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Foraminiferal palynomorphs from the marine and brackish water sediments of the southern Red Sea coast of Saudi Arabia, their palaeoenvironmental and palaeoecological implications

Arun Kumar

Carleton Climate and Environment Research Group (CCERG), Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada.
E-mail: arunkumarlko@hotmail.com

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ABSTRACT

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A baseline study was carried out on distribution of foraminiferal palynomorphs from marine and brackish water environments (intertidal, mangrove, algal mat, and coral reef) using Holocene sediments of the southern Red Sea coast of Saudi Arabia. Foraminiferal palynomorphs are simply defined as any microfossil of foraminiferal affinity observed in palynological slides. The objective of this study was to investigate palaeoenvironmental and palaeoecological utility of foraminiferal palynomorphs in absence of any foraminiferal data in marine and brackish water environments. This study demonstrates that there are significant differences in relative abundances among informally described morphotypes of foraminiferal palynomorphs in various environments. In the intertidal and mangrove environments smaller benthic calcareous foraminifers were common and forms like miliolids and *Ammonia* were identified. However, in the coral reef environments smaller benthic, both calcareous and porcelaneous forms were observed. The porcelaneous foraminifera are referable to *Sorites* sp. /*Parasorites* sp. and/or *Archaias* sp. Common occurrence of foraminiferal palynomorphs related to small-sized opportunistic *Ammonia* has palaeoecological significance due to its abundance in the mangrove sediments in proximity to roots of mangrove plant *Avicennia marina*. No foraminiferal palynomorphs were observed in the algal mat environment. Thus, in absence of data on foraminiferal assemblages, relative abundances of foraminiferal palynomorph morphotypes may be used for distinguishing various coastal (brackish and marine) environments.

Keywords: Red Sea, non-pollen palynomorphs, mangroves, algal mats, intertidal and coral reef environments, benthic calcareous and porcelaneous foraminifers

INTRODUCTION

According to Stancliffe (1989) to interpret the palaeoecology of fossil foraminiferal palynomorphs, it is necessary to analyse their occurrence and distribution patterns in modern sediments. Generally, foraminiferal palynomorphs are remains of benthic foraminifera. However, some planktonic species of foraminifera produce an inner lining as well (Hemleben et al. 1977) and may be preserved in the sediments (Arai & Koutsoukos 1998). It is important to understand numerous biological and environmental factors that control their distribution in modern sediments. In a discussion about wide ranging applications of foraminiferal research, Hallock (1995) listed several fields of research that use foraminifera and listed them under three broad categories as Biology/Ecology, Geology/Earth History, and Contemporary Issues. Among the contemporary issues, she listed few topics, among them environmental assessment, environmental change, coastal processes, and global climate change are of significance to the present study on distribution of foraminiferal palynomorphs in various environments along the southern Red Sea coast of Saudi Arabia. She (Hallock 1995) emphasised the importance of foraminifera in interdisciplinary (palaeo) environmental studies. Martin (1991, 1995) promoted the idea of using micropalaeontology (thus foraminifera) to study issues of resource conservation and environmental quality. He (Martin 2000) further discussed a new research path for micropalaeontology in which he emphasised utility of foraminifera in monitoring natural environmental disturbances, such as the one caused by frequency of storms, and anthropogenic disturbances.

There are several coastal regions of the world where natural hazards and contemporary environmental issues both natural and anthropogenic, are needed to be addressed, for example the regions around the Arabian Peninsula (Kumar 2009, 2013). However, data on distribution of benthic foraminifera is not necessarily available everywhere that can be used as proxies to address such environmental issues. Under these circumstances palynological research may be helpful to address such environmental problems. Since foraminiferal palynomorphs invariably occur in palynological preparations of marine and brackish water sediments, their studies could be an alternative to benthic foraminiferal studies.

Taphonomic processes leading to benthic foraminiferal assemblages have been widely studied. It was found that carbonate dissolution of calcareous tests and their transport are part of taphonomic process of benthic foraminifera as indicated by the fragility of some tests observed under microscope (Alve & Murray 1997). However, in a microtidal environment where transport of foraminifera is limited, the major foraminiferal taphonomic process appears to be carbonate dissolution of calcareous tests as indicated by etching and breakage of test walls (Murray & Alve 1999). Foraminiferal palynomorphs are usually damaged and broken foraminiferal linings. However, it is not clear that damaged specimens of foraminiferal palynomorphs are result from the maceration process that involves severe chemical and mechanical treatment or are a result of taphonomic process involving preservation of benthic foraminifera. Most likely both these processes control the nature of damaged specimens of foraminiferal palynomorphs.

To understand this issue, an integrated study of benthic foraminiferal (living and dead shells) and palynological study of the same samples from various coastal environments could be useful. This would offer an insight on possible causes of damaged and/or incomplete specimens of foraminiferal palynomorphs. Were they the result of taphonomic processes of benthic foraminiferal preservation or of processes involving palynological maceration techniques? A comparison between foraminiferal palynomorph assemblage with benthic foraminiferal assemblage from the same sample could provide significant information useful for research on environmental assessment, environmental change, coastal processes, and global climate change. Thus, there is a possibility that foraminiferal palynomorphs could also be used as proxies for benthic foraminiferal assemblages in studies such as documenting Holocene relative sea-level change and large prehistoric earthquakes (Patterson et al. 1999, Kumar & Patterson 2005), and bioindicators of heavy metal pollution as has been used by benthic foraminifera (Coccioni 2000).

Environmental applications of micropalaeontology use diverse groups of microfossils such as foraminifera, dinoflagellates, diatoms, pollen, ostracodes and thecamoebae (Martin 2000). Dinoflagellates and pollen are routinely studied by palynologists in various environmental and climate change studies, since foraminiferal palynomorphs co-occur in the same slides could provide additional information for such studies.

In palynological context the term 'foraminiferal palynomorphs' is defined here as a morphologically diverse group of palynomorphs having biological affinity with Foraminifera. Mudie et al. (2021a) and Tyszka et al. (2021) provide morphological descriptions of foraminiferal remains in palynological preparations by defining new terminologies. In palynological literature, such morphologically distinct palynomorphs have been variously termed. The term 'microforaminifera' was used for specimens of foraminifera that were treated with hydrofluoric acid that resulted into small translucent mineralised tests <150 µm in size (Wilson & Hoffmeister 1952). 'Microforaminifera' are also considered to be resistant to the action of hydrochloric acid (Riding 2021).

Wetzel (1957) recorded microforaminifera from flint flakes and termed them as 'organic remains of foraminifera'. Deák (1964) considered the term 'microforaminifera' as misleading and suggested to replacing it with a new term 'Scytinascia' which eventually was rejected. Other commonly used terms by palynologists are 'microforaminifera test linings', and 'microforaminifera linings' (Stancliffe 1989), or just 'foraminiferal linings' as suggested by Pawlowski et al. (1993). Tyszka et al. (2021) suggested a new term 'foraminiferal organic linings' to avoid confusion with terms like 'calcareous inner linings', 'foraminiferal linings', and 'microforaminiferal tests linings. Thus, microforaminifera are different from the organic-walled inner linings of foraminifera commonly termed as foraminifera linings (Riding 2021). I suggest a simpler term 'foraminiferal palynomorphs' for a morphologically diverse group of palynomorphs having biological affinity with Foraminifera. Foraminiferal palynomorphs are acid resistant morphotypes that are commonly observed in palynological slides of marine and brackish water sediments, thus, are not 'microforaminifera' described by Wilson and Hoffmeister (1952).

Stancliffe (1989) described morphology of microforaminiferal linings and classified them into fourteen types from the Late Jurassic (Oxfordian) marine sediments of England. These linings are put into five broad categories, they are, single chamber (type 1); uniserial (types 1 and 2); biserial (types 1 and 2); coiled (planispiral types 1, 2, 3, 4 and 5) and trochospiral types 1 and 2); and compound (coiled uniserial and coiled biserial). Russel et al. (1991) described microforaminiferal linings from coastal Holocene sediments off the island of Kyushu, Japan in which they described and illustrated a new morphotype trochospiral type 3. While working on the present assemblage of foraminiferal palynomorphs, I found that it was not always possible to distinguish between various planispiral and trochospiral morphotypes described by Stancliffe (1989) and Russel et al. (1991). A simplified version of Stancliffe's (1989) morphotypes was provided by Tyszka et al. (2021), that is classified into five categories, they are, single chamber, uniserial, biserial, coiled (planispiral and trochospiral), and compound (coiled uniserial and coiled biserial). The present study follows Tyszka et al. (2021) for its simplicity and clarity in identifying morphotypes of microforaminiferal linings.

A detailed baseline palynological study of the Holocene intertidal sediments of the southern Red Sea coast of Saudi Arabia was published by the present author (Kumar 2020). This study was followed by another similar study of the adjoining Holocene sediments from mangrove swamps, Middle Holocene palaeochannel deposit, algal mat, and Sabia Island coral reef (Kumar 2021). A rich and diverse assemblage of palynomorphs was described from all these environments. An assemblage of foraminiferal palynomorphs from the intertidal, mangrove and Sabia Island coral reef was mentioned and several microforaminiferal test linings were informally described. It was observed that relative abundance of foraminiferal palynomorphs and their morphotypes significantly varied among these environments. Foraminiferal palynomorphs were not observed in the algal mat samples.

Sabia Island coral reef, intertidal and mangroves are distinct environments along the southern Red Sea coast of Saudi Arabia. So far, there is no published account of any foraminiferal studies from these environments. The objective of this study was to evaluate the differences between relative abundances of foraminiferal palynomorph morphotypes in these environments. The results suggest that in absence of any data about benthic foraminiferal assemblages, foraminiferal palynomorph morphotype assemblages may be used for distinguishing these depositional environments.

AN OVERVIEW OF STUDIES ON FORAMINIFERAL PALYNOMORPHS

During the 1950s, palynological studies recognized the occurrence of microscopic foraminiferal specimens that survived hydrochloric and hydrofluoric acid treatments. They were termed 'microforaminifera' because of their relatively smaller size (30–150 μm) than the size range of foraminiferal tests (Wilson & Hoffmeister 1952, Hoffmeister 1955, Grayson 1956, van Veen 1957, Wetzel 1957). These studies were reviewed by Tappan and Loeblich (1965), Muir and Sarjeant (1977) and Stancliffe (1989, 1996). Smaller size of these foraminiferal remains was not related to dwarfism, but directly linked to preferential preservation of linings from the juvenile parts of complete test (Tyszka et al. 2021). Dissolution experiments in 5% hydrochloric acid indicated that not all species produced visible organic remains (Cohen et al. 1968). A similar experimental study demonstrated that the number of species producing microforaminifera is considerably smaller compared to the number of species in the original untreated microfauna (Traverse & Ginsburg 1966).

Microforaminifera represent remains of chitinous inner skeletons of true foraminifera (Muller 1959, Traverse & Ginsburg 1966). There are terms like "microforaminifera test linings" and "microforaminifera linings" applied in palynology (Mathison & Chmura 1995). Pawlowski et al. (1993) recommended the term foraminiferal linings instead of microforaminiferal linings for foraminiferal remains found in palynological slides. Tyszka et al. (2021) proposed a new term "Foraminiferal Organic Linings" (FOLs) to avoid confusion with calcareous "inner linings" known from bilamellar wall of calcareous foraminifera. Therefore, FOLs refer only to residual organic remnants of foraminifera left after chemical dissolution of their mineral tests, usually following palynological extraction procedures. de Vernal et al. (1992) described organic linings of foraminifera as "a semi-transparent to brownish series of individual chambers linked by a foramen".

Definition and various names of foraminiferal palynomorphs

Foraminifera are classified as *Protista* formerly Phylum *Protozoa*, now Class *Granuloreticulosae*, Order *Foraminiferida* (Mudie et al. 2021a). These are single-celled organisms that leave two types of fossil records, viz. mineralized shells (tests) and their organic linings. Their fossil record is highly biased towards tests, acid resistant organic linings are generally limited to palynological preparations of sedimentary rocks of marine and brackish water sediments, however, also occasional studies of thin sections of sedimentary rocks (Mišík & Soták 1998). Organic linings of foraminifera should be distinguished between organic linings in the palynological context from the organic linings recognized in the structural studies of complete foraminiferal tests (Tyszka et al. 2021).

Goczan (1962) suggested that microforaminifera should be described and classified following morphologic criteria. Later Deák (1964) recognized four shapes of microforaminifera as uniserial, biserial, coiled, and rose-like. Traverse and Ginsburg (1966) also used morphologic classification criteria based on their coiling morphology and recognized that 100% of forms from the Great Bahama Bank sediment were either planispiral or trochospiral (trochoid). This morphological approach was followed by other researchers (e.g. Head & Westphal 1999), including Stancliffe (1989) who classified fossil organic remains of foraminiferal linings into fourteen morphological types from palynological samples collected from the Oxfordian sediments. All morphologies are included into five major morphological types: single chamber, uniserial, biserial, coiled, and compound (Stancliffe 1989, figure 4). This informal classification system was also used in the Holocene marine sediment studies (Stancliffe & Matsuoka 1991, Matsuoka & Ishii 2018).

Mudie et al. (2021a) defined microzoobenthic non pollen palynomorphs (NPP) as the acid resistant remains of heterotrophic benthic microzooplankton, in the size range of 20–200 µm primarily represented by the organic linings and skeletal remains of foraminifera recovered after acid treatment of rock/sediment samples (Stancliffe & Matsuoka 1991, Stancliffe 1996). Most of the 40000 recognized taxa of foraminifera are benthic forms that are the probable sources of microforaminiferal linings in palynological samples (Mudie et al. 2021a).

de Vernal et al. (1992) demonstrated that laboratory experiments show that none of the nine planktic taxa treated with dilute hydrochloric acid produced any organic lining. In contrast, 41% of the 39 benthic species tested from the Gulf of St Lawrence produced organic linings, compared to 25% of 20 species from deeper water in the NW Atlantic Ocean. Not all benthic foraminiferal linings survive lithification and/or palynological processing with strong acids. However, several noncalcareous, arenaceous (agglutinant) benthic foraminifers also produce acid-resistant linings (de Vernal 2009, Frail-Gauthier et al. 2019).

There seems to be a recognizable similarity in the test and the lining morphology, for example, subspherical unilocular lagenids or uni- to triseriate glandulinids resembling a chain of beads or small braided bread-loaf, and as spherical rotalid taxa. In the rotalids, growth occurs outwards from the prolocular chamber, in a flat spiral (planispiral lining) or a domed (trochospiral) structure. Mudie and Yanko-Hombach (2019) reviewed literature on variations in chamber number and categories of damage established by Mathison and Chmura (1995) for tropical salt marsh microforam linings, and they record microforam lining deformities associated with test growth impairment of rotalids in the polluted bottom waters of the Black Sea. The uniserial or triserial morphotypes are generally infaunal, while trochospiral forms are more commonly epifaunal (Hartman et al. 2018).

Mišík and Soták (1998) carried out a thin section study of Callovian-Oxfordian limestones and Lower Cretaceous cherts from Western Carpathians. They observed many microforaminiferal organic linings stained in red by iron oxides during early diagenesis that made them visible in thin sections. The morphology of these microforaminiferal organic linings was associated with morpho-groups and form genera that were assigned to generic and subgeneric classification of foraminiferal taxa. Some forms could also be attributed to the known Jurassic and Early Cretaceous foraminifer taxa. They described the following seven morphotype groups, 1. textularid, bolivinid, and buliminid foraminifers; 2. ataxophragminid and verneulinid foraminfers; 3. trochamminid, haplophragmoid and lituolid foraminifers; 4. involutinid, ammodiscid, and spirillinid foraminifers; 5. "dentaliferous" foraminifers; 6. nubeculariid foraminifers; and 7. uncertain linings. Various Jurassic foraminiferal taxa were assigned to each of these morphotype groups. Mudie et al. (2021a, table 1) provides a list of benthic foraminifera identified to genus/species level with corresponding foraminiferal linings from the Gulf of St. Lawrence, and Chezzetcook salt marsh, Nova Scotia.

Stratigraphic distribution of foraminiferal palynomorphs

Microforaminiferal linings were reported from marine sediments from the Lower Cambrian to Recent (Mudie et al. 2021a). The following list provides such reports in which foraminiferal palynomorphs were reported as microforaminifera or microforaminiferal linings. There are several reports from Holocene marine and brackish water sediments, they have been discussed separately under environmental proxies and palaeoenvironmental utility. The following reports of occurrence of foraminiferal palynomorphs are from oldest occurrences to youngest. Lower Cambrian (Winchester-Seeto & McIlroy 2006), Pennsylvanian (di Pasquo 2009), Early Pennsylvanian (Gutiérrez et al. 2016), Upper Pennsylvanian (Utting et al. 2004), Lower Carboniferous and Permian (Stephenson et al. 2002, 2004, 2007), Silurian-Devonian (Machado Cardoso & Rodrigues 2006), Devonian (Winchester-

Seeto & Bell 1994, 1999), Permian and Triassic (Visscher 1971), Permian-Triassic boundary (Bercovici et al. 2015), Early and Middle Jurassic (Davies 1985), Oxfordian (Stancliffe 1989), Callovian-Oxfordian (Miêk & Sotak 1998), Late Jurassic (Courtinat 1989), Callovian and Cretaceous (Shevchuk et al. 2015), Cretaceous (Davey 1978), Cretaceous (Goczan 1962), Cretaceous (Macko 1963), Early Cretaceous (Piasecki 1986), Lower Cretaceous (Batten 1973,1982), Cenomanian (Davey 1970), Cenomanian-Turonian (Courtinat & Meon 1991), Upper Cretaceous (Lantos et al. 1996), Early Tertiary (Monga et al. 2015), Eocene (Deak 1964), and Early to Middle Miocene (Boonstra et al. 2015). The palynological literature from India shows that presence of microforaminiferal linings were documented from the Mesozoic, Tertiary and Quaternary sediments. However, very few studies like Baksi (1962), Venkatachala (1968), Jain and Dutta (1978), Phadtare and Thakur (1992), Tabaei and Singh (2002) and Monga et al. (2015) provided morphological, stratigraphical and palaeoenvironmental details about the foraminiferal palynomorphs.

There are a large number of reports of foraminiferal palynomorphs from the Holocene marine sediments from almost all over the world, some of them representing various regions are as follows: Traverse and Ginsburg (1966), Warrington (1978, 1982), Decommer (1982), Melia (1984), Davies (1985), Stancliffe and Matsuoka (1991), Mudie et al. (2011), Srivastava et al. (2013), Hartman et al. (2018), Mudie and Yanko-Hombach (2019), Pieñkowskia et al. (2020), and Mudie et al. (2021a, b).

Environmental proxies

To interpret the palaeoecology of fossil linings, it is necessary to analyse their occurrence in modern sediments. In one of the earliest studies McKee et al. (1959) recorded distribution of foraminiferal linings from the Kapingamarangi atoll of the Caroline Islands, the southernmost point of Micronesia. They found the highest concentrations of foraminiferal linings in water less than 7 meters deep. However, foraminiferal linings were recorded from as far deep as 9200 meters from offshore Japan (Boulouard & Delauze 1966). Cross et al. (1966) studied surface samples from the southern Gulf of California, Mexico, and related presence of microforaminiferal linings to the upwelling of nutrient rich waters, higher salt concentrations and local shallow water conditions. They suggested that future investigations should be done in the environmental and taphonomic contexts. Bradford (1977) studied distribution of microforaminiferal linings in the Persian Gulf and adjacent regions, he recorded higher counts of foraminiferal linings in samples of coarser sediments in shallower water depth with a higher salinity, and higher summer temperatures. He matched the microforaminiferal linings data with distribution of benthic Foraminifera. Foraminiferal palynomorphs have also been used as proxies for variable salinity in estuarine marsh environments (Batten 1996b). It is difficult to determine the foraminifer species from the benthic foraminifer linings. Uniserial, or triserial forms are generally infaunal, while trochospiral forms are more commonly epifaunal (Corliss 1991).

Foraminiferal organic linings, along with calcareous tests were found to be useful in reconstructing palaeoenvironments at the interface of the terrestrial and marine realms (Mamo et al. 2009). Boonstra et al. (2015) used tests and/or organic linings of euryhaline calcareous foraminifera and marine palynomorphs from Miocene sediments in north-western Amazonia to extend current estimates for salinity ranges, palaeoenvironments and palaeogeography by dividing organic linings into three morphotypes. Morphotype 1 was characterized by slowly evolving, pitted chambers, with a distinctly wide umbilicus having affinity with the *Rotaliaceae* (*Ammonia* or *Elphidium*). The calcareous tests of these taxa are pitted and can be replicated in their organic linings. Morphotype 2 was relatively small, with a wide umbilicus; with no more than four chambers was assigned to juveniles that probably belonged to the Rotaliaceae (*Ammonia* or *Elphidium*). Morphotype 3 was characterized by large, inflated chambers with solid and thick walls without any visible pits tentatively assigned to *Trochammina*, an agglutinated species with a wall with thicker lining than

Ammonia. Foraminifera and dinocyst taxa jointly pointed to varying degrees of salinities, with aberrant forms of *Ammonia* indicating lower limits of 0–10 psu (practical salinity units) whereas dinocyst associations suggest more marine conditions. Two relative higher sea levels were identified in an early-middle Holocene section of Bahía, Tierra del Fuego, Argentina based on increased abundance of dinoflagellate cysts, foraminiferal test linings and copepod egg-envelopes (Borromei & Qattrocchio 2007).

Foraminiferal palynomorphs may provide additional information for marine productivity (Boessenkool 2001, de Vernal et al.1992), and their abundance also indicates benthic production (de Vernal & Giroux 1991). Pieñkowskia et al. (2020) reported several types of foraminiferal linings from the modern marine sediments from the Northwest Passage – Baffin Bay region of Arctic Canada. Foraminiferal linings type A, B, C, D, E and F sensu Stancliffe and Matsuoka (1991) were reported from Holocene sediments off the Coast of northwestern Kyushu.

Shevchuk et al. (2015) described microforaminifers from Callovian, Berriasian, Aptian, Albian, Cenomanian, Turonian, Coniacian, Ñampanian and Maastrichtian deposits of Ukraine. They identified the microforaminifers at generic and species levels and divided them into planktic and benthic, agglutinated, and calcareous forms. These assemblages were used to demonstrate changes in palaeogeographic and palaeoecological conditions, assessment of sea basin temperature, cycles of sedimentation and conditions of stagnation. Gutiérrez et al. (2016) reported microforaminiferal linings from the early Pennsylvanian of Argentina and classified them as Trochospiral Type I, Planispiral Type II, and cf. Uniserial indet (sensu Stancliffe 1989) indicating estuarine or shallow marine environments in the western part of the basin during the Pennsylvanian.

Stratigraphic and palaeoenvironmental utility

Historically foraminiferal studies were used as a tool for time control in biostratigraphy and reconstruction of palaeoenvironments. Additionally foraminiferal palynomorph studies were used for identification of marine vs. terrestrial facies, primary productivity/export flux, bottom water oxygenation and circulation, dissolution/acidification, and palaeosalinity (Batten 1996a, b, Mišík & Soták 1998, Londeix et al. 2009, Mudie et al. 2011, Mudie & Yanko-Hombach 2019). The Palynological Marine Index (PMI) was used to interpret marine vs. terrestrial depositional facies that included "chitinous internal moulds of foraminifera" along with dinoflagellate cysts and acritarchs. Low PMI values were interpreted as indicative of brackish water influence, and higher PMI values as indicative of marine conditions (Helenes et al.1998). Likewise, Mudie et al. (2011) and Mudie and Yanko-Hombach (2019) used non-pollen palynomorphs (NPP), that included foraminiferal linings to reconstruct salinity and environmental changes along the Caspian-Black Sea-Mediterranean seaway. Foraminiferal organic linings were also used as a proxy for foraminiferal production when carbonate preservation is reduced (Mathison & Chmura 1995).

Other significant uses of foraminiferal palynomorphs were as markers of marine transgression in coastal lakes (van Geel 1978), and indicators of brackish and marine environments in deltaic regions (Muller 1959, Mathison & Chmura 1995, Hardy & Wrenn 2009, Mudie & Yanko-Hombach 2019). In palynofacies models, presence, or absence of foraminiferal palynomorphs distinguished transition from coastal lakes across delta front, prodelta and shelf sub-environments (Batten1996b, Hardy & Wrenn 2009).

Description of foraminiferal palynomorphs

Although microforaminiferal linings were reported from palynological slides from the early 1950s (Wilson & Hoffmeister 1952, Hoffmeister 1955, Grayson 1956, Wetzel 1957), first classification of morphotypes of microforaminiferal linings were proposed very late by Stancliffe (1989). This was a pioneering attempt to classify such microfossils in which fourteen morphotypes were informally proposed from the Oxfordian marine sediments of England. Subsequent studies on microforaminiferal linings followed this classification system primarily for palaeoenvironmental research.

Stancliffe and Matsuoka (1991) reported microforaminiferal linings from the Holocene marine sediments, offshore north-western Kyushu, Japan. The assemblages included a new microforaminiferal lining morphotype named Trochospiral type III which was described and illustrated. Monga et al. (2015) described and illustrated microforaminiferal linings from the early Tertiary sediments of north-eastern and north-western India and used classification system of Stancliffe (1989) to describe the following morphotypes: uniserial type II, biserial type II, planispiral types II, III, and IV, trochospiral types I and II.

There are studies on microforaminiferal linings which followed the informal classification system of Stancliffe (1989) with certain modification, for example, marshes of Louisiana, USA study by Mathison and Chmura (1995). They classified their microforaminiferal morphotypes as uniserial, biserial, planispiral and trochospiral, and they used chamber spacing as a distinct parameter in grouping their morphotypes. Chambers widely spaced were designated as open, and closely spaced as proximate.

Microforaminiferal morphotypes such as single chamber, uniserial (types I and II), biserial (types I and II), and compound (coiled uniserial and coiled biserial) were easily discernible in the present study. The coiled forms were also easily distinguished between planispiral and trochospiral, however, their further classification into smaller subgroups were found to be impractical to use. The five planispiral forms described by Stancliffe (1989) became confusing and not always clearly discernible in the present fossil material. To overcome this issue the classification of Tyszka et al. (2021) was followed which includes the following forms: single chamber, uniserial, biserial, coiled (planispiral and trochospiral), and compound (coiled uniserial and coiled biserial).

In this study descriptions of foraminiferal palynomorphs include measurement of dimensions of the first chamber (proloculus), second chamber and the last preserved complete chamber since it gives a good indication of the growth rate of the lining with respect to the number of chambers found (Stancliffe 1989). Additionally, external wall surface of the microforaminiferal linings is described which sometimes can be smooth or granular. Since the linings also react to the application of heat, showing a gradation in colour from orange to red, then brown and finally black, thus their colour is also recorded. Whether the chamber is widely spaced (open) or closely spaced as (proximate) is noted as well.

GEOLOGY AND ENVIRONMENTS OF THE STUDY AREA

Study area

The study area, the Wadi Hali Quadrangle, is located west of Abha, a small town in southwestern Saudi Arabia. The area is on the southern Red Sea coast of Saudi Arabia between Jeddah in north and Jizan in south (Figure 1.A). It covers Wadi Hali, a short ephemeral stream that originates in the hilly regions east of the coastal region and its surroundings (18°49'35.27" N, 41°22'44.23" E). The area under study covers mainly a mixture of marginal-marine and non-marine environments that include upper intertidal and supratidal flats (Figure 1.C). Algal mats and mud flats, scattered patches of mangroves and their muddy environments (Figure 1.B), sand flats, both rippled and non-rippled areas of the upper intertidal environments are covered under this study. Sediment samples from the Sabia Island coral reef environment were studied as well (Figure 1.D).

Oceanographic and environmental details about the Red Sea and geology of the coastal sediments of the Wadi Hali Quadrangle were discussed by Kumar (2020). Further, geographical, and environmental details about a variety of coastal environments were provided as follows: intertidal (Kumar 2020), mangrove swamps, algal mats, and Sabia island coral reef (Kumar 2021).

MATERIALS AND METHODS

This study is based on 18 samples collected from various localities representing four different coastal environments around the Wadi Hali area (18°49'35.27" N, 41°22'44.23" E) and its surroundings in the southern Red Sea coast of Saudi Arabia (Figure 1.A, B, C, D). These samples were collected during a geological field trip in the first week of March 2011. The present study is from the same samples and palynological slides as published earlier (Kumar 2020, 2021). Sample locations are shown in Figure 1.

Procedures of microscopy were followed as described in Kumar (2020, 2021). Well preserved specimens were used to make photo plates to illustrate morphological diversity of foraminiferal palynomorphs (Figures 4, 5 and 6). Since palynomorph numbers are low, all palynomorphs in each slide were counted. All the palynological slides are stored in the palynology laboratory of Carleton Climate and Environment Research Group (CCERG), Department of Earth Sciences, Carleton University, Ottawa, Canada.

Measurements of foraminiferal palynomorph morphotypes

Initial counts were made on total number of palynomorphs in all the 18 samples belonging to four different environments. This was followed by counting

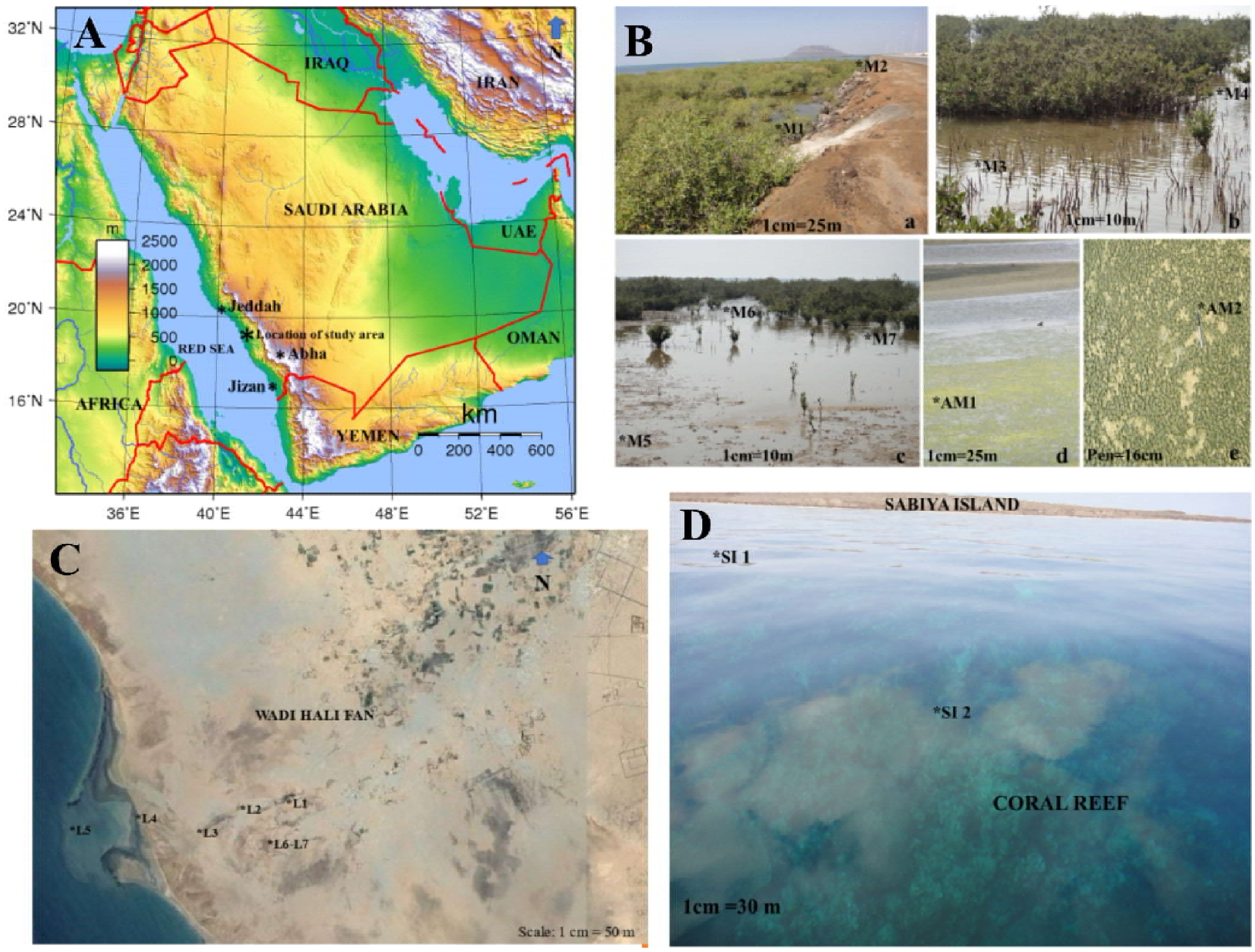

Figure 1. A. Topographical map of the Arabian Peninsula showing various countries and Red Sea coast indicating the location (the star) of area of study. (Modified after https://commons.wikimedia.org/wiki/File:Saudi_Arabia_Topography.png). **B.** Sample localities from various mangrove swamps; a. two clay samples (M1 and M2), b. two clay samples (M3 and M4), and c. three clay samples (M5, M6 and M7). Sample localities from the algal mats; d. one sample (AM1 under water depth 50 cm or less, and e. one sample (AM2) from dried part (after Kumar 2021). **C.** Samples L1 through L7 were collected from the intertidal flat (after Kumar 2020). **D.** Two fine sand samples SI 1 and SI 2 were collected from offshore Sabia Island (after Kumar 2021).

the number of foraminiferal palynomorphs in each sample (four slides in each sample), and percentage of foraminiferal palynomorphs were calculated for each sample (Table 1). Total numbers of palynomorphs and total numbers of foraminiferal palynomorphs were counted by summing counts from each sample from each environment. Finally, the average percentage of foraminiferal palynomorphs was calculated for each environment (Table 1). This dataset provided a clear understanding of relative abundance of palynomorphs and foraminiferal palynomorphs in various environments. No foraminiferal palynomorphs were observed in the samples from algal mat environment.

Foraminiferal palynomorphs observed in this study were classified into the following six morphotypes, they are, uniserial, biserial, planispiral, trochospiral, coiled uniserial, and coiled biserial following the classification of Tyszka et al. (2021). No isolated chamber of any foraminiferal palynomorph was observed in this study. All the six morphotypes from each environment were subjected to measurements following Russel et al. (1991), they are, size range (based on number of specimens measured), number of whorls, number of chambers, size of first chamber (proloculus), size of second chamber, size of the last complete chamber (Table 2). This table demonstrates the relative abundance of various morphotypes of foraminiferal palynomorphs in various environments along with their morphometric details. Quantification of chamber relationship is measured by their length and breadth. Measurement of the first chamber, second chamber and the last preserved complete chamber provides an indication of the growth rate of the lining with respect to the number of chambers found. Comments are made about relative presence and/or absence of broken specimens of foraminiferal palynomorphs in each environment. The presence of benthic porcelaneous foraminifera in coral reef samples of Sabia Island is noted as well (Table 2).

Table 1. Numerical distribution of palynomorphs and foraminiferal palynomorphs in various environments.

Sample number	Total number of palynomorphs	Number of foraminiferal palynomorphs	Percentage of foraminiferal palynomorphs
		Intertidal	
L1	61	0	0
L2	55	0	0
L3	74	5	6.75
L4	19	2	10.52
L5	52	0	0
L6	66	1	1.51
L7	11	0	0
Total	338	8	Average = 2.68
		Mangrove	
M1	99	10	10.1
M2	84	2	2.38
M3	67	3	4.47
M4	26	1	3.84
M5	107	28	26.16
M6	132	6	4.54
M7	57	5	8.77
Total	572	55	Average = 8.60
		Algal Mat	
AM 1	60	0	0
AM 2	58	0	0
Total	118	0	0
		Coral Reef (Sabia Island)	
SI 1	66	14	21.21
SI 2	141	59	41.84
Total	207	73	Average = 31.52

RESULTS AND DISCUSSION

All palynomorphs were counted in each slide. The number of palynomorphs counted in various samples varies considerably within the same environment. Similarly, number of palynomorph counts significantly varies within various environments as well (Table 1, Figure 2). In the intertidal environment, counts vary from

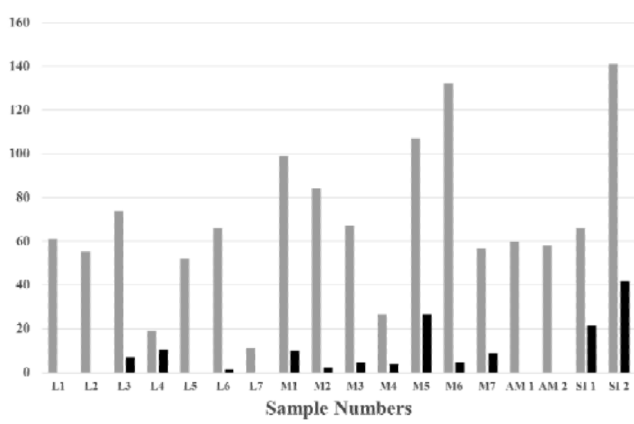

Figure 2. Comparison of total number of palynomorphs in various samples vis-à-vis percentage of foraminiferal palynomorphs in those samples.

Table 2. Numerical distribution of foraminiferal palynomorph morphotypes, whorl counts and chamber measurements in various environments.

Environment	Morphotypes	Size µm (# measured)	Whorls #	Chamber #	1st chamber size (µm)	2nd chamber size (µm)	Last chamber size (µm)	Comments
Intertidal	Uniserial	None						Rare broken specimens were observed which could not be classified
	Biserial	Length 117.6 (1)	0	10	18 × 15.5	18 × 16	28.6 × 28.4	
	Planispiral	57.5 × 53.5 (1)	2	8	11 × 10	11 × 6	32.8 × 19.5	
	Trochospiral	76–105 × 51–80 (5)	1.5–2.5	7–12	6–30.9 × 8.7–25	8.7–25.9 × 5.5–20.2	24.5–62 × 15.5–35.6	
	Coiled Uniserial	62–139.6 × 42–103 (3)	1	4–7	29.7–37 × 18.8–34.4	22.8–35.5 × 18.2–35.3	32–41 × 16.4–36.3	
	Coiled Biserial	None						
Mangrove	Uniserial	198 × 84 (1)	0	9	20.7 × 9.8	21.5 × 10.8	73.8 × 61.6	Several broken specimens were observed which could not be classified
	Biserial	None						
	Planispiral	67–167.7 × 71–105.3 (9)	1–2.5	7–13	11–26.5 × 9.8–20.5	8.8–27 × 7.8–19	42.6–66 × 26.5–45.4	
	Trochospiral	57.8–140 × 37.6–133 (12)	1.5–2.5	8–13	7.8–26.5 × 6.6–24.8	7.6–27.2 × 5.5–18	31.5–62.8 × 22–48	
	Coiled Uniserial	76–137 × 47–150.2 (10)	1–1.5	7–16	16–34 × 11.5–24.3	14.2–27 × 12.5–18	34–61.5 × 22.5–43.4	
	Coiled Biserial	178 × 64 (1)	0	11	21.6 × 15.5	27 × 26.4	37 × 35	
Sabia Island coral reef	Uniserial	136.5 × 17 (1)	0	9	Diameter 39.9	33 × 15.7	43 × 38	Benthic porcelaneous foraminifera and several broken specimens were observed
	Biserial	None						
	Planispiral	29.8–161.6 × 26.5–137.2 (20)	1–2.5	7–19	4.5–43 × 4–40.4	5.2–40 × 3.3–31.5	15–84.1 × 7.4–50	
	Trochospiral	46.6–180.5 × 36–178 (16)	1–2.5	5–14	8–29.6 × 5.5–21.5	7.3–24.5 × 6–20.2	20.2–109 × 12–62.5	
	Coiled Uniserial	187.7–278.6 × 139–158 (2)	1–1.5	13	20.5–38.8 × 20.2–30	24.7–35.7 × 14.6–27.8	47.6–82 × 39.3–72	
	Coiled Biserial	None						
Algal Mats								None observed

a low of 11 in sample L7 to a high of 74 in sample L3, and total number of palynomorphs counted from seven samples in this environment is 338. In the mangrove environment, counts vary from a low of 26 in sample M4 to a high of 132 in sample M6, and total number of palynomorphs counted from seven samples in this environment is 572. Two samples from Sabia Island coral reef environment have remarkably different counts, 66 in sample SI 1, and 141 in sample SI 2. Palynomorph counts from two samples in the algal mat environment were almost same: 60 in AM 1 and 58 in AM 2 (Table 1). The average number palynomorphs in the samples of intertidal environment is 48.28, mangrove environment is 81.71, coral reef environment 103.5, and algal mat environment 59. This shows that palynomorph count per sample is minimum in the intertidal environment and highest in the coral reef environment. The foraminiferal palynomorphs observed in intertidal and mangrove environments are remnants of smaller benthic calcareous foraminifera, whereas Sabia Island coral reef has smaller benthic, both calcareous and porcelaneous forms.

Counts of foraminiferal palynomorphs also vary considerably among the samples within the same environment and among different environments as well (Table 1, Figure 2). In only three out of seven intertidal samples, foraminiferal palynomorphs were observed and their numbers were low ranging from one in sample L6 to five in sample L3. Thus, their average percentage

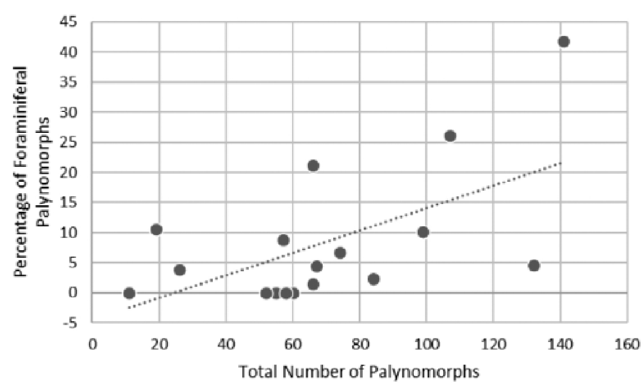

Figure 3. Scatter plot of pairs showing positive correlation between total number of palynomorphs in various samples with corresponding percentages of foraminiferal palynomorphs based on data from Table 1.

is as low as 2.68. However, in the mangrove environment foraminiferal palynomorphs were observed in all samples, but their numbers varied greatly ranging from a low of one in sample M4 to a high of 28 in sample M5, thus their average percentage is relatively higher 8.60. Two samples of Sabia Island coral reef yielded very high numbers of foraminiferal palynomorphs, 14 in sample SI 1 and 59 in SI 2, thus their average percentage is very high 31.52. No foraminiferal palynomorphs were observed in the two samples of algal mats. In these southern Red Sea coastal environments of Saudi Arabia there seems to be a positive relationship between total number of palynomorphs and percentage of foraminiferal palynomorphs (Figure 3).

The reason for a low palynomorph count in the sample L7 is due to its location away from the present-day shoreline minimizing marine influence. Since it is a silty to sandy laminated sediment sample collected from the edge of a small pond (Kumar 2020) indicates greater influence of the surrounding desert environment. Due to these factors no foraminiferal palynomorphs were observed in this sample. Sample L6 is a mud and fine sand sample collected from the middle of this pond yielded a high number of terrestrial palynomorphs (66) but no foraminiferal palynomorphs indicating almost no marine influence. Samples L3 and L4 are mud samples closer to the shoreline demonstrating marine influence due to presence of foraminiferal palynomorphs. Surprisingly sample L5 is subtidal mud that yielded several marine microfossils (Kumar 2020) but no foraminiferal palynomorph. However, shallow subtidal environments generally are good environments where benthic foraminiferal production is common. de Stigter et al. (1999, Figure 1) shows an overview of processes affecting the generation of the benthic foraminiferal assemblage in the surface sediments. It seems more samples should be studied from this environment to isolate foraminiferal palynomorphs. Berkeley et al. (2007) reviewed foraminiferal production and taphonomic loss in intertidal environments and investigated how these processes can affect the development of foraminiferal assemblages in intertidal environments. They stated that the upper one cm of sediment may not adequately characterise baseline for identifying 'true' taphonomic trends downcore. The most important taphonomic processes in intertidal environments are those associated with early diagenesis.

Foraminiferal palynomorphs result once calcium carbonate is removed from original benthic foraminiferal tests, due to taphonomic and palynological maceration process. Thus, it is difficult to relate them to their original tests. Lining morphotypes described by Tyszla et al. (2021) are used to describe and classify them. The intertidal environment only has biserial, planispiral, trochospiral and coiled uniserial morphotypes. Counts of foraminiferal palynomorphs in this environment is low, measurements of each morphotypes are given as size in µm, number of whorls, number of chambers, 1st chamber size, 2nd chamber size and the size of complete last chamber (Table 2). Such measurements give a good idea about the size of the original test and its growth rate. Trochospiral and coiled uniserial morphotypes are common, however, rare broken specimens were observed as well which could not be classified into any morphotypes.

Foraminiferal palynomorphs were observed in all the mangrove samples and total counts of palynomorphs were higher than the samples from intertidal environment. The counts of total number of palynomorphs and foraminiferal palynomorphs in the mangrove environment vary probably due to the depths of the collected samples. There is a possibility that in some of the surface samples where counts are higher may represent more than one cm deep sediment. Samples representing higher depths may have higher counts of foraminiferal palynomorphs. In such a study on taphonomy of tidal marsh foraminifera Patterson et al. (1999) found that the upper 10 cm of sediment contain most infaunal foraminifer species, whereas the top centimetre commonly lacks some of these species. A similar case may be in the mangroves as well. There is also a possibility that marine influence is not uniform over these scattered patches of mangrove stands where some are closer to the coastline than others.

Mangroves are widely known to be one of the most productive ecosystems in which a diverse range of organisms including microfauna such as benthic foraminifera inhabit. High-diversity assemblages of benthic foraminifera were reported from mangroves in different parts of the world (Sen et al. 2016, Sariaslan & Langer 2021, Abd Malek et al. 2021). Likewise, Fiorini et al (2019) reported agglutinated foraminifera from Recent mangrove environments of the United Arab Emirates. Similarly, there are several publications on palynology of mangrove sediments from different parts of the world (Grindrod 1985, van Campo & Bengo 2004, Srivastava et al. 2021). However, none of them did any detailed study on foraminiferal palynomorphs. In all likelihood, foraminiferal palynomorphs were present in the palynological slides of mangrove sediments but were largely ignored by palynologists. It is emphasised here that detailed study of foraminiferal palynomorphs from mangrove sediments can be a substitute for benthic foraminiferal studies useful for various geological, environmental and palaeoenvironmental studies.

The mangrove environment has uniserial, planispiral, trochospiral, coiled uniserial and coiled biserial morphotypes, among them planispiral, trochospiral, and coiled uniserial are most common. Counts of foraminiferal palynomorphs in this environment is higher than the counts in intertidal environment (Table 2). Several broken specimens were observed which could not be classified.

Two samples from Sabia Island coral reef environment produced the highest counts of foraminiferal palynomorphs in this study, 66 in sample SI 1, and 141 in sample SI 2. This indicates abundance of benthic foraminifera in this environment. There are several studies on reef sediments and reef-dwelling foraminifers. Objectives of such studies included using reef foraminifera as bioindicators of coral reef health, coral reef assessment and monitoring, and spatial patterns in the distribution, diversity, and abundance of benthic foraminifera (Hallock et al. 2003, Fajemila et al. 2015, A'ziz et al. 2021).

The Sabia Island coral reef environment has uniserial, planispiral, trochospiral, and coiled uniserial morphotypes, among them planispiral and trochospiral are most common. Counts of foraminiferal palynomorphs in this environment is highest among all the coastal environments (Table 2). Benthic porcelaneous foraminifera and several broken specimens were observed as well.

An important element of foraminiferal palynomorphs from the coral reef samples is the presence of several specimens of porcelaneous forms. Benthic foraminifera are either the agglutinated or calcareous and tests of calcareous forms may either be translucent (hyaline) with tiny pores or white and opaque without pores are known as porcelaneous forms. The proportions of these tests (agglutinated, hyaline, porcelaneous) in a sample characterises various environments in modern seas and oceans. Foraminiferal assemblages dominated by porcelaneous species characterize shallow tropical environments (Haynes 1981). Generally calcareous-porcelaneous forms are shiny and smooth tests, for example, *Miliolina*. They are opaque in polarized light (Haq & Boersma 1978).

Relationship between foraminiferal palynomorphs and benthic foraminifera

Benthic foraminiferal linings preserve better than the calcareous shell and have been considered a better representation of benthic (palaeo) productivity than the calcareous shells (de Vernal 2009). However, it is seldom possible to determine the foraminifer species from the benthic foraminifer linings. Uniserial or triserial forms are generally infaunal, while trochospiral forms are more commonly epifaunal (Corliss 1991).

Since organic linings of foraminifers are remains of calcareous and agglutinated benthic foraminifer taxa; de Vernal (2009) performed in vitro dissolution of many calcareous and few agglutinated foraminifer shells to identify the taxa that produce organic linings (Table 3 in de Vernal 2009). Mathison and Chmura (1995) studied distribution of microforaminiferal test linings of marshy environments of the Mississippi Delta region and concluded that these linings have potential for palaeoenvironmental interpretation. They assumed that *Rotalidae* foraminifers *Miliammina fusca* and *Ammonia beccari* are important constituents of the test lining assemblages.

Mudie and Yanko-Hombach (2019) studied microforaminiferal linings as proxies for palaeosalinity and pollution in the Danube River Delta complex. They used cold acids in palynological processing and found that the test linings of the most common benthic foraminifera (the rotaliids *Ammonia tepida, A. ammoniformis, A. compacta, N. matagordanus* and *P. subgranosus mediterranicus*) could be distinguished by test morphology, size, and surface features (papillae, granules) reflecting the pores and sutures of the calcareous tests. Mudie et al. (2021a, Table 1) provide a list of benthic foraminifera (mostly calcareous but few agglutinated and one arenaceous) with corresponding morphotypes of foraminiferal linings from the Gulf of St Lawrence, NW Atlantic Ocean, NW Black Sea and Chezzetcook salt marsh, Nova Scotia. Mudie et al. (2021b) studied palynology of surface sediments of the NW Black Sea. By visual

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Figure 4. Magnification ×400 (Slide numbers, co-ordinates and actual size are given)

I. Intertidal samples

A. Slide L3a; 143 × 6.5; size 104 × 74 µm; Trochospiral, proximate, brownish, number of chambers 8, first chamber 26.2 × 18.8 µm, second chamber 25.9 × 20.2 µm, and the last chamber 57 × 35.6 µm, number of whorls 1.5. **B.** Slide L1b; 164.8 × 11.6; length 117.6 µm; Biserial, brownish; number of chambers 10, first chamber 18 × 15.5 µm, second chamber 18 × 16 µm, and the last chamber 28.6 × 28.4 µm. **C.** Slide L3b; 157.5 × 5.5; size 105 × 66 µm; Trochospiral, open, brownish, number of chambers 9, first chamber 30 × 25 µm, second chamber 18.6 × 15.5 µm and the last chamber 48 × 19.6 µm, number of whorls 1.5. **D.** Slide L3b; 134.5 × 7.5; size 65.5 × 50 µm; Trochospiral, proximate, brownish, number of chambers 7, first chamber 20.2 × 19.5 µm, second chamber 15.7 × 9 µm, and the last chamber 65.5 × 50 µm, number of whorls 1.5. **E.** Slide L3b; 156.5 × 13.5; size 76 × 51 µm; Trochospiral, open, brownish, proximate, number of chambers 7, first chamber 15.5 × 15 µm, second chamber 11.6 × 8.5 µm, and the last chamber 46.8 × 15.5 µm, number of whorls 2.5. **F.** Slide L4a; 156.7 × 14.5; diam. 82 × 80 µm; Trochospiral, proximate, yellow, number of chambers 12, first chamber 9.6 × 8.7 µm, second chamber 8.7 × 5.5 µm, and the last chamber 62 × 29.5, number of whorls 2.5. **G.** Slide L4a; 144.5 × 21.5; size 114 × 70 µm, coiled uniserial, open, light grey, number of chambers 7, first chamber 33 × 18.8 µm, second chamber 25 × 18.5 µm, and the last chamber 37.5 × 27.6 µm, number of whorls 1. **H.** Slide L6b; 157.2 × 4.5; size 57.5 × 53.5 µm; Planispiral, proximate, grey, number of chambers 8, first chamber 11 × 10 µm, second chamber 11 × 6 µm, and the last chamber 32.8 × 19.5 µm, number of whorls ? 2 (a broken specimen). **I.** Slide L3a; 144.8 × 8; size 62 × 42 µm; coiled uniserial, open, grey, number of chambers 4, first chamber 29.7 × 23 µm, second chamber 22.8 × 18.2 µm, and the last chamber 32 × 16.4 µm, number of whorls 1. **J.** Slide L4b; 142 × 11.8; size 139.6 × 103 µm; coiled uniserial, open, light greyish yellow, number of chambers 5, first chamber 37 × 34.4 µm, second chamber 35.5 × 35.3 µm, and last chamber 41 × 36.3 µm, number of whorls 1.

II. Mangrove swamp samples

K. Slide M1a; 152.4 × 19; size 103 × 96 µm; Planispiral, open, greyish yellow; number of chambers 13, first chamber 11 × 9.8 µm, second chamber 8.8 × 7.8 µm, and the last chamber 42.7 × 44 µm, number of whorls 2.5. **L.** Slide M1c; 134.5 × 5.8; size 95.6 × 84 µm; Coiled uniserial, open, yellow, number of chambers 9, first chamber 29.6 × 24.3 µm, second chamber 15 × 14.5 µm, and the last chamber 36 × 22.5, number of whorls 1. **M.** Slide M1c; 139.5 × 12.5; size 145.5 × 76 µm; Planispiral, open, brown, number of chambers 9, first chamber 26.5 × 20.5 µm, second chamber 21.7 × 19 µm, and the last chamber 55 × 42.5 µm, number of whorls 1. **N.** Slide M1c; 151 × 17.3; size 74 × 53.5 µm; Trochospiral, proximate, brown, number of chambers 8, first chamber 19.6 × 12.5 µm, second chamber 15.3 × 10.2 µm, and the last chamber 47 × 26.7 µm, number of whorls 1.5. **O.** Slide M1d; 133.5 × 11; size 129 × 97 µm; Planispiral, open, brown, number of chambers 12, first chamber 18 × 16.4 µm, second chamber 10.4 × 9.2 µm, and the last chamber 66 × 45.4 µm, number of whorls 1.5. **P.** Slide M1d; 156.8 × 17.2; size 94 × 62.5 µm; Trochospiral, proximate, brownish, number of chambers 9, first chamber 20 × 17.8 µm, second chamber 13 × 11.3 µm, and the last chamber 62.8 × 37.7 µm, number of whorls 1.5. **Q.** Slide M2c; 150.8 × 17; size 67.2 × 55.7 µm (a fragment of smaller benthic foraminifera). **R.** Slide M3a; 135.4 × 15; size 107 × 82 µm; Trochospiral (damaged), proximate, brownish, number of chambers 7, first chamber missing , second chamber unknown since first chamber (proloculus) is missing , and the last chamber is also damaged, number of whorls 1. **S.** Slide M3b; 155 × 7; size 173 × 77 µm; Coiled uniserial, greyish yellow, number of chambers 10, first chamber 23.8 × 19.5 µm, second chamber 14.2 × 12.4 µm, and the last chamber 42 × 34 µm.

T. Slide M4a; 157 × 18.5; size 167.7 × 105.3 µm; Planispiral, open, yellowish grey, number of chambers 10, first and second chambers covered under debris, and the last chamber 64 × 35 µm, number of whorls 1.5. **U.** Slide M5c; 150 × 15; size 92.6 × 83 µm; Coiled uniserial, open, light brownish, number of chambers 8, first chamber 34 × 21 µm, second chamber 25 × 17.5 µm, and the last chamber 55 × 28 µm, number of whorls 1.5. **V.** Slide M5d; 154 × 6.5; size 116.4 × 56 µm; Coiled uniserial, open, light brownish, number of chambers 9, first chamber 32 × 17.5 µm, second chamber 27.6 × 17.3 µm, and the last chamber 61.5 × 43.4 µm, number of whorls 1.5. **W.** Slide M5d; 157 × 17; size 86.6 × 47 µm; Coiled uniserial, open, light brownish, number of chambers 7, first chamber 20.5 × 19.5 µm, second chamber 26.7 × 18 µm and the last chamber 34 × 31.5 µm, number of whorls 1.5. **X.** Slide M5d; 130.5 × 19.5; size 99.4 × 71 µm; Planispiral, open, brownish, number of chambers 9, first chamber 25.5 × 17.2 µm, second chamber 27 × 15.5 µm, and the last chamber 55 × 30 µm, number of whorls 1.5.

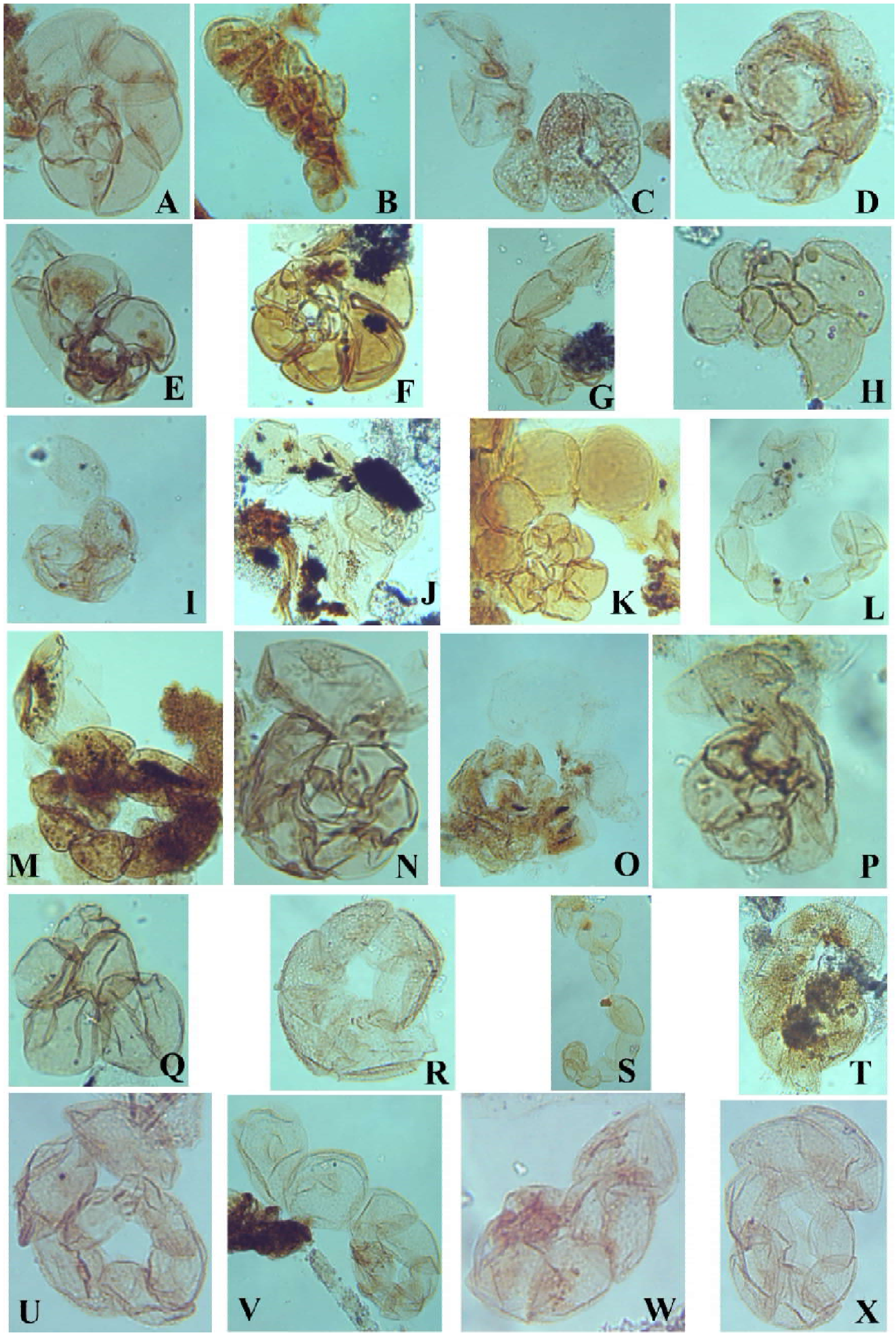

Figure 4

comparison they established relationship between microforaminiferal organic linings with seven taxa of benthic foraminiferal species including spiral rotalid and the uniseriate lagenid linings. However, acid treatment was needed to confirm identifications of the unilocular linings of *Fissurina lucida* and *Parafissurina dzemetinica*. Corresponding well-preserved organic linings of calcareous foraminifera from orders *Rotaliida* and *Lagenida*, and from agglutinated order *Ammodiscida* were also identified.

The present foraminiferal palynomorph assemblages from intertidal and mangrove environments are most likely derived from the smaller benthic calcareous foraminifera. Few among them maybe associated with *Ammonia* (Figures 4.F; 5.A, B, W; 6.A, Z). Sabia Island coral reef assemblages have smaller benthic foraminifera, having both calcareous and porcelaneous forms. Porcelaneous forms are (Figures 6.O, P, T are miliolids; and Figures 6.G, AD, AH, AI

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Figure 5. Magnification ×400 (Slide numbers, co-ordinates and actual size are given).

II. Mangrove swamp samples (continued)

A. Slide M6a; 153.5 × 10.5; size 70.4 × 61 µm; Trochospiral, proximate, yellowish grey, number of chambers 11, first chamber 11.7 × 9.7 µm, second chamber 7.6 × 5.5 µm, and the last chamber 47 × 27.5 µm, number of whorls 2.5. **B.** Slide M6b; 142.8 × 11.8; size 57.8 × 37.6 µm; Trochospiral, proximate, yellowish grey, number of chambers 9, first chamber 10 × 66 µm, second chamber 9.2 × 6.5 µm , and the last chamber 38.4 × 26 µm, number of whorls 2.5. **C.** Slide M6b; 147.7 × 17; size 121.5 × 90 µm; Trochospiral, proximate, brownish, number of chambers 9, first chamber 26.5 × 24.8 µm, second chamber 27.2 × 18 µm, and the last chamber 52.7 × 35 µm, number of whorls 2.5. **D.** Slide M6c; 147 × 2.3; size 67 × 57 µm; Planispiral, proximate, light grey, number of chambers 7, first chamber 20 × 11.5 µm, second chamber 13 × 8.5 µm, and the last chamber 42.6 × 26.5 µm, number of whorls 1. **E.** Slide M6d; 134 × 5; size 76 × 73.3 µm; Coiled uniserial, open, brownish, number of chambers 8, first chamber 27 × 19 µm, second chamber 21.5 × 16 µm and last the chamber (keeled) 35 × 23.7 µm, number of whorls 1. **F.** Slide M6c; 164.6 × 10.8; size 198 × 84 µm; Uniserial, brownish, number of chambers 9, first chamber 20.7 × 9.8 µm, second chamber 21.5 × 10.8 µm, and the last chamber 73.8 × 61.6 µm. **G.** Slide M7a; 164.5 × 7; size 93.5 × 84 µm; Trochospiral, proximate, brownish, number of chambers 11, first chamber 14.4 × 13.4 µm, second chamber 12.6 × 10.5 µm, and the last chamber 56.5 × 28 µm, number of whorls 2. **H.** Slide M7a; 132.8 × 8; size 133 × 134 µm; Trochospiral, proximate, greyish brown, number of chambers 12, first chamber 11 × 7.8 µm, second chamber 16.5 × 11.5 µm, and the last chamber 54.4 × 37.7 µm, number of whorls 2.5. **I.** Slide M7a; 135.5 × 10.5; size 165 × 150.2 µm; Coiled uniserial, open, brownish, number of chambers 16, first chamber 16 × 11.5 µm, second chamber 13.6 × 9 µm and the last chamber 58 × 28.2 µm, number of whorls 1. **J.** Slide M7c; 154.5 × 19.5; size 178 × 64 µm; Coiled uniserial, open, greyish yellow, number of chambers 11, first chamber 21.6 × 15.5 µm, second chamber 27 × 26.4 µm and the last chamber 37 × 35, number of whorls 0, uniserial chambers arranged in 'U' shape. **K.** Slide M7b; 158.4 × 14.5; size 140 × 79 µm; Trochospiral, proximate, brown, number of chambers 13, first chamber 22 × 16 µm, second chamber 20.8 × 17.2 µm, and the last chamber 52 × 48 µm, number of whorls 2.5.

III. Sabia Island coral reef samples

L. Slide SI1a; 145.2 × 7; size 150 × 120.8 µm; Planispiral, proximate, greyish, number of chambers 10, first chamber 43.6 × 40.4 µm, second chamber 40.1 × 31.5 µm, and the last chamber 60.3 × 38.8 µm, number of whorls 1. **M.** Slide SI1a; 150.5 × 12; size 68 × 67 µm; Planispiral, open, grayish brown, number of chambers 9, first chamber 13.7 × 9.5 µm, second chamber 14.1 × 6.0 µm, and last total length 24.4 × 21.4 µm, number of whorls 1.5. **N.** Slide SI1b; 142 × 13.3; size 132.9 × 107.6 µm; Trochospiral, proximate, yellowish grey, number of chambers 11, first chamber 22 × 20 µm, second chamber 17 × 15 µm, and the last chamber 72 × 58 µm, number of whorls 1. **O.** Slide SI1b; 155.5 × 9; size 110.7 × 93.5 µm; Planispiral, proximate, yellowish grey, number of chambers 13, first chamber 11 × 10 µm, second chamber 7.2 × 4.8 µm and the last chamber 60.2 × 35.8 µm, number of whorls 2. **P.** Slide SI1b; 142 × 11; size 95.2 × 78.8 µm; Trochospiral, proximate, yellowish grey, number of chambers 14, first chamber 6.8 × 6.2 µm, second chamber 7.4 × 6.6 µm and the last chamber 49.6 × 38 µm, number of whorls 2. **Q.** Slide SI1a; 155 × 12; size 185.7 × 158 µm; Coiled uniserial, open, greyish, number of chambers 13, first chamber 20.5 × 20.2 µm, second chamber 24.7 × 14.6 µm and the last chamber 47.6 × 39.3, number of whorls 1. **R.** Slide SI1c; 138 × 12; size 151.7 × 93.3 µm; Trochospiral, proximate, greyish yellow, number of chambers 12, first chamber 13.4 × 11.2 µm, second chamber 13.1 × 9.2 µm and the last chamber 69.6 × 38.3 µm, number of whorls 1.5. **S.** Slide SI1c; 139.4 × 16.2; size 95 × 92.5 µm; Trochospiral, proximate, yellowish grey, number of chambers ?13 (under debris), first chamber 15 × 13.2 µm, second chamber 14 × 9.5 µm, and the last chamber (no measurement, under debris), number of whorls 2. **T.** Slide SI1c; 135.5 × 18; size 161.6 × 137.2 µm; Planispiral, proximate, brown, number of chambers 10, first chamber 30.9 × 27 µm, second chamber 29.5 × 19.5 µm, and the last chamber 84.1 × 50 µm, number of whorls 1. **U.** Slide SI1c; 134.8 × 11.2; size 86.5 × 79 µm; Trochospiral, proximate, greyish yellow, number of chambers 11, first chamber 22.9 × 19.4 µm, second chamber 22.4 × 12.3 µm, and the last chamber 50.2 × 27.8 µm, number of whorls 1.5. **V.** Slide SI1c; 136.5 × 17; size 131.2 × 41.2 µm; Uniserial, yellowish grey, number of chambers 9, first chamber 39.9 µm, second chamber 33 × 15.7 µm, and the last chamber 43 × 38 µm. **W.** Slide SI1c; 156 × 18; size 137.3 × 123 µm; Planispiral, proximate, yellow, number of chambers 12, first chamber 15.8 × 16.2 µm, second chamber 15.8 × 12 µm, and the last chamber 99.3 × 45.3 µm, number of whorls 2. **X.** Slide SI1c; 148.5 × 17.5; size 42 × 38 µm; Planispiral, proximate, greyish blue, number of chambers 9, first chamber 9.5 × 9 µm, second chamber 7.5 × 5.5 µm, and the last chamber 23.6 × 15.5 µm, number of whorls 1. **Y.** Slide SI1d; 151 × 11.5; size 180.5 × 178 µm; Trochospiral, proximate, greyish blue, number of chambers 14, first chamber 14 × 13.5, second chamber 13.5 × 9, and the last chamber 109 × 62.5 µm, number of whorls 2.5.

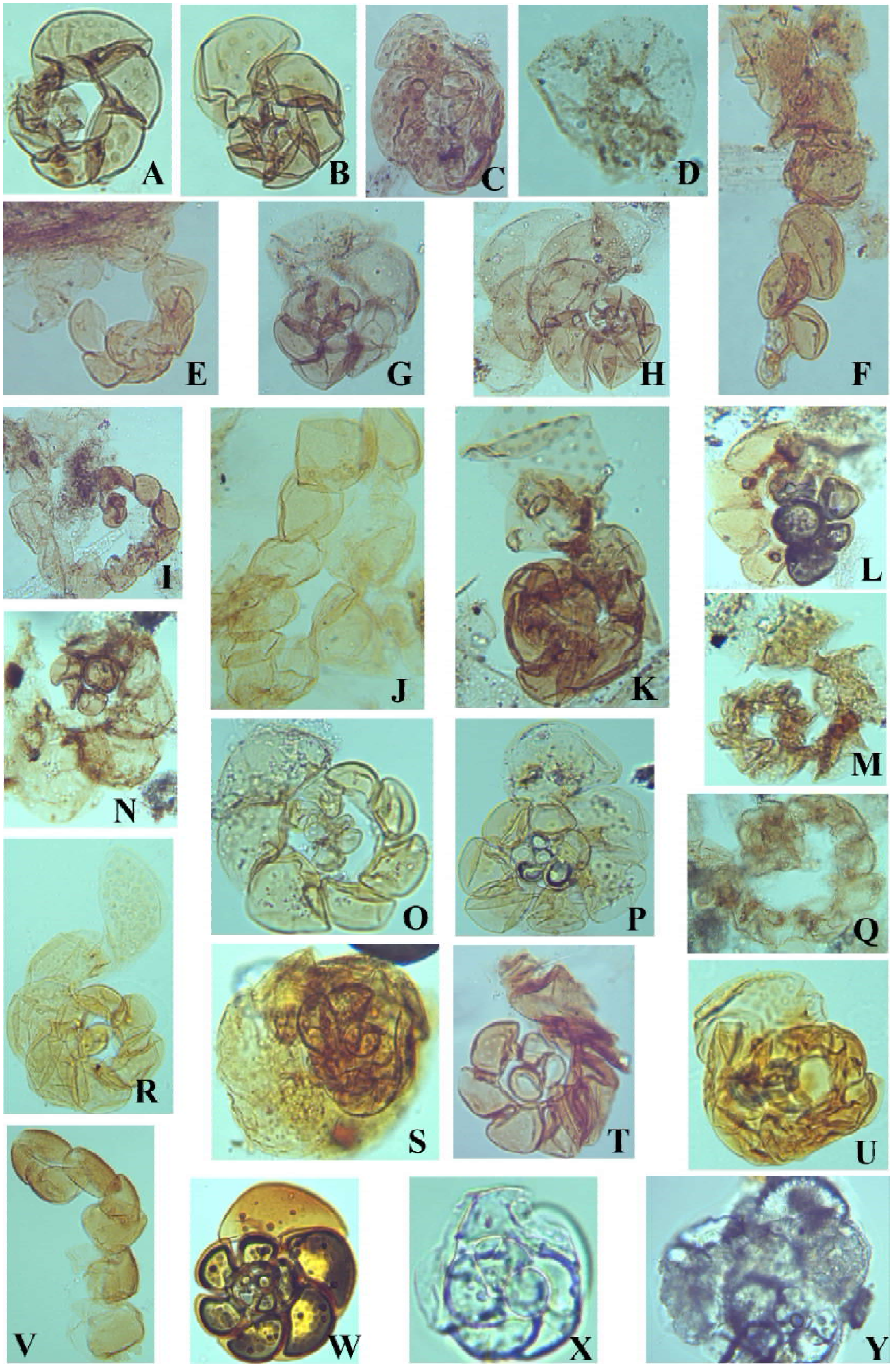

Figure 5

are referable to *Sorites* sp./*Parasorites* sp. and/or *Archaias* sp. It is important to investigate if such foraminiferal forms inhabit these environments in the present area of study. There is no published account of benthic foraminiferal assemblages from these environments in the southern Red Sea coast of Saudi Arabia. However, there are a few published accounts of similar study along the northern Red Sea coastal environments and along the coastal sediments in the Arabian Gulf region.

Miliolina and *Sorites* were reported from benthic foraminiferal assemblages from the Recent subtidal zone

Figure 6. Magnification ×400 (Slide numbers, co-ordinates and actual size are given)

III. Sabia Island coral reef samples (continued)

A. Slide SI2a; 152 × 4; size 29.8 × 26.5 µm; Planispiral, proximate, greyish, number of chambers 7, first chamber 9.2 × 8 µm, second chamber 5.6 × 5.2 µm, and the last chamber 15.5 × 7.4 µm, number of whorls 1. **B.** Slide SI2a; 145.5 × 4; diam. 46.6 × 45.5 µm; Trochospiral, proximate, greyish, number of chambers 5, first chamber 16.2 × 13.4 µm, second chamber 12.2 × 9.5 µm, and the last chamber 27.7 × 21.5 µm, number of whorls 1. **C.** Slide SI2a; 141 × 6.5; size 67 × 64.5 µm; Planispiral, proximate, greyish, number of chambers 11, first chamber 10.6 × 9.5 µm, second chamber 7.5 × 7.1 µm, and the last chamber 39 × 16 µm, number of whorls 1. **D.** Slide SI2a; 136.5 × 8.6; 112 × 78.8 µm; Trochospiral, proximate, yellowish grey, number of chambers 9, first chamber 29 × 21.5 µm, second chamber 24.5 × 20.2 µm, and the last chamber 77.7 × 42.4 µm, number of whorls 1.5. **E.** Slide SI2a; 135.5 × 9; size 61.2 × 57.7 µm; Trochospiral, proximate, yellowish grey, number of chambers 9, first chamber 13.7 × 9 µm, second chamber 9.2 × 8.7 µm, and the last chamber 35.5 × 20 µm, number of whorls 1. **F.** Slide SI2a; 136 × 11.5; size 181.4 × 148.2 µm; Trochospiral, proximate, yellowish grey, number of chambers 12, first chamber 37 × 35 µm, second chamber 30.8 × 18.8 µm, and the last chamber 67 × 53 µm, number of whorls 2. **G.** Slide SI2a; 141 × 16; diam. 46 µm (benthic porcelaneous foraminifera) **H.** Slide SI2a; 164 × 16.5; size 73 × 68 µm; Trochospiral, proximate, yellowish grey, number of chambers 13, first chamber 8 × 7.4 µm, second chamber 8 × 6.5 µm, and the last chamber 43.6 × 19.2 µm, number of whorls 2. **I.** Slide SI2a; 151.5 × 16; size 89.8 × 80.5 µm; Planispiral, proximate, greyish, number of chambers 17, first chamber 7.8 × 7.6 µm, second chamber 9.6 × 5.5 µm, and the last chamber 54.6 × 23.3 µm, number of whorls 2. **J.** Slide SI2b; 140.5 × 14; 278.6 × 139 µm (×100); Coiled uniserial, open, greyish, number of chambers 13, first chamber 38.9 × 30 µm, second chamber 35.7 × 27.8 µm and the last chamber 82 × 72 µm, number of whorls 1.5. **K.** Slide SI2a; 137.2 × 21; size132.8 × 122.6 µm; Planispiral, proximate, greyish, number of chambers 19, first chamber 4.5 × 4 µm, second chamber 5.2 × 3.3 µm, and the last chamber 57.5 × 36.4 µm, number of whorls 2. **L.** Slide SI2d; 137.4 × 15.8; size 60.4 × 51.5 µm; Planispiral, proximate, greyish, number of chambers 10, first chamber 7 × 6.6 µm, second chamber 11 × 6 µm, and the last chamber 42 × 21.5 µm, number of whorls 2.5. **M.** Slide SI2b; 128.6 × 10.4; size 132 × 130.9 µm; Trochospiral, proximate, yellowish grey, number of chambers 13, first chamber 14.5 × 1.8 µm, second chamber 12 × 8.8 µm, and the last chamber 63.7 × 37.6 µm, number of whorls 2. **N.** Slide SI2b; 137 × 14; size 137 × 111.8 µm; Planispiral, open, brown, number of chambers 9, first chamber 27.8 × 19 µm, second chamber 27 × 22.7 µm , and the last chamber 78.7 × 44 µm, number of whorls 1. **O.** Slide SI2c; 163.4 × 7; size 89.3 × 50 µm (benthic porcelaneous foraminifera). **P.** Slide SI2c; 163.5 × 7; size 148.5 × 74.3 µm (benthic porcelaneous foraminifera). **Q.** Slide SI2b; 146.5 × 12.5; size 40.7 × 32 µm; Trochospiral, proximate, bluish grey, number of chambers 7, first chamber 16 × 9.8 µm, second chamber 12.7 × 8.4 µm, and the last chamber 25.8 × 11 µm, number of whorls 1. **R.** Slide SI2b; 159.3 × 13.5; size 48 × 41 µm; Planispiral, proximate, brownish, number of chambers 9, first chamber 13.4 × 7.6 µm, second chamber 10 × 9.2 µm, and the last chamber 25.5 × 10.6 µm, number of whorls 1. **S.** Slide SI2c; 149.5 × 2.3; size 44.5 × 43 µm; Planispiral, proximate, bluish grey, number of chambers 8, first chamber 16.1 × 16 µm, second chamber 8.1 × 7.8 µm, and the last chamber 22 × 11.5 µm, number of whorls 1. **T.** Slide SI2c; 151.8 × 16; size 243 × 113 µm (×100) (benthic porcelaneous foraminifera). **U.** Slide SI2c; 134.5 × 4; diameter 36 µm; Trochospiral, proximate, bluish grey, number of chambers 7, first chamber 7 × 5.5 µm, second chamber 7.3 × 6 µm, and the last chamber 20.2 × 12 µm, number of whorls 1. **V.** Slide SI2c; 163 × 11.5; size 116 × 90 µm; Planispiral, proximate, brownish, number of chambers 17, first chamber 8.5 × 6.5 µm, second chamber 12 × 6.4 µm, and the last chamber 50.5 × 30 µm, number of whorls 2. **W.** Slide SI2c; 159 × 11.5; size 43 × 32 µm; Planispiral, proximate, bluish grey, number of chambers 5, first chamber 17 × 16.8 µm, second chamber 13 × 9.2 µm, and the last chamber 28.7 × 11.3 µm, number of whorls 1. **X.** 27.Slide SI2d; 163 × 14.3; diameter 60 µm (benthic porcelaneous foraminifera). **Y.** Slide SI2c; 135.5 × 16; size 128.8 × 88.6 µm; Trochospiral, proximate, greyish yellow, number of chambers 14, first chamber 13.2 × 10 µm, second chamber 12.4 × 8 µm, and the last chamber 60.8 × 47.8 µm, number of whorls 1.5. **Z.** Slide SI2c; 164 × 16.5; size 151 × 131 µm; Trochospiral, proximate, brown, number of chambers 12, first chamber not distinct, second chamber not distinct, and the last chamber 77 × 26.6 µm, number of whorls 1.5. **AA.** Slide SI2c; 143.8 × 20; size 81.7 × 73 µm; Planispiral, proximate, bluish grey, number of chambers 8, first chamber 22.4 × 16.4 µm, second chamber 26.3 × 12 µm, and the last chamber 45.5 × 28 µm, number of whorls 1. **AB.** Slide SI2d; 149 × 5.2; size 95.6 × 92 µm; Planispiral, proximate, greyish, number of chambers 10, first chamber 20 × 16.8 µm, second chamber 12.5 × 10 µm, and the last chamber 35.6 × 17 µm, number of whorls 1. **AC.** Slide SI2d; 141 × 7.5; size 69.6 × 58 µm (benthic porcelaneous foraminifera). **AD.** Slide SI2d; 138 × 16.5; diameter 85.6 µm (benthic porcelaneous foraminifera) .**AE.** Slide SI2d; 149.8 × 7.4; size 89.5 × 76.9 µm (benthic porcelaneous foraminifera). **AF.** Slide SI2d; 155.2 × 9.2; size 45.6 × 44 µm; Planispiral, proximate, bluish grey, number of chambers 9, first chamber 14.9 × 15.5 µm, second chamber 9.5 × 7.5 µm, and the last chamber 21.8 × 14.5 µm, number of whorls 1. **AG.** Slide SI2d; 142 × 13; size 60.3 × 51.2 µm; Planispiral, proximate, purplish, number of chambers 14, first chamber 9.2 × 8.5 µm, second chamber 5 × 4.1 µm, and the last chamber 32.2 × 12.5 µm, number of whorls 1.5. **AH.** Slide SI2d; 160 × 15.3; diameter 117.3 µm (benthic porcelaneous foraminifera). **AI.** Slide SI2d; 143.5 × 19; diameter 127.3 µm (benthic porcelaneous foraminifera).

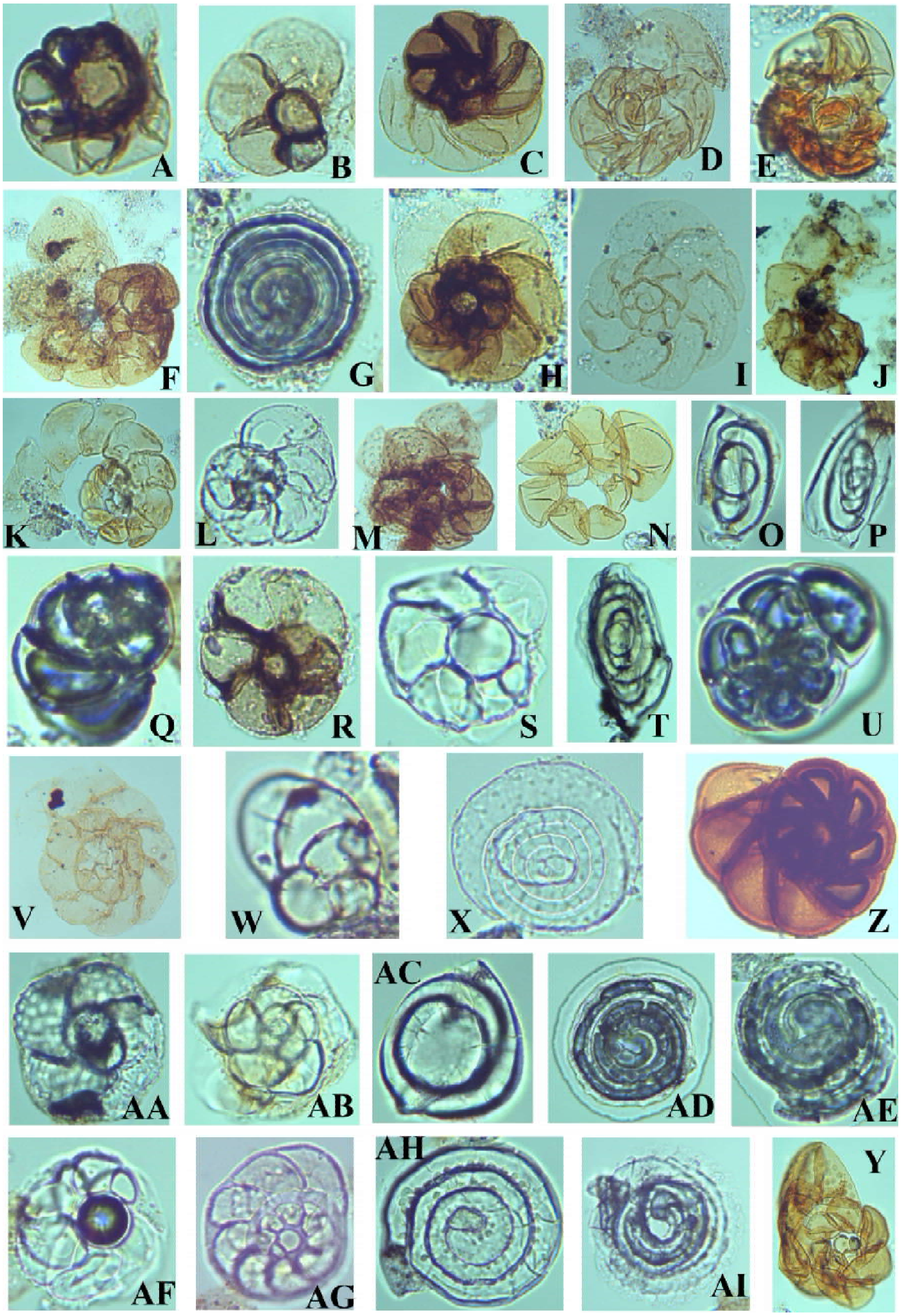

Figure 6

(1–15 cm deep) sediment of Red Sea-Gulf of Aqaba coastal environments (Youssef et al. 2021). *Miliolina* was the most dominant among the benthic foraminifera. Further south of this study site is the Al Kharrar Lagoon, Red Sea Coast of Saudi Arabia. This area has extensive intertidal and supratidal flats in the southern and eastern parts of the lagoon, and southern part of this lagoon is covered by mangroves. Several grab samples were studied, and a large number of benthic foraminiferal species were identified, including abundant Miliolina and few *Sorites orbiculus* (Youssef et al. 2022). Common occurrence of *Ammonia tepida* was identified from the early to mid-Holocene sediments of saline lake at Taymain northern Saudi Arabia, (Pint et al. 2017). An assemblage of benthic foraminifera was reported from Holocene sediments from the coast of Oman, in which *Ammonia beccarii, Ammonia convexa, Ammonia topida* (*Ammoniidae*) were reported (Al-Sayigh et al. 2015). Fiorini et al. (2019) reported an assemblage of agglutinated foraminifera from Recent mangrove environments of the United Arab Emirates (UAE). Samples collected in proximity of mangrove plant *Avicennia marina* roots produced an assemblage exclusively composed of small-sized opportunistic *Ammonia* and *Cribroelphidium*, together with abundant specimens of agglutinated foraminifera belonging to the genus *Trochammina*. Al-Kahtany et al. (2020) reported on benthic foraminifera from Dammam Al-Jubail area, Arabian Gulf, Saudi Arabia. They recorded several species including *Sorites orbiculus* and the opportunistic species *Ammonia tepida* in larger numbers from the coastal sediments of a lagoon just north of Dammam and south of Tarout Island. This coastline is highly polluted due to a range of human activities and is covered by dwindling stands of mangroves (Kumar 2017).

The benthic foraminifers like Miliolids, *Ammonia* and *Sorites* sp. were identified from the foraminiferal palynomorphs in the present study. All these benthic foraminifera are known to inhabit the coastal regions of the Arabian Peninsula. It is interesting to note that Miliolina, and *Sorites* were reported from the Arabian Sea coastal sediments. Several specimens related to *Ammonia* were identified from the mangrove environment. Fiorini et al. (2019) reported *Ammonia* from mangrove environment in UAE and considered them to be small-sized opportunistic species.

CONCLUSIONS

1. A baseline study was carried out on the distribution of foraminiferal palynomorphs in intertidal, mangrove, algal mat and coral reef environments.
2. Foraminiferal palynomorphs are microfossils of foraminiferal affinity observed in palynological slides.
3. This study demonstrates significant differences in relative abundances among informally described morphotypes of foraminiferal palynomorphs in various environments.
4. The intertidal and mangrove environments are characterised by smaller benthic calcareous foraminifers having common forms like Miliolids and *Ammonia*.
5. The coral reef environment is characterised by smaller benthic, both calcareous and porcelaneous forms. The porcelaneous foraminifera are referable to *Sorites* sp./*Parasorites* sp. and/or *Archaias* sp.
6. Common occurrence of foraminiferal palynomorphs related to small-sized opportunistic *Ammonia* has palaeoecological significance due to its abundance in the mangrove sediments in proximity of roots of mangrove plant *Avicennia marina*.
7. No foraminiferal palynomorphs were observed in the algal mats.
8. In absence of foraminiferal data, relative abundance of foraminiferal palynomorph morphotypes may be used for distinguishing various coastal (brackish and marine) depositional environments.

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