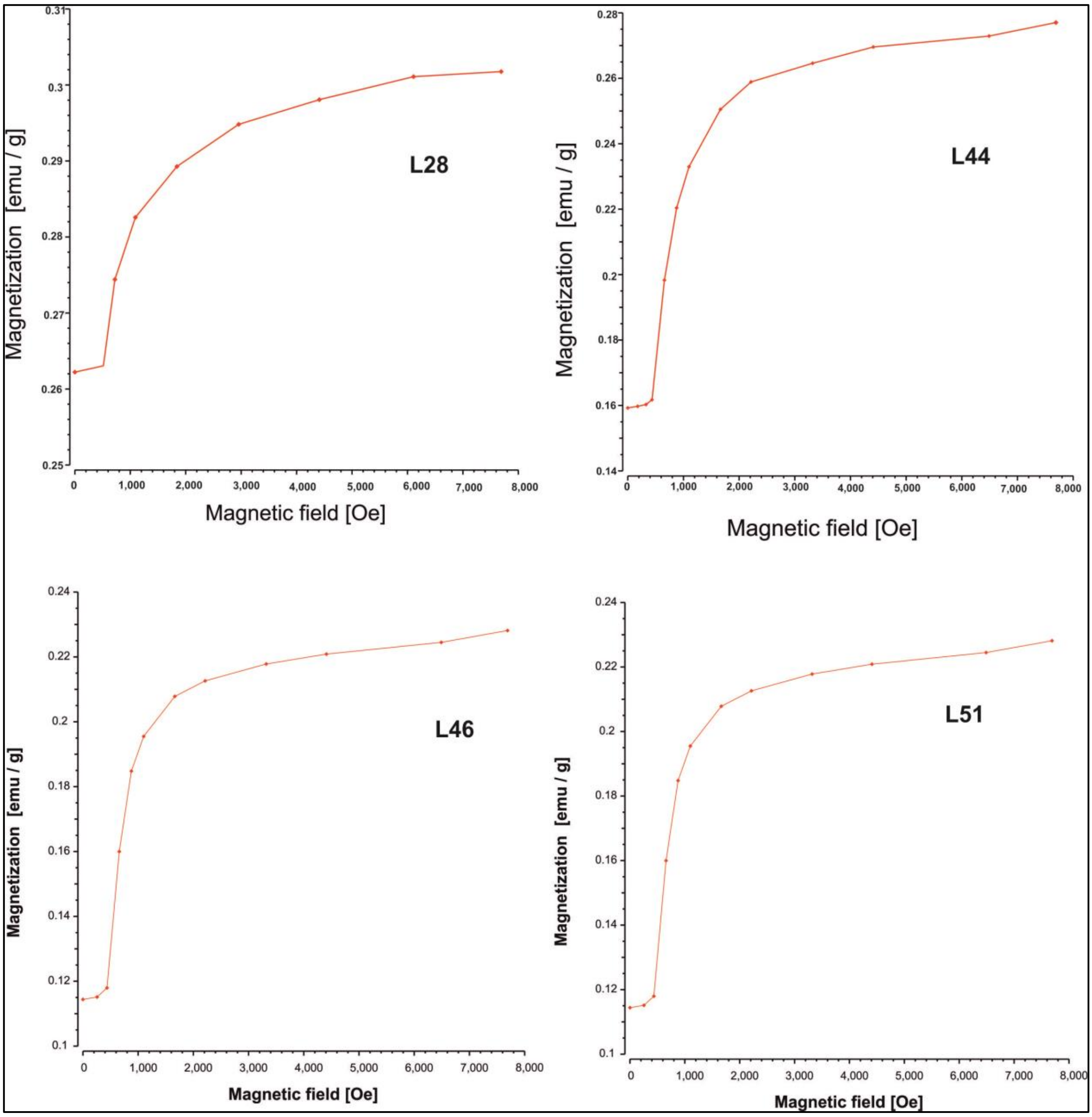

Fig. 4.15 Isothermal Remanent Magnetization (IRM) curves for some representative samples of outer channel of Chilika Lagoon.

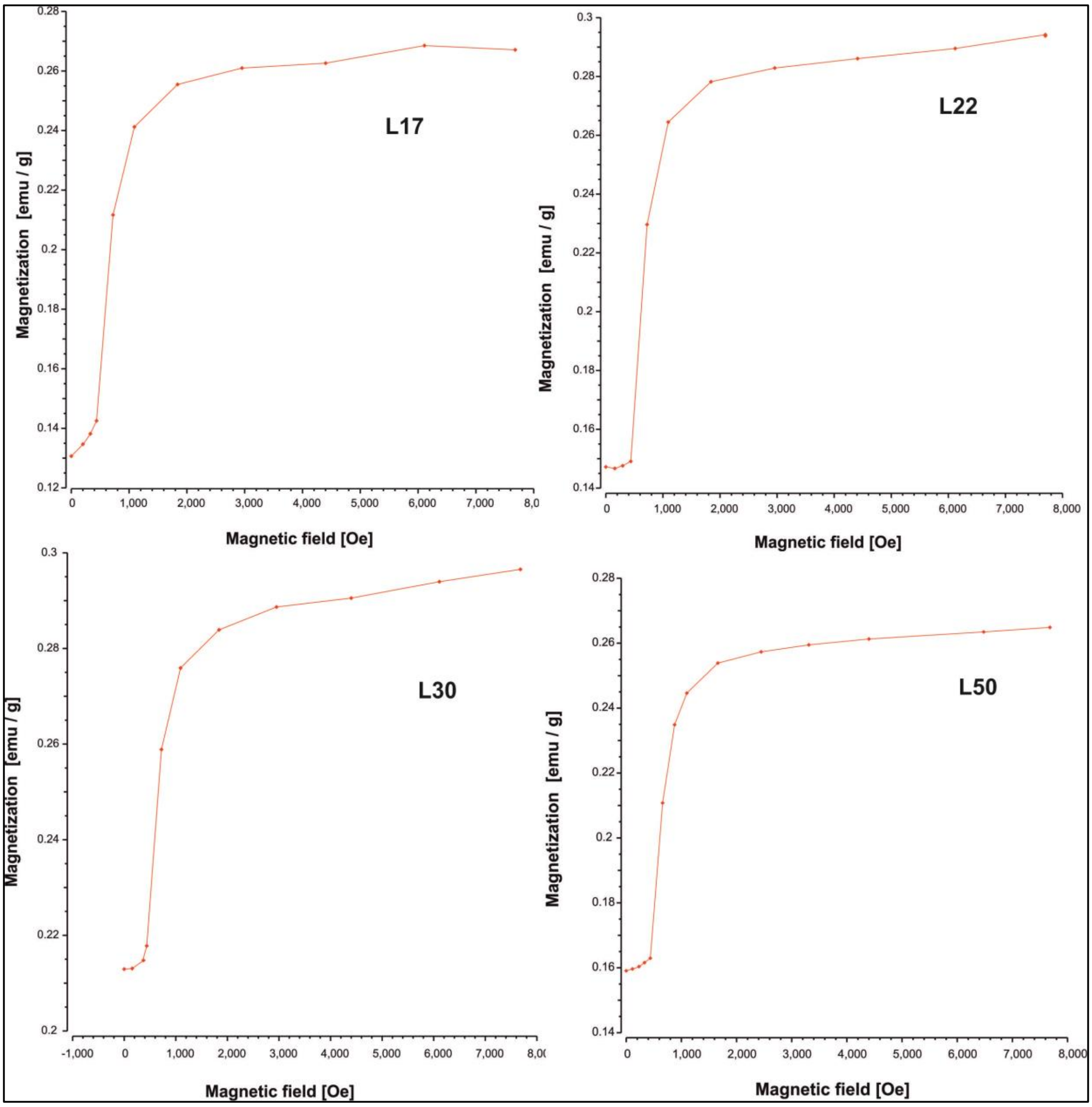

Fig. 4.16 Isothermal Remanent Magnetization (IRM) curves for some representative samples of outer channel of Chilika Lagoon.

5.1 DISCUSSION

Foraminiferal tests, which act as the basis for paleontological proxies, largely work under the belief that the relationship between various environmental factors and foraminiferal assemblage has remained consistent over a range of time scales (Scott & Medioli, 1980; Engelhart et al., 2013). Therefore, important information about the environmental conditions at the time of their test development can be obtained from the diversity of such fossil assemblages. Studies of total assemblages, including both living and dead individuals, offer an averaged perspective on population dynamics over a period (Goldstein & Watkins, 1999; Walker & Goldstein, 1999). Increased organic content in sediments is a common characteristic of coastal lagoon ecosystems, resulting in the dominance of stress-tolerant foraminiferal species (Hallock, 2012). Foraminifera, not only evaluates various environmental conditions like salinity, dissolved oxygen content, and pH changes, but also the impact of anthropogenic and natural stressors. Therefore, an evaluation of the lagoon's health based on benthic foraminiferal diversity would be beneficial in developing effective management practices (Engle, 2000; Armynot du Chatelet et al., 2016). Magnetic properties of soft sediments are very useful paleoenvironmental and paleoclimatic indicators for lacustrine sediments (Peck et al., 1994, Nie et al., 2018). Magnetic parameters of soft sediments in lagoon environments can be affected by sediment deposition (Snowball and Thompson, 1988, Roberts et al., 1996, Demory et al., 2005, Ao et al., 2010, Murdock et al., 2013, Su et al., 2013, Roberts, 2015, Just et al., 2016) as well as erosion and sediment transport processes (Thompson and Morton, 1979, Oldfield et al., 1985, Evans et al., 1997, Hu et al., 2015). Therefore, interpreting magnetic characteristics is another very useful method for detecting environmental contamination in a lagoon's soft substrate (Radan & Radan., 2011).

5.1.1 **Foraminiferal Analysis**

The total foraminiferal number (TFN), including both living and dead forms, has been used for all the analysis. Previous studies (Kumar et al., 2014) reported an abundance of living foraminifera from the outer channel of Chilika Lagoon, which is marine-influenced. Previous investigation (Sen & Bhadury, 2016; Barik et al., 2019) reported a low abundance of foraminifera from the interior part of the lagoon, which is characterised by marginal environments. However, the present study of the lagoon shows a poor count of living foraminifera. Here, it must be noted that the seasonally controlled hydrodynamics, intensified freshwater influx, and algal growth impacted the foraminiferal assemblages. This has led to the increase of dead specimens or, at places, with rare living foraminifera (Dimiza et al., 2016).

Among 14 species of agglutinated form, *Milliamina fusca*, *Ammotium salsa*, *Trochammina* spp., *Ammobaculites* sp. and *Haplophragmoides* sp. indicate a stressed environment where water circulation is stagnant and are considered predominating in nearshore vegetated settings (Horton et al. 2003, 2005, Murray & Alve 2000). Among these agglutinated forms in Chilika lagoon, *Milliamina fusca* (25%) was the most dominant one. They are strongly euryhaline and show high-temperature tolerance, and their mode of life is restricted in the marsh and shallow lagoonal environment (Murray & Alve, 2011). *Trochammina* sp. can sustain in low oxygenic conditions with high salinity (Murray & Alve, 2011; Kumar et al., 2014). *Ammobaculites* sp are mud lovers. Hence, their presence indicates low oxygen and muddy substrate (Murray & Alve, 2011). *Haplophragmoides* sp are generally found in sandy to muddy substrates (Murray & Alve, 2011). So, these agglutinated species indicate high temperate and muddy substrate with low oxygenic conditions. In the lagoon's outer channel, agglutinated specimens made up the majority of the assemblages and were more abundant (35%) than those in the central sector (< 1%).

Benthic foraminiferal assemblages throughout the outer channel of Chilika Lagoon are dominated by *Ammonia beccarrii, Ammonia parkinsoniana,* and *Pararotalia nipponica*. *Ammonia* spp. (*Ammonia tepida* and *Ammonia parkinsoniana*) dominates the lagoon's central section, with a high occurrence rate of 80%. The broad range of tolerance displayed by *Ammonia* spp. may be the cause of their abundance (Moodley & Hess, 1992; Le Cadre & Debenay, 2006; Hallock, 2012). According to Badawi and El-Menhawey (2016) and Saraswat et al. (2015), the maximum abundance of living foraminifera in the interior brackish region without significant seasonal variations suggests that either foraminifera frequently receive the ideal substrate and bottom water conditions for their reproduction, or they are adapted to reproduce in low salinity conditions as they prefer to grow and reproduce in permanent saline or brackish water bodies with muddy substrate. Earlier studies reported that *Ammonia beccarii* are opportunistic and pollution-tolerant. They can easily sustain the salinity variation in the shallow ocean, lagoons, and delta (Debenay et al., 2005; Frontalini et al., 2009; Koukousioura et al., 2012; Martins et al., 2013; Dimiza *et al*. 2016). This species can sustain under low oxygen conditions and tolerate fluctuations in temperature (Walton and Sloan, 1990). The dominance of this species increases with the low availability of primary production (Debenay et al., 1998). According to Rao et al. (1979), *A. beccarii* is more prevalent in the shallow depth samples due to wave action and substrate dominated by sand. *Ammonia tepida* is an opportunistic species that can withstand fluctuations in salinity and is tolerant of lower salinities and prefers to live in fine sediments (Debenay et al., 1998). It typically occurs in shallow marine, lagoonal, and deltaic environments (Almogi − Labin et al. 1992, Yanko et al. 1998; Debenay et al. 2005, Frontalini et al. 2009, Koukousioura et al. 2012, Martins et al. 2013, Dimiza et al. 2016). *Ammonia parkinsoniana* is generally found in low-salinity zones (Schönfeld et al., 2021). Thus, *Ammonia* species across the stations indicate a stress-tolerant and cosmopolitan environment throughout the lagoon. Members of this species are known to exhibit strong resistance to hypoxic conditions, which is consistent with the significant negative connection with dissolved oxygen (DO) (Kitazato, 1994; Platen & Sen Gupta, 2001). Studies show *Ammonia* spp. are worldwide and have a broad tolerance range for pollution, salinity, and organic matter (Debenay et al., 2000; Hayward et al., 2004; Carnahan et al., 2009). *Pararotalia nipponica*, the inner shelf benthic foraminifera, can sustain extensive saline conditions (Nigam et al., 2006). The presence of the genus *Elphidium* indicates a low oxygen state in the water (Gupta et al., 1996). Also, *Elphidium crispum* is rich in a sandy substrate (Gupta et al., 1996; Gupta & Platon, 2006; Eichler et al., 2015). *Haynesina germanica* is typically found in fine sediment and well documented in a stressed environment (Alve, 1995; Yanko et al., 1998), whereas *Haynesina depressula* prefers to live in silty substratum (Das et al., 2023).

A low number (<5%) of *Quinqueloculina seminulum* was recorded during our study along the sampling stations. This porcelaneous species is primarily found in low vegetated zones and shallow marine waters (Jorissen, 1988; Sgarrella & Moncharmont Zei, 1993; Murray, 2006; Dimiza et al., 2016). This porcelaneous taxa showed a positive correlation with the amount of fine sediments and a negative correlation with the concentration of dissolved silicate (Gupta et al., 2018). Thus, the low population of miliolids tests indicates a low saline and shallow brackish water habitat prevalence (Anbuselvan & Senthil, 2018).

The present study observed that the abundance of total foraminifera was high during pre-monsoon in the outer channel sector of the lagoon. This might occur as the months before the monsoon are considered the reproductive season of foraminifera (Ghosh et al., 2014). These assemblages also depend on different abiotic components as salinity, temperature, pH and dissolved oxygen (Kumar et al., 2014; Sen & Bhadury, 2016). As the recorded salinity and temperature were high during pre-monsoon, it might be another cause of increased foraminiferal assemblages in the outer channel of the lagoon. During the study, the central sector of the lagoon shows a high abundance of total foraminifera during post-monsoonal months. The lagoon gets a large amount of dissolved nutrients and freshwater from the distributaries of Mahanadi during and after the monsoon.

Benthic communities in Chilika are facing stress as a result of the lagoon's eutrophication and prolonged water residence time (Ganguly et al. 2015).

In comparison to the outer channel, which had a larger composition of very coarse sand, stations in the central sector of the lagoon showed a higher proportion of silt-clay fraction. As the seawater intrudes into the outer channel by three inlets, the sand (%) remains high towards the mouth part of the outer channel. The abundance of foraminifera could be more noteworthy, with a few exceptions in stations away from the outer channel. As we move away from the mouth, the agglutinated foraminifera dominates with a high ratio of agglutinated/calcareous tests. The innermost part of the outer channel is characterized by relatively stagnant water and poor circulation (Rao et al., 2000; Sen & Bhadury, 2016; Sen et al., 2018) with higher salinity (Kumar et al., 2014). The substrate was dominated by mud towards the inner part of the outer channel. Thus, a low oxygen state with poor circulation and high salinity may be responsible for agglutinated forms in the channel. The mouth of the outer channel has no agglutinated form. The same has been recorded from the central sector of the lagoon. Murray's Ternary plot indicates that the outer channel of the lagoon is interpreted as a marginal marine environment, whereas the central sector is influenced by fluvial discharge. Fisher’s alpha index interpreted that the lagoon has low to moderate foraminiferal diversity. In the case of the outer channel, the pre-monsoon periods show more abundant and diverse forms than the post-monsoon months. This is evident due to favourable salinity and temperature conditions during pre-monsoon. Moreover, the Evenness index indicates the high evenness of the population, while the Dominance index is categorized as low to moderate. This result indicated that foraminifera is evenly distributed in this area, with relatively equal abundance. It means no opportunistic taxa are present in this section of the lagoon. In contrast, the central sector exhibits greater diversity and abundance of forms during the post-monsoon season. The previous study found that improving the lagoon's water quality led to an increase in foraminiferal diversity (Gupta et al., 2018). This sector of the lagoon is dominated by the members of the single genus, i.e., *Ammonia.* A positive correlation between the calcium concentration and the diversity and abundance of foraminifera was noted by Mishra et al. (2019). In comparison to the outer channel, the central sector had a higher calcium concentration, and this area was rich in *Ammonia* species. It is clear that organic matter, clay, fine sand, and calcium carbonate all have a significant impact on regulating the distribution and variety of foraminifera throughout the study area (Mishra et al., 2019).

In the Q-Mode clustering, group A shows low diversity with a high abundance of agglutinated taxa. In contrast, group B shows high diversity and a high quantity of the calcareous hyaline group.

This Q mode clustering showed that the innermost part of the outer channel was dominated by agglutinated test, and calcareous forms characterized the lagoonal mouth region. Total organic carbon (TOC) correlates positively with agglutinated species, as do depth and salinity (Gupta et al., 2018). The existence of a positive correlation suggests that the taxonomic content of assemblages is influenced by the amount of food accessible to the sedimentary benthos, independent of environmental factors like salinity, depth, and dissolved oxygen (Gupta et al., 2018).

The study of benthic foraminifera in the central sector helps understand the impact of various environmental conditions on their assemblages. A matrix for cluster analysis was formed using specific species, and the analysis focused on the six most abundant taxa (occurring in over 5% of specimens from a single sampling site). R-mode cluster analysis of foraminiferal fauna in surface sediments offers information about the foraminiferal community structure, revealing two clusters that define the presence of two assemblages. All members of the genus *Ammonia* are grouped in cluster A, indicates presence of high organic matter with minimal sand fraction in the substrate. Cluster B grouped those taxa who prefer to live in medium to fine sediment.

Depending on the significant abundance data of total foraminiferal number along with the multivariate study, by using similarity index for grouping of station and species, three distinct biofacies zones (Fig 5.1) were identified. One was the innermost part of the outer channel, which was dominated by *Miliammina fusca, Ammobaculites exiguus*, *Textularia earlandi*, second one was the mouth part of the outer channel, dominated by *Ammonia beccarii*, *Ammonia parkinsoniana* and *Pararotalia nipponica* and the third was the central sector of the lagoon where *Ammonia tepida*, *Ammonia parkinsoniana*, *Ammonia sobrina,* and *Pararotalia nipponica* are predominant. Low salinity, shallow water depth, low oxygen conditions and nutrient influx are the major factors that affect this zonation of foraminifera. The inflow of freshwater from different streams and catchments, added with precipitation, was the leading cause of the lagoon's salinity variation as well as the amount of nutrient influx.

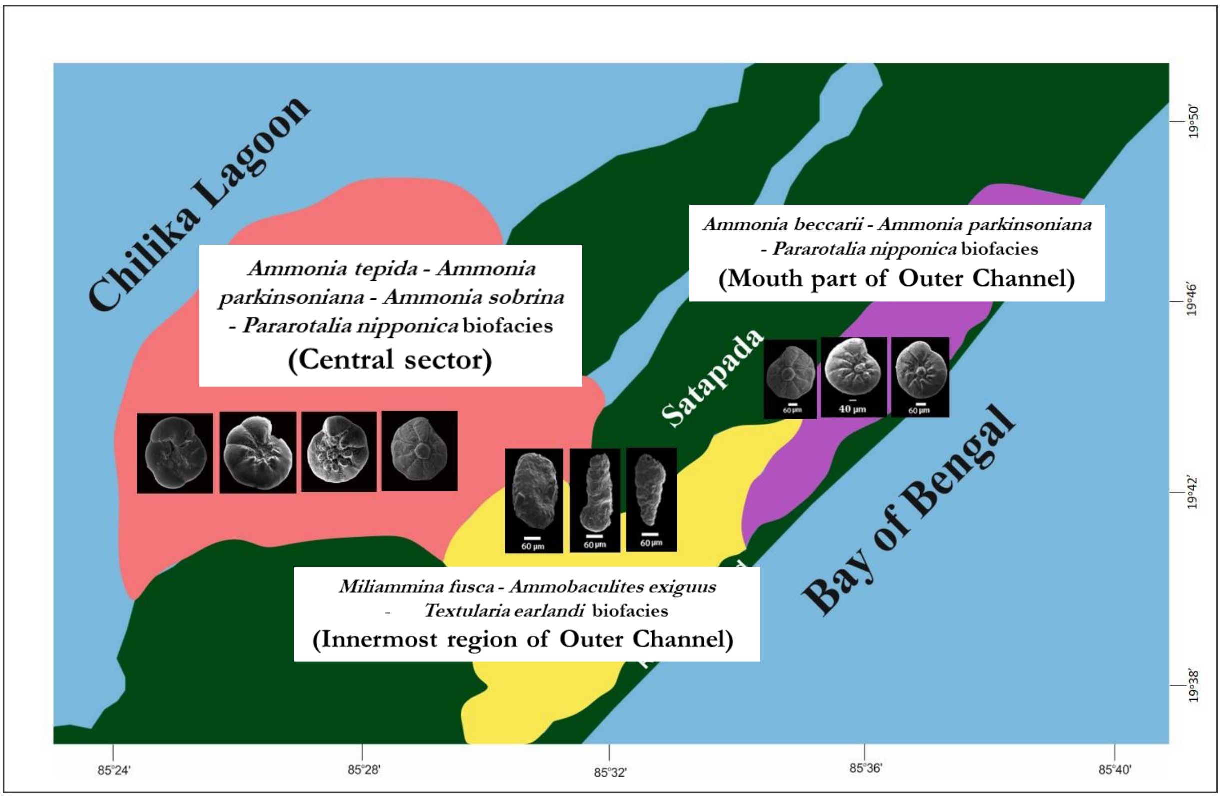

Fig. 5.1 Biofacies zones of foraminiferal assemblages along the sampling stations.

5.1.2 **Magnetic Mineral Analysis**

Analysis of magnetic susceptibility on soft sediments of Lagoon, as indicated by "MS" values, revealed a distinct magnetic characteristic corresponding to different sedimentary environments (Radan and Radan, 2007). The variations in MS (k) values primarily signify changes in lithology across the soft sediments. Furthermore, the findings suggest that MS (k) values can indicate metallic contamination within finer sediments; elevated magnetic susceptibilities correlate with higher levels of heavy metal content (Radan and Radan, 2007). The present study is focused on the soft sediments from standing bodies of water, i.e., the lagoon. Here, soft sediments are collected from the lagoon's outer channel. As the area leads to the lagoon mouth, it is heavily influenced by sea water (the Bay of Bengal). As a result, this area may be marine in nature rather than lacustrine (Sahu & Pandey, 1989). The innermost part of the outer channel is influenced by small channels that flows from the land part. As a result, the soft sediments at the mouths of these supply channels are coarser muds, whereas the mouth part of the outer channel is dominated by sand. Thus, the area is characterized by dynamic habitats, with active changes in water and sediment supply. From the result, it is evident that the samples that are collected from the mouth part of the outer channel shows comparatively high MS values in respect to the areas that are in the inner part of the outer channel. Magnetic susceptibility appears to be an effective basis for tracking the transfer of fine particles into the lagoon by different channels. It may be the case that the lagoon's sediment has a high concentration of phosphate (0-0.4 ppm), nitrate (10-60 ppm), and silicates (1-8 ppm), as well as ferromagnetic minerals from the catchment that were extensively affected through the residential area (Nayak et al.,2004). Anthropogenic activities such as agriculture, drainage, river runoff containing urban sewage, and drainage from agro-based industries (prawn processing units), fishing, and boating, among others, may cause nutrient accumulation, resulting in increased external sediment loading to the lagoon (Orissa State Pollution Control Board, unpublished data, 1998). Heavy minerals accumulate in fine (>0.125 mm to <0.25 mm) to ‘very’ fine (>0.063 mm to <0.125 mm) sediments (Pradhan & Panigrahy, 1995), which causes lower magnetization in the inner part of the study area compared to the mouth part of the outer channel.

The majority of thermomagnetic curves suggest the presence of multi-component magnetic minerals containing both ferromagnetic and paramagnetic minerals, as there is a sharp decrease in intensity of magnetization indicating the Curie temperatures of about 580 °C and 680 °C respectively. However, the heating curves of some samples show a drop in the magnetic intensity at around 575 °C with a reversible behaviour (in heating and cooling cycles), indicating the presence of very stable magnetite in the studied sediments.

The hysteresis loops of studied soft sediment samples exhibit both ferro- and paramagnetic characteristics. The results show that the hysteresis loop shapes range from thinner to wider. Thinner loops with saturation of magnetization indicate the existence of low-coercive components, such as ferromagnetic minerals, whereas widely open loops with unsaturated nature indicate the presence of a medium to relatively high-coercive magnetic mineral, such as paramagnetic minerals.

Three types of IRM acquisition curves are detected, indicating that the samples may include more than one magnetic material. The majority of the examined samples exhibit approximately 90% saturation around 1000 Oe, owing to the preponderance of soft magnetic minerals such as magnetite. Those samples that are unsaturated near 1000 Oe and trend beyond it suggest the existence of a hard magnetic mineral, possibly haematite.

All magnetic measurements show that ferromagnetic minerals, such as magnetite, are the primary magnetic carriers in all samples, with certain paramagnetic elements, such as haematite, is also present. This study concludes that magnetic measurements can be more useful in identifying pollution-prone areas for subsequent systematic chemical analysis while also decreasing efforts and costs.

5.1.3 **Corelation**

According to the findings of this study, agglutinated species (*Miliammina fusca, Ammobaculites exiguus, Textularia earlandi*) dominate regions with low magnetic susceptibility (MS) ranges, whereas calcareous hyaline species (*Ammonia beccarii, Ammonia parkinsoniana, Pararotalia nipponica*) dominate regions with high MS ranges (Table 4). The data show that the average MS value is lower in the inner section of the outer channel than in the mouth region. The mouth of the outer channel is dominated by sand. Previous studies (Zhou et al., 2014; Amir et al., 2021) shown that MS concentrations are increased with sediments larger than 63 μm and are decreased with finer ones. The results also show a high number and diversity of foraminifera near the mouth of the outer channel, which is also dominated by calcareous species. The innermost section of the outer channel contains a distinct biofacies zone dominated by agglutinated forms, indicating a stressed environment with stagnated water circulation and a significant influx of nutrients. The significant ingress of seawater, along with the tidal movement, prevents organic matter accumulation in the mouth. Increased nutrient load, combined with lower DO values during pre-monsoon versus monsoon seasons, may play a significant influence in foraminiferal dispersion (Panigrahi et al. 2009). Gupta et al. (2018) observed greater TOC concentrations during and after monsoonal precipitation, supporting the hypothesis that enhanced production in the lagoon is aided by external nutrient influx. Study showed a positive relationship between TOC and agglutinated species, as well as a positive link between depth and salinity. The presence of a positive relationship shows that the amount of food available to sedimentary benthos, independent of environmental circumstances (such as salinity, depth, and dissolved oxygen), determines the taxonomic composition of assemblages (Gupta et al., 2018). Previous research has also demonstrated a definite negative relationship between TOC and MS. According to those researches, high TOC occurs in medium-fine-grained silt and clay, where the amount of magnetic minerals is less, whereas peak MS values coincide with reductions in TOC in the sandy-silty substrate (Zhou et al., 2014).

	Innermost part	Mouth Part
Average value of Sand %	75.14	95.29
TFN	4 - 69	8 -103
Average value of A/C	8.22	0.57
Diversity	0 - 9	1- 8
Average MS value	25.03 x 10^{-6} SI Unit	30.24 x 10^{-6} SI Unit

Table 4. Corelation between the innermost part and mouth part of the outer channel

5.2 CONCLUSIONS

- The outer channel and central sector of the lagoon are home to a diverse range of foraminiferal species, with a total of thirty-three species identified, including both agglutinated and calcareous forms.

- Dominant calcareous forms are *Ammonia beccarii, A. tepida, A. parkinsoniana, A. sobrina, Pararotalia nipponica*, and dominant agglutinated forms are *Miliammina fusca, Ammobaculites exiguus, Ammobaculites* spp. and *Textularia* spp.

- The abundance of foraminifera is high during pre-monsoon in the outer channel while during post-monsoon the same is higher in the central sector

- Low-to-moderate diversity has been observed throughout the study area.

- 3 biofacies zones are established:

  a) *Ammonia beccarii - Ammonia parkinsoniana - Pararotalia nipponica* (Nearer to mouth of lagoon)

  b) *Miliammina fusca - Ammobaculites exiguus - Textularia earlandi* (Innermost part of the lagoon)

  c) *Ammonia tepida - Ammonia parkinsoniana - Ammonia sobrina - Pararotalia nipponica* (Central sector of lagoon)

- The outer channel has a more stressed ecosystem, whereas the central sector is influenced by fluvial discharge and has a stable ecosystem.

- Magnetic Susceptibility (MS) values show a high range towards the mouth part of the lagoon.

- Both soft magnetic minerals (like magnetite) and hard magnetic minerals (like haematite or maghemite) are present in lagoon sediment.

- Results indicate the presence of low coercive components in the most of soft sediment of the lagoon and few samples exhibit a relatively moderate to high coercive components.

- Different mineral magnetic parameters indicate the presence of both ferromagnetic and paramagnetic minerals in the studied soft sediments.

- Region having low MS range shows dominance of agglutinated species (*Miliammina fusca, Ammobaculites exiguus, Textularia earlandi*) and high MS range is dominated by calcareous hyaline species (*Ammonia beccarii, Ammonia parkinsoniana, Pararotalia nipponica*).

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