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Posted Date: 24 June 2024

doi: 10.20944/preprints202406.1637.v1

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Article

Source and Distribution of Palynomorphs in Southern Red Sea Coastal Environments of Saudi Arabia: Their Palaeoenvironmental and Palaeoecological Inferences

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Abstract: Palynomorph assemblages and mineral microfossils from five southern Red Sea coastal environments were studied to demonstrate their distribution pattern and suggest their source. The environments studied were 1. mangrove swamp 2. middle Holocene paleochannel 3. algal mat, 4. Sabia Island coral reef, and intertidal zone. The samples studied were from the top 3 cm semi-consolidated sediments from various environments. Standard palynological maceration technique was used to isolate palynomorphs. These sediment samples are mainly clay and fine sand and yielded low numbers but high diversity of palynomorph assemblages. They are grouped into pollen and spores, dinoflagellate cysts, and algal remains, fungal spores, hyphae and fruit bodies, protists, and invertebrates. A few Ascidian and sponge spicules, and phytoliths (mineral microfossils) occur in the Sabia Island coral reef environment. The protists and invertebrate remain include microforaminifera, thecamoebians, tintinnomorphs, crustacean and annelid palynomorphs. The assemblage also includes six form taxa belonging to the form genera *Katora* and *Mangrovia*. These palynomorphs belong to both marine and terrestrial environments and are of autochthonous and allochthonous origins. The source and genetic relationship of each palynomorphs is discussed.

Keywords: Red Sea coastal environments; non-pollen palynomorphs (NPP); palynology; foraminiferal palynomorphs; tintinnomorphs; rotifers; ascidian and sponge spicules; phytoliths

1. Introduction

Since non-pollen palynomorphs (NPP) are sourced from a wider range of environments, they have become an important part of palynological research. Primarily NPP are microscopic remains belonging to a variety of plants, algae, fungi, protists, and invertebrates or to a lesser extent the whole organisms like dinoflagellate cysts. During the past few decades their identifications and possible sources have been studied. Initially palynological research mainly concentrated on pollen, spores, and dinoflagellate cysts, and generally NPP was overlooked. Although NPP studies were initiated from freshwater sediments in Europe [1–4]. However, other important NPP studies are from the Black Sea corridor [5], the Caspian-Black Sea-Mediterranean corridor [6], and Holocene sediments of offshore Adélie Land, East Antarctica [7]. An extensive discussion on a variety of marine NPP was recently published [8,9].

In the Arabian Peninsula region, there are very few studies reporting on NPP. The earliest publications from this region were recent dinoflagellate cysts from the Persian Gulf, Gulf of Oman, and northwestern Arabian Sea [10,11]. Palynological report on two offshore Oman samples [12] and palynological studies from Egypt [13,14] were other publications reporting presence of NPP from this region. Kholief [15] reported on palynology of mangrove sediments from the northern Red Sea coastal environments that reported few NPP. The present author published on palynology of the southern Red Sea coastal environments [16,17] reporting on in addition to pollen and spores, a wide range of NPP that included 1. dinoflagellate cysts and other algal remains, 2. fungal spores, hyphae, and fruit bodies, 3. microforaminiferal test linings, 4. thecamoebians, 5. tintinnomorphs and worms, and 6.

crustacean and annelid palynomorphs. Additionally mineral microfossils like Ascidian and sponge spicules, and phytoliths were reported as well. Subsequently, new form taxa of NPP were proposed [18], followed by a morphometric study on foraminiferal palynomorphs [19], and a detailed morphological and taxonomic study of fungal remains were also published [20]. The present study compiles all the previously published palynomorph assemblages from five coastal environments, describes their proportional composition in various environments, discusses their sources, and environmental and palaeoecological implications. To avoid duplication of microphotographs of all the palynomorphs reported in this study, no photo plates are added to this manuscript. They have been illustrated in several photo plates in the previous publications [16–20].

Another objective of this study is to provide comprehensive palynological baseline data about the southern Red Sea coastal environments. Since the discovery of oil in the Arabian region during the 1920s the economic explosion continues to this day [21,22]. Extensive infrastructure projects, both on and offshore, are progressing on the eastern and western coastal regions of the Arabian Peninsula. It is resulting in adverse environmental consequences to the coastal ecosystem where mangroves and offshore sea-grass communities are being negatively impacted [23,24]. Baseline data about the coastal environments and their flora and fauna is required to define the present health of the coastal ecosystem. Study of palynomorphs occurring as fossils or subfossils in various coastal sedimentary settings represent local and regional climate, and environments. The present area of study has not yet been significantly influenced by any anthropogenic activity, except for a road and a few small buildings. Thus, the present study becomes significant as it provides baseline data for undisturbed parts of southern coastal Red Sea environments.

This study presents a palynological analysis of sediments of various coastal environments of the Wadi Hali area of the southern Red Sea coast of Saudi Arabia (Figures 1 and 2), and discusses vegetation types, geological and environmental factors that control the distribution of palynomorphs in various coastal environments of Wadi Hali. The study describes environmental parameters controlling palynomorph distribution is also discussed. Finally, this research presents a palynological database that could be utilized for future environmental monitoring in this region.

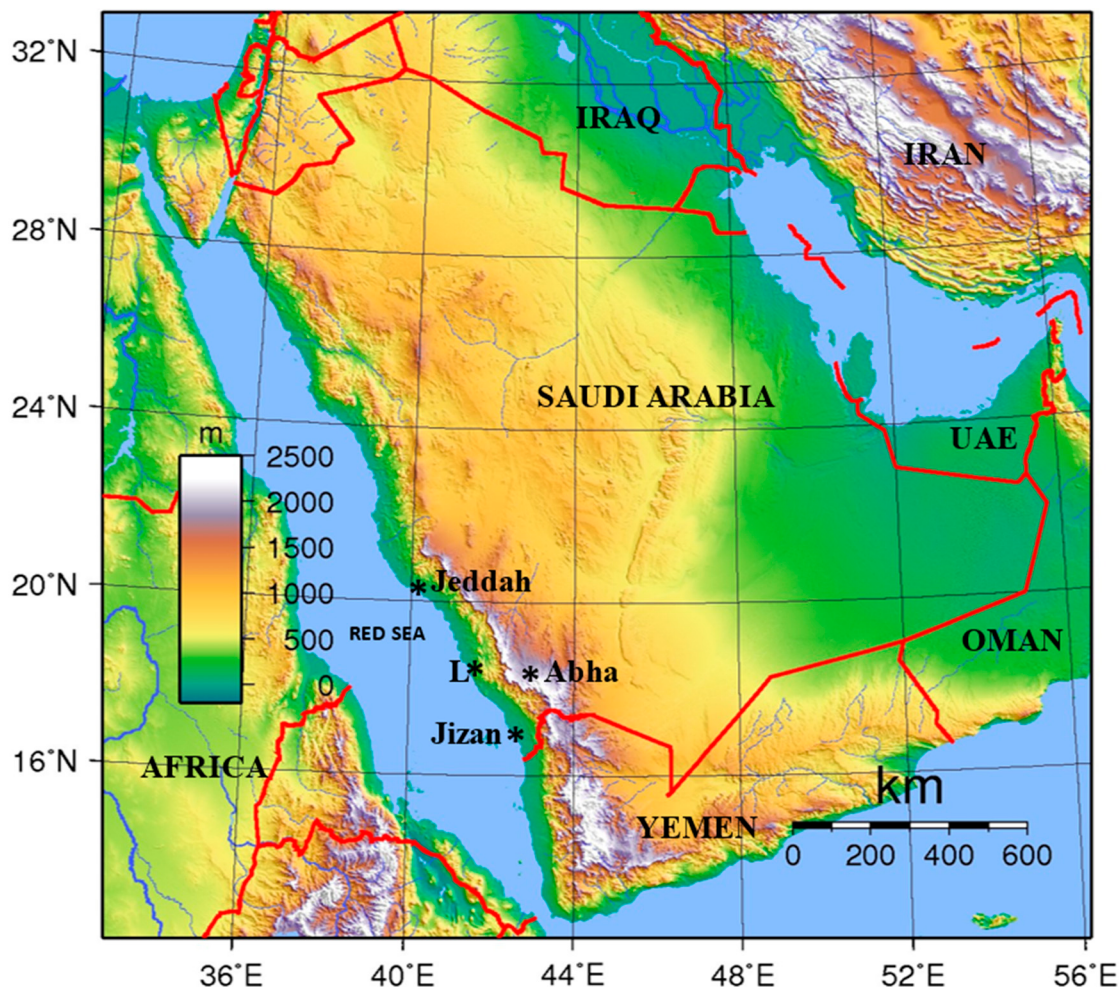


Figure 1. Topographical map of the Arabian Peninsula showing locations of various countries and Red Sea. Location of study is marked by L. (modified after https://commons.wikimedia.org/wiki/File:Saudi_Arabia_Topography.png).

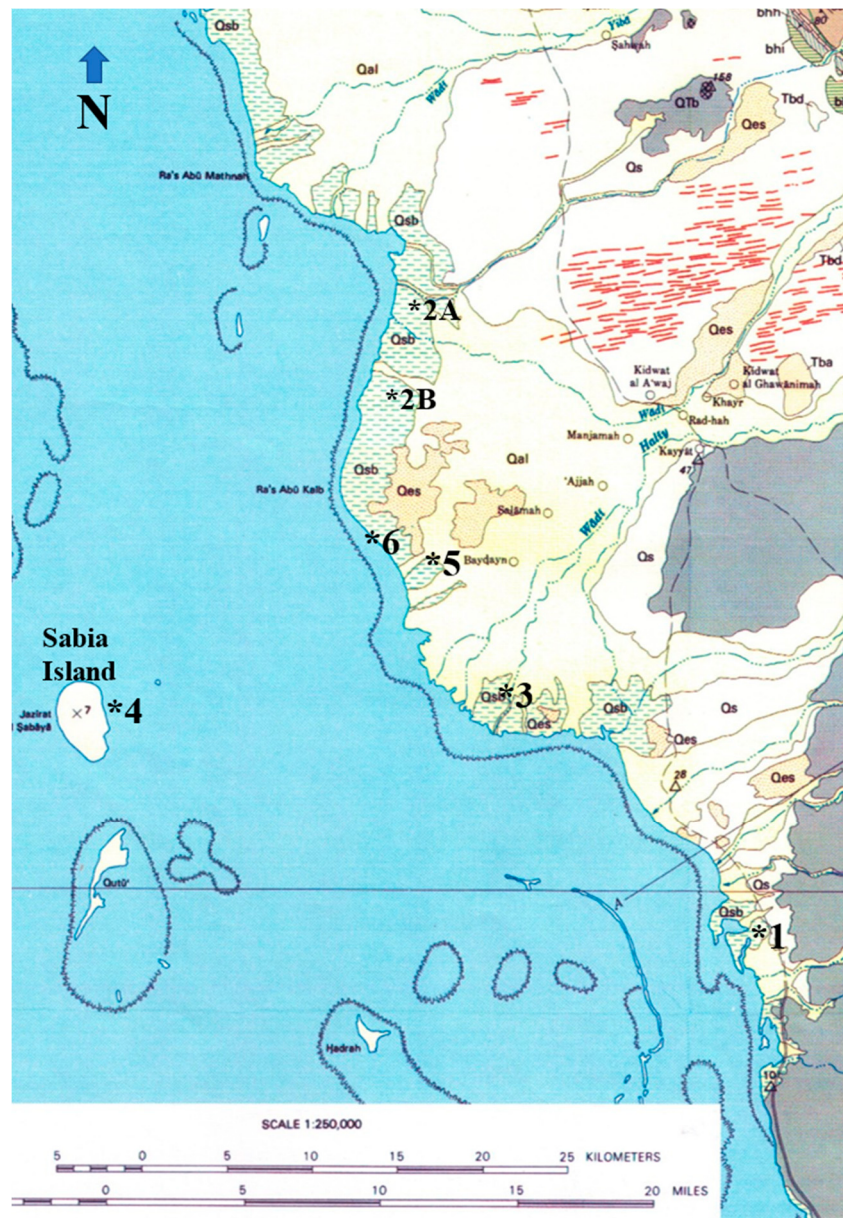


Figure 2. A part of the Geological Map of the Wadi Hali Quadrangle, sheet 18E, Kingdom of Saudi Arabia [29]. The map shows offshore islands, coral reefs and surficial deposits that include two fans that were formed by ancient streams now wadis (dry riverbeds). The region is covered with Holocene-Recent flood plain deposits, sabkhas (salt plains), scattered patches of mangrove swamps and eolian sand fields. Sample locations (1 through 6) are as follows. Mangrove Swamp Environment: Locations 1, 2A and 2B; Paleochannel Section: Location 3; Sabia Island Coral Reef Environment: Location 4; Algal Mat Environment: Location 5; Intertidal Environment: Location 6.

2. Study Area and Its Environment

The Red Sea is a long and narrow body of water, its surface water temperatures are constant year-round at 21°-25°C [25]. Its salinity ranges between ~ 36‰ (3.6‰ on the Practical Salinity Scale or PSU, meaning actual dissolved salts) in the southern region and ~ 41‰ (4.0‰ PSU) in the northern region. The world average is ~ 35‰ or 3.5‰ PSU [26]. Mangroves, seagrasses, coastal vegetation and associated flora, and terrestrial mammals are common around the coastal zones. Latitudinal trends indicate increased abundance of mangroves, seagrasses and coastal flora towards the southern Red Sea, and a decrease in the number of coral reefs [27]. The littoral area of Red Sea sediments is related to a complex system of fringing and barrier reefs and alluvial fans. They belong to the arid regions covered by Quaternary terraced alluvial deposits, eolian sands, river-bed alluvium and sabkhas (salt

pans). Mangrove swamps and wadis (dry riverbeds) are scattered all along the coast. Environmental changes along the Red Sea coast are influenced by anthropogenic activities, such as tourism, new towns, and port development. The natural causes for coastal changes are either wadi run-off or variations in longshore drift and erosion events [21].

The present study covers the Wadi Hali (also spelled Haliy) fan that lies on the Red Sea coast of Saudi Arabia, south of Jeddah and north of Jizan (Figure 1). This is a small region covering an area of around 50 km N-S and 40 km E-W. This area has several distinct environments like aeolian, fluvial, coastal, intertidal, brackish-water ponds with mangrove stands and saline lagoons. Estuarine clastic sediments have been deposited in this region since Quaternary [28]. Wadi Hali now is an ephemeral stream; however, it must have been active since at least Quaternary [28]. This area was semi-arid, having intense rainfall during the humid phase (Late Pliocene to Early Pleistocene and Late Pleistocene – Early Holocene). It is likely that in the past Wadi Hali was a permanent stream and during the intervening arid phase it became an ephemeral stream during the past 4 kyr phase of the present aridity. Massive flooding events are common in the SW regions of the Arabian Peninsula due to periodic intense cloud bursts. This wadi has been eroding the Arabian Shield and transporting sediments to the Red Sea. A brief description of coastal flora and vegetation of the southern Red Sea coast was provided by the author [16].

The study area covers Wadi Hali and its surroundings. Wadi Hali is a short ephemeral stream that originates in the hilly regions east of the coastal region (Figure 2). The area covers marginal marine to marine environments; that includes intertidal environments (Figure 3), scattered patches of mangrove stands and their muddy environments (Figure 4A,B,C), algal (microbial) mats and mud flats (Figure 4D,E), Sabia Island coral reef environment (Figure 5A), and A mid Holocene paleochannel section is also included in this study because it contains palynomorphs belonging to the extant plants and animals (Figure 5B).

Such studies are significant in understanding the ecology of various life forms that inhabit such environments. This type of data set has palaeoecological significance as well since it may also be used in the study of fossil sediments representing similar environments. The present paper describes palynomorph assemblages from mangrove swamps, a middle Holocene paleochannel deposit, algal mat and Sabia Island coral reef and discusses their sources and environmental significance. This study also provides comprehensive palynological baseline data about the southern Red Sea coastal environments. Baseline data about the coastal environments and their flora and fauna is required to define the present health of the coastal ecosystem. Study of palynomorphs occurring as fossils or subfossils in various coastal sedimentary settings represent local and regional climate, and environments.

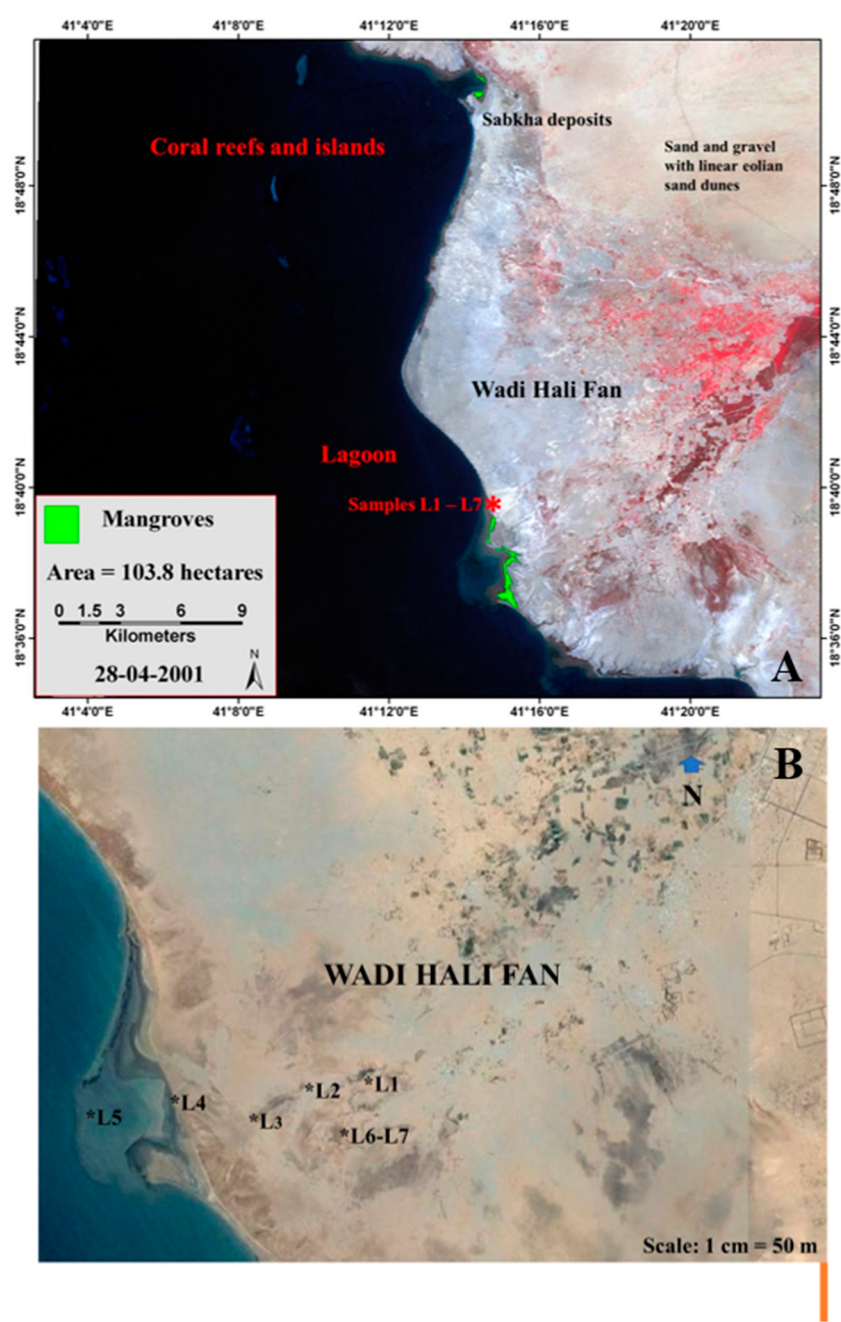


Figure 3. A. Coastal and terrestrial environments around the area of study. Satellite image of the area showing marine and coastal environments. Mangroves are shown in green (modified after Khan et al. 2010). B. close-up of the area where samples (L1 through L7) were collected showing sample localities.

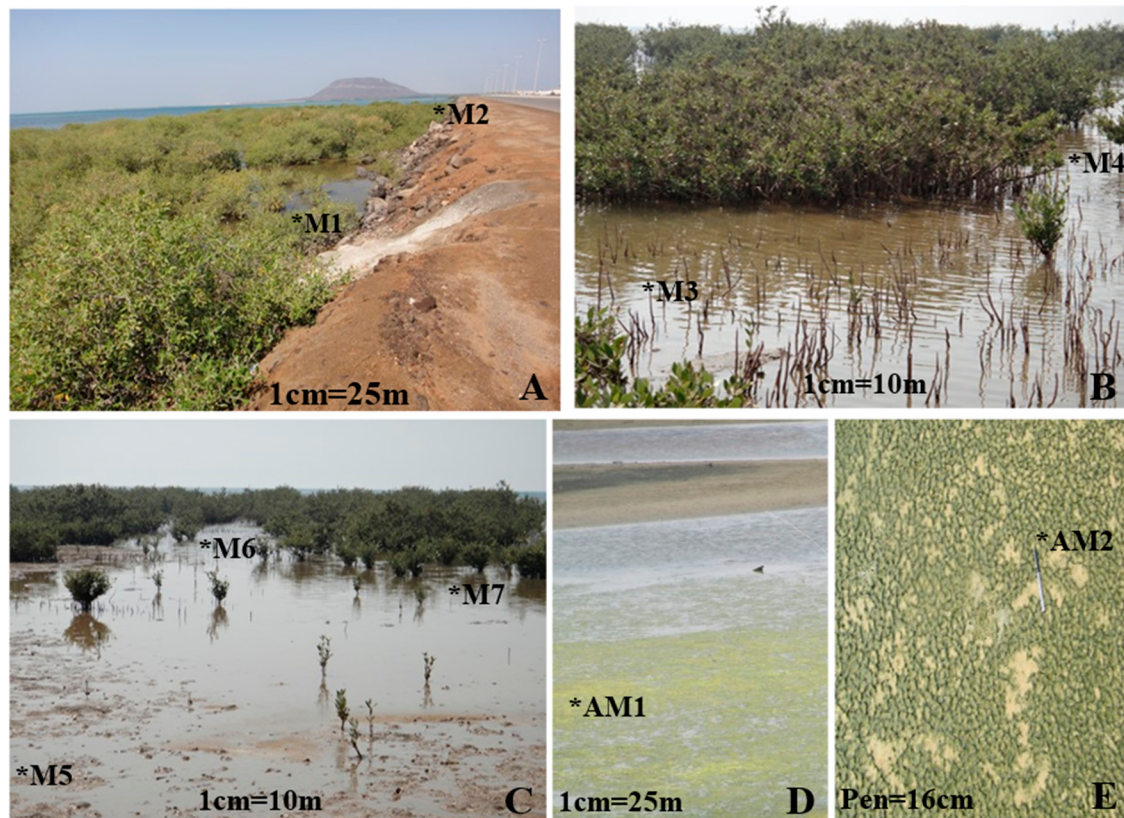


Figure 4. Various localities of samples collected for this study. A. Two clay samples (M1 and M2) from the mangrove swamp (Figure 2, Location 1) B. Two clay samples (M3 and M4) from the mangrove swamp (Figure 2, Location 2A) C. Three clay samples (M5, M6 and M7) from the mangrove swamp (Figure 2, Location 2B) D. One sample (AM1) from algal mat (water depth 50 cm or less; Figure 2, Location 5) E. One sample (AM2) from dried part of the algal mat (Figure 2, Location 5).

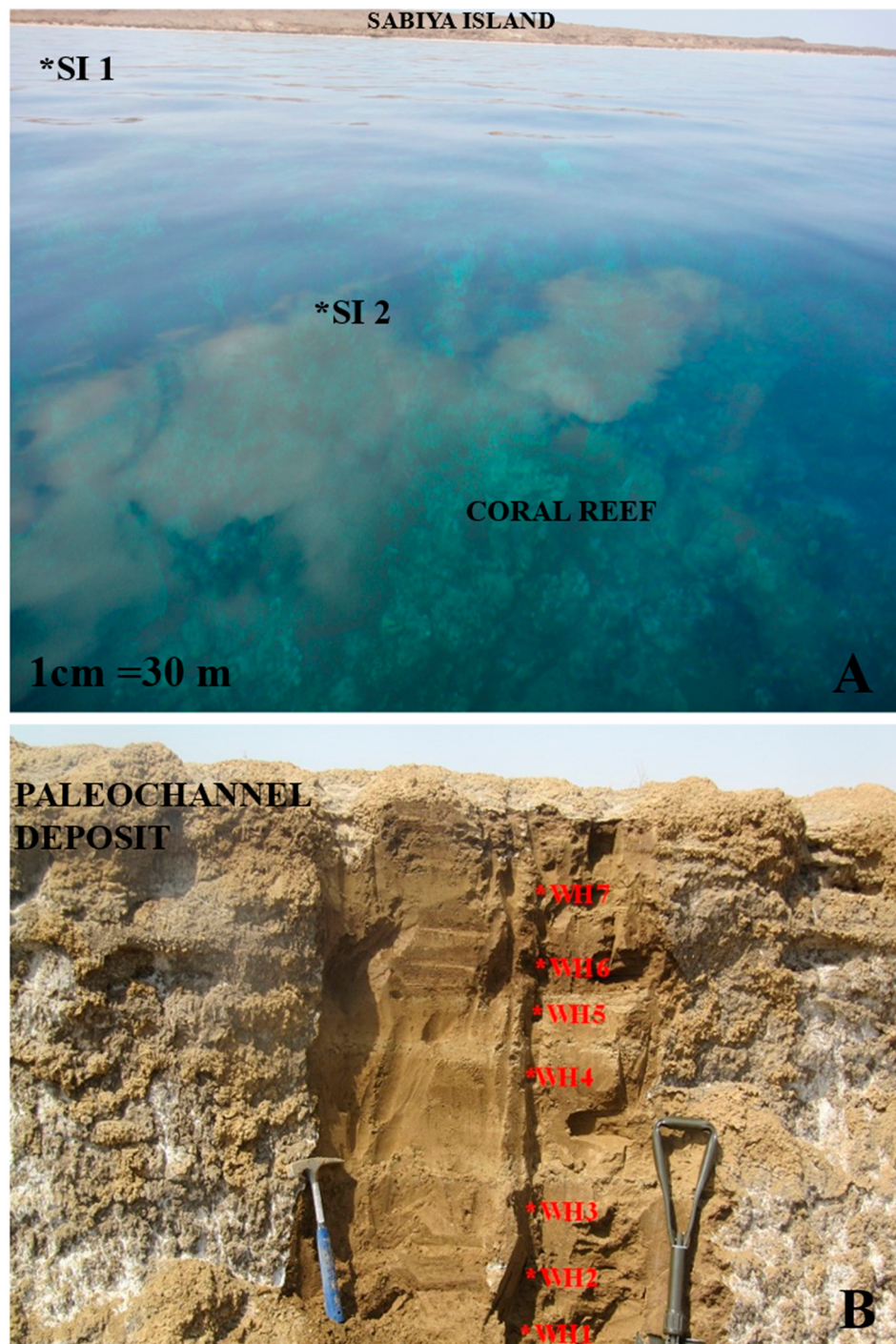


Figure 5. The locations of samples collected for this study. A. Two fine sand samples (SI1 and SI2) from offshore Sabia Island (location 4) B. Seven clay and fine sand samples (WH1 through WH7) from the paleochannel section (location 3).

3. Materials and Methods

This study is based on 25 samples collected on March 1 and 2, 2011, from five different localities representing five different coastal environments around the Wadi Hali area (180°49'35.27"N; 410°22'44.23"E) and its surroundings in the southern Red Sea coast of Saudi Arabia (Figures 3–5). The samples and their locations are as follows.

A. Mangrove Swamp Environment (Figures 2 and 4A,B,C)

Locality 1: Two surface (top one cm) mud samples (M1 and M2).

Locality 2A: Two surface (top one cm) mud samples (M3 and M4).

Locality 2B: Three surface (top one cm) mud samples (M5, M6 and M7).

B. Middle Holocene paleochannel Section (Figures 2 and 5B)

This is a small outcrop at the base of one of the channels of Wadi Hali; it is located about 2 km inland from the coastline.

Locality 3: Paleochannel outcrop is 1.5 m thick. Seven clay to fine sand samples (WH1 through WH7) were collected from bottom to top at 20 to 25 cm interval, except the samples WH3 and WH4 which are about 40 cm apart. Samples represent lithological variations in the outcrop.

C. Algal Mat Environment (Figures 2 and 4D,E)

Locality 5: Two surface (top one cm) mud samples (AM1 and AM2) from the algal mats of the hyper-saline pools on the tidal flats.

D. Sabia Island Coral Reef Environment (Figures 2 and 5A)

Locality 4: Two surface calcareous sand samples (SI1 and SI2) from the coral reefs around the island. These are grab samples collected by diving in the shallow water.

a. Close to the shore in one m water depth (SI1)

b. Further offshore in two m water depth (SI2)

E. Intertidal Environment (Figures 2 and 3)

Location 6: Seven surface samples (L1-L7). Four clay to fine sand samples (L1 through L4) from tidal flats close to the shoreline and two clay samples (L6 and L7) from a small pond with abundant algae. The sample L5 is subtidal mud collected 100 m away from the coastline under 1.5 m water depth.

Sediment samples were macerated following the techniques described in Kumar [16]. One cubic centimeter (cm³) of dry sample was used in the maceration process using the following method. (1) 10 % HCl treatment for 15 minutes to remove carbonates. (2) Overnight cold HF (40 %) treatment to remove silicate minerals. (3) Commercial grade HNO₃ (sp. gr. 1.35) treatment for two hours at 80° C for oxidation of organic matter to remove unwanted organic debris. (4) 10% KOH treatment for 15 minutes followed by rotation at 1,000 rpm for 5 minutes to remove humic matter. (5) Treatment of solution with 5 % HCl to neutralize pH. (6) Residue sieved through 10 µm mesh size sieve to remove clay minerals. (7) Residue with fraction larger than 10 µm fraction mixed with 3 drops of polyvinyl alcohol, mixed thoroughly, and smeared over coverslip and dried at 60° C over hot plate. (8) Mounted with Canada Balsam and kept for 20 minutes over hot plate at 80° C. (9) Four slides of each sample were made. There is a possibility of fungal contamination after the samples were collected and sealed in a sample bag since fungus can grow and may contaminate them.

The slides were studied under an OMAX Optical Microscope (MD827S30L Series) using transmitted light. Each slide was scanned under ×400 magnification and palynomorphs were photographed at ×400 and ×1,000 (oil immersion) using an inbuilt camera system in the microscope. A few large palynomorphs were photographed at ×100 as well. Since palynomorph numbers are generally low (see tables), all palynomorphs in each slide were counted (except in few slides where numbers of one form exceeded 500).

4. Results

The palynomorphs recovered in this study are classified into the following groups: pollen and spores, dinoflagellate cysts and algal remains, fungal spores, hyphae and fruit bodies, protists, and invertebrates. Mineral microfossils (ascidian spicules, sponge spicules and phytoliths) are not palynomorphs because are not organic, however, since they occur in palynological preparations, they are included in the assemblage. Fragments of a variety of cuticles, tracheid, wood and charcoal occur commonly in almost all samples. Palynomorph preservation ranges from moderate to good. Several palynomorphs belonging to various groups could not be identified, thus labelled as indeterminate. The distribution of palynomorphs recorded from various environments is shown in Tables 1–6 (Table 1; pollen and spores, Table 2; dinoflagellate cysts and other algal remains, Table 3; fungal taxa, Table 4. microforaminifera, thecamoebians and tintinnomorphs, and form taxa, Table 5. numerical distribution of palynomorphs and foraminiferal palynomorphs in various environments, Table 6.

invertebrate remains and mineral microfossils. Table 7 summarizes distribution of palynomorphs and palynomorph groups in various environments. The relative abundance of palynomorphs are denoted as Rare (R): 1-4 specimens; Few (F): 5-10 specimens; Common (C): 11-25 specimens; Very Common (VC): 26-50 specimens; Abundant (A): 51 or more specimens. The occurrences of various groups of palynomorphs and their possible source is discussed.

4.1. Pollen and Spores

Pollen and spores form a minor component of the palynomorph assemblages, only rare occurrences of individual pollen and spore were observed. A total of 25 taxa of pollen (21 angiosperms and 4 gymnosperms) and 6 taxa of spores were observed in this study (Table 1). The pollen and spores identified were *Acacia* sp. (Leguminosae), *Artemisia* sp. (Asteraceae), *Avicennia marina* (Avicenniaceae), cf. Cyperaceae pollen, *Euphorbia* sp. (Euphorbiaceae), Inaperturate pollen, *Juniperus* sp. (Cupressaceae), *Nypa* sp. (Arecaceae), *Palmaepollenites* sp. (Arecaceae), *Palmidites* sp. (Arecaceae), cf. *Potamogeton* sp. (Potamogetonaceae), *Proxapertites* sp. (Araceae/Arecaceae), Rannunculaceae pollen, *Rhizophora mucronata* (Rhizophoraceae), *Trichotosulcites* sp., and *Zea mays* (Graminae; cultivated).

There is no published pollen atlas of Saudi Arabian plants. However, there are few publications on the palynology of Quaternary and Recent sediments in and around the Arabian Peninsula describing both pollen and NPP. They describe and illustrate the morphology of common recent pollen and spores [15,30–33]. Few other publications also describe and illustrate pollen [12,13,34]. These papers helped in identifying certain pollen and spores. Most importantly floral composition of various vegetation types in Saudi Arabia [35] was used to discuss the provenance of pollen types identified. A 12-month long aerobiological survey of pollen in Riyadh, the capital city of Saudi Arabia located in the east-central region of the country, recorded several types of pollen taxa including Palmae/Arecaceae (36). In order from the most to least common taxa were Chenopodiaceae, grasses, plantain, *Artemisia*, and *Ambrosia*. Grasses and Chenopodiaceae released pollen 11 to 12 months of the year [36]. This study shows the presence of airborne pollen in the central part of Saudi Arabia and most of them are reported in the present study. However, Palmae (Arecaceae) pollen dominates the coastal assemblages because mostly they inhabit the coastal regions.

Among the angiosperms, the monocotyledonous family Arecaceae (syn. Palmae) is represented by the largest number of taxa; they are *Neocouperipollis* sp., *Palmaepollenites* sp., *Palmidites* sp. *Spinizonocolpites* sp. (*Nypa* palm), *Trichotomosulcites* sp. and *Verrualetes* sp. According to Thomas [35] four palm species occur in Saudi Arabia; they are *Hyphaene thebaica*, *Phoenix caespitosa*, *Phoenix dactylifera*, and *Phoenix reclinata*. The date palm (*Phoenix dactylifera*) is an important crop in Saudi Arabia. This family also contains commercial species such as coconuts, areca nuts and date palms, and many indoor and ornamental species as well. Presence of Arecaceae pollen taxa reported in this assemblage probably belong to these species of palms transported by wind (sand and dust storms) and water (flash floods and rains) from the neighboring regions and beyond since various species of palms occur widely in the Arabian region and northeast Africa. The genus *Proxapertites* sp. (Araceae/Arecaceae) too is sourced from one of the palm species found in the region. _

Acaciapollenites sp., *Euphorbia* sp., unidentified tricolpate pollen and Chenopodiaceae/ Amaranthaceae pollen are other significant pollen taxa of the assemblage. Most of them were derived from the vegetation of the coastal plains, sabkhas and wadis characterized by low sand dunes and saline marshes. These environments are inhabited by open, drought-deciduous thorn woodlands, mangroves, halophytes, open xeromorphic and thorn woodlands. *Avicennia marina* and *Rhizophora mucronata* are mangrove pollen found in this assemblage._

Cyperaceae pollen and pollen of *Artemisia* sp. and *Calligonum* sp. are probably derived from open xeromorphic grasslands where common shrubs of the sand-dunes are *Artemisia monosperma* and *Calligonum comosum*. All these shrubs co-occur with perennial herbs and grasses such as *Cyperus conglomeratus*.

Presence of a single pollen of cf. *Casuarina* sp. is problematic because it is not native to this area, but *Casuarina* trees planted near Dammam along the Arabian Gulf coast of Saudi Arabia were

observed (A. Kumar, personal observation). Most likely the *Casuarina* pollen may have been transported during thunderstorms or dust storms which are common in this region.

The presence of cf. *Potamogeton* pollen in this assemblage is problematic because it is a pond weed that occurs in submerged aquatic habitats. At present there are only rare ponds along the Tihama Plain in this desert environment where *Potamogeton* could grow. Although Saudi Arabia does not have rivers or perennial streams, its seasonal streams and ponds do contain a few species. The aquatic flora in Saudi Arabia contains more than forty aquatic or semi aquatic species, of which Potamogetonaceae has the maximum number of species [35]. Formation of ponds occurs during flooding events caused by thunderstorms in which heavy to very heavy rainfall occurs within a short period of time [37]. I suggest that a species of *Potamogeton* might have grown in one such pond contributing to the pollen assemblage.

Several plant species belonging to the family Ranunculaceae occur in Saudi Arabia as well. In the southwestern region of Saudi Arabia plant species belonging to this family are *Clematis hirsute*, *Clematis simensis*, *Ranunculus multifidus* and *Ranunculus forskoehlii* [35]. There is a possibility that a Ranunculaceae pollen reported in this study might be sourced from one of these plants.

Among the gymnospermous pollen *Juniperus* sp., *Pinuspollenites* sp. and *Podocarpus* sp. were observed. The *Juniperus* sp. pollen is related to *Juniperus procera* that inhabits higher altitudes in the southwestern parts of the Arabian Peninsula. *Pinus* and *Podocarpus* are not known in the Arabian region. However, *Pinus* and *Podocarpus* pollen were reported from Pleistocene and Holocene sediments of the Nile Cone, Egypt [14]. *Pinus* is a genus of the Pinaceae family; it has a characteristic bisaccate pollen. This family has worldwide distribution including North Africa. *Pinus radiata* was introduced for timber production in sub-Saharan Africa and *Podocarpus* is known from the tropical highlands of Africa. Tropical cyclones originating in the Arabian Sea are known to impact the Arabian Peninsula, mainly in the southern regions such as Yemen and Oman. Pollen of *Pinus* and *Podocarpus* are most likely wind transported from East Africa by these cyclones or the southwest monsoon, when the summer wind blows across the Arabian Sea from northeast Africa to India with a branch that veers north towards the Arabian Peninsula.

The monoporate pollen *Zea mays* (Graminae; cultivated) is known from the Arabian region and have been reported in a few studies from Iraq [32,34,38]. Monoporate pollen could also be derived from the family Poaceae/Gramineae which are common in the Asir Mountains, Jizan and in the wadis of southwestern regions of Saudi Arabia [35].

Six taxa of pteridophytic spores were observed belonging to the fern families Lycopodiaceae and Polypodiaceae. In Saudi Arabia there are twenty-seven species of Pteridophytes. They occur in most terrestrial habitats and in some aquatic communities. The observed spore taxa must be related to these plants and most likely transported by both wind and water to the site of deposition. Rare specimens of Hypnaceae spore (Moss) were observed in algal mat samples. The genus *Hypnum* has a cosmopolitan distribution occurring on all continents except Antarctica. They are typically found in moist forest areas, while some species are aquatic. They can also be found living on soil, rocks, and live trees.

Table 1.

[illegible]

Triplanosporites				1
sp.				
Verrucosiporites	2	1	2	1
sp.				

4.2. Dinoflagellate Cysts and Algal Remains

4.2.1. Dinoflagellate Cysts

Four known and fourteen unknown dinoflagellate cyst taxa were observed in this study (Table 2). The known taxa are cf. *Brigantedinium simplex*, *?Operculodinium* sp., *Peridinium* sp., and Spiny round brown cyst. The following six unknown taxa were informally described as dinoflagellate cyst types A, B, C, D, E and F [16], and further eight more were described as dinoflagellate cyst types G, H, I, J, K, L, M and N [17]. Rare specimens of acritarchs were observed as well, usually they are indeterminate, and a known form identified as *Micrhystridium* sp.

These morphotypes are commonly thin walled and lack complete dinoflagellate cyst like paratabulation characters except for their shape, thin and generally psilate autophragm with indistinct archaeopyle. Their comparison with any known dinoflagellate cyst is difficult because of their poor preservation and incomplete morphological features. Such morphotypes types were found only as one or two specimens and appear to have morphological affinities with fresh and brackish water dinoflagellate cysts. Their low abundance may be due to treatment with HNO₃ and KOH which may have destroyed such thin-walled cysts.

Dinoflagellate cysts taxa are a minor part of the overall palynomorph assemblage. They appear to be an assortment of fresh or brackish water forms mixed with very few marine forms that are most likely derived from the coastal lagoons of the Red Sea. Fresh water dinoflagellates are characteristically thin walled and often the archaeopyle is not visible because it might be hidden by folds in the autophragm or due to poor preservation. Furthermore, paratabulation features are either not well developed or not identifiable [39]. Fresh to brackish water dinoflagellate cysts typically are smaller, have thin autophragm and have simple proximate shapes. They are often associated with tidal channel and tidal mudflat facies that provide evidence of a possible upper estuarine setting [40]. There are approximately 350 freshwater dinoflagellate species, and 84 resting cyst species. Their shapes, wall ornamentations, archeopyles and colors are important morphological characteristics for identification at the generic level [41].

The dinoflagellate cyst assemblage observed in this study is marine (cf. *Brigantedinium simplex*, *?Operculodinium* sp.; Spiny Round Brown Cyst (SRBC) with theropylic archaeopyle but also has some freshwater forms especially *Peridinium* sp. Resting cysts attributed to the freshwater dinoflagellate genus *Peridinium* sp. have been described from the lakes of North America [42–44].

4.2.2. Algal Remains

There are no published accounts of any algal remains from the Red Sea coastal sediments. However, there are few such studies from Egypt [14,45]. As with pollen and spores and dinoflagellate cysts, algal remains are minor constituents of the palynomorph assemblages; only rare occurrences were observed in various samples (Table 2).

Long slender filaments, generally septate, branched, or unbranched are found commonly in most samples. Thin-walled spherical cysts with psilate or scabrate, intact or broken wall, usually ranging between 25-40 µm are common in few samples. They have been attributed to algal cell types A and B and algal cysts (unidentified). *Botryococcus*, *Concentricystis* and *Spirogyra* zygospore, *Lecaniella* (*Spirogyra* zygospore), Cyanobacteria *Gleotrichia* sp. and *Rivularia* are the other algal remains in the present assemblages. A total of 13 algal forms were recorded in this study (Table 2).

Botryococcus is a colonial green alga of the order Chlorococcales that tolerates variable salinities, thus inhabits brackish or freshwater environments including ponds and temporary pools and found in temperate to tropical oligotrophic lakes and estuaries [46]. *Concentricystis* is another algal spore found in freshwater habitats. These are zygospores of spheroid to obovoid shape, have hyaline,

ornamented wall with concentric rings in polar view. It is indicative of freshwater marshy environments. It is also known as *Pseudoschizaea* [47].

Cyanobacteria or the blue-green algae normally occur in lakes and ponds. *Gloeotrichia* is a Cyanobacteria (blue-green algae) and their filaments [6] occur in the assemblage indicates fresh-water input in the brackish water condition [47,48], thus indicates brackish water, littoral environment. *Rivularia* is a modern cyanobacteria belonging to the family Rivulariaceae, order Nostocales, grows on plants and could also be free-floating and photosynthetic, and become abundant when there is an incursion of salt-water, thus, their abundance could be a proxy for brackish water, littoral environment [47,48].

Lecaniella is a *Spirogyra* zygospore. *Spirogyra* is a filamentous chlorophyte green algae of the order Zygnematales and is commonly found in freshwater habitats. According to Hoshaw and McCourt [49] “Zygospores (resting, encysted zygotes of some chlorophyte algae) are often produced during seasonal dessication of the habitat, and changes in water chemistry (nitrogen depletion and rise in pH) and light regime seem to be responsible for triggering zygospore formation.” Seasonal desiccation of habitat and changes in water chemistry in the Red Sea coastal ponds is an annual occurrence when *Spirogyra* zygospore might have formed. Additional fresh-water algal remains that occur in the present assemblages are *Zygnema*-type spore [5] and zygospore of *Debraya glyptosperma* [50]; they belong to a family of fresh-water algae Zygnemataceae. Oospores of *Oedogonium* sp., which is a fresh water green alga, also occurs in these assemblages [51]. Many broken pieces of marine diatoms were also observed in the Sabia Island coral reef samples.

Several spherical to subspherical cells of variable diameters having psilate, scabrate or granulate walls were observed in this study. All such forms are grouped as algal cells, their morphological characters were described earlier [17]. A typical algal cell is oval to ovoidal in shape, light grey to light brown, wall thick, unevenly granulate, grana size variable.

Thus, it is evident from the dinoflagellate cysts and algal remains that these assemblages contain a mixture of freshwater or brackish and marine forms. This interpretation is also confirmed by the presence of microforaminifera and thecamoebians in these assemblages.

Table 2.

Dinoflagellate Cysts	Mangrove Swamp							Palaeochannel (Middle Holocene)							Algal Mat		Sabia Is.		Intertidal						
	M1	M2	M3	M4	M5	M6	M7	WH	WH	WH	WH	WH	WH	WH	AM1	AM2	SI1	SI2	L1	L2	L3	L4	L5	L6	L7
								1	2	3	4	5	6	7											
cf.																									
Brigantedinium simplex																	1								
?Operculodinium sp.																						1			
Peridinium sp.																				1					
Spiny round brown cyst																				1					
Dinoflagellate cyst type A							1												1						
Dinoflagellate cyst type B																			1						
Dinoflagellate cyst type C																			1						
Dinoflagellate cyst type D	2					5	1								1	2	2			1					
Dinoflagellate cyst type E																					1				

Zygosporae

Debraya 1

glyptosperma

4.3. Fungal Spores, Hyphae, and Fruit Bodies

Fungal remains are a significant part of the palynomorph assemblages in most samples. Several taxa of fungal spores, fruit bodies and hyphae were observed (Table 3). Fungal palynomorphs were tentatively identified, described, and illustrated in earlier study [16,17]. Later, a morphological and taxonomic restudy of these fungal palynomorphs was carried out and these morphotypes were placed in various genera and species [52]. The generic identifications are based on comprehensive treatises on fossil fungi by Kalgutkar and Jansonius [53], and Saxena and Tripathi [59]. Fungal remains were represented by 23 genera and 27 named species [52]. In addition, there are several specimens which could be identified only up to generic level and have been described as sp. 1, sp. 2, etc. The assemblage consists mainly of fungal spores whereas sporocarps are poorly represented by only three genera. The extant relationship of fungal sporocarps, spores, mycelia and other fungal remains is presented. Eight new species were proposed, they are: *Dicellaesporites bisariae*, *Dicellaesporites foveolatus*, *Inapertisporites choudharyi*, *Inapertisporites khareii*, *Inapertisporites foveolatus*, *Inapertisporites microverrucatus*, *Monoporisporites rotundus* and *Pluricellaesporites mishrae* (Table 3).

Several specimens of *Glomus* sp. were observed in many samples [16,17]. *Glomus* sp. (family Glomeraceae) is an endomycorrhizal fungus showing a symbiotic relationship with roots of higher plants. These are globose chlamydospores, aseptate, inaperturate and are of variable size (18-138 µm). They are formed below the soil surface and are not normally transported [54]. They are indicative of soil erosion in the catchment area and provide a useful line of evidence in palaeoecology [55].

Fungal fruit bodies (Microthyriaceae) are multicellular, epiphyllous forms; they occur most likely on the coastal mangrove stands and are indicative of tropical to subtropical moist humid climate and heavy rainfall. Fungal hyphae are unicellular to multicellular, branched, or unbranched forms that occur primarily in freshwater marsh/flood plain environments and are indicative of high organic input and heavy rainfall. Fungal spores vary from unicellular to multi-cellular, septate or aseptate, with or without pores and occur in the present assemblages.

Since fungi lack chlorophyll, thus are heterotrophs and survive as epiphytes, saprophytes, parasites or in symbiotic associations on or in living or dead plants and animals. They rarely produce hard resistant tissues thus not prone to fossilization, however their spores, hyphae and fruit bodies are preserved as organic matter and can be isolated using palynological maceration techniques [53]. A comprehensive account of the diverse aspects of Palaeomycology which includes study of fossil fungal palynomorphs their morphology, descriptive terminology, identification and nomenclature, geological history and paleoenvironmental and paleoclimatic significance, etc. is discussed [53,56]. Fungi provides evidence for relative humidity, atmospheric pressure, and precipitation rates. The assemblage of fungal spores in higher diversity and numbers are usually considered to be indicative of warm and humid climatic conditions [47,48].

Fossil fungal remains have been used as proxies for environmental perturbations and vegetation changes caused by climate change, as well as floristic changes, and the sequence of vegetational modifications during the past. Microclimatic and edaphic interactions of fossil fungi with geological soils have also been investigated by Kalgutkar and Jansonius [53]. A useful review of the relationship between fungi and their environment in the geological past is provided by Stubblefield and Taylor [57] and Taylor [58]. Saxena and Tripathi [59] suggested that it is advisable to take into consideration the complete palynological assemblage for paleoenvironmental interpretations rather than just based on fungal remains.

In these marginal marine environments, there is free mixing of fresh water. Many of the fungal palynomorphs were transported from land in these environments by wind and water. Conidia of *Tetraploa* are found generally associated with grasses indicating grass supporting environment nearby. Similarly, *Alternaria* spores indicate the presence of herbaceous flora. It is well known that to survive, *Alternaria* needs a moist warm environment. This fungus lives in seeds and seedlings and is

spread by spores. *Nigrospora* (being represented by *Exesisporites*) grows in soil, air, and plants as a leaf pathogen. Microthyriaceous ascocarps, viz. *Callimothallus*, *Spinosporonites* and *Trichothyrites* are also epiphyllous fungi growing on leaves. In general, the assemblage indicates warm and moist conditions in the area as indicated by dry, hot, and brackish coastal environments that periodically become wet and humid due to short term excessive rainfall during tropical storms.

Table 3.

Fungal Taxa	Intertidal	Palaeochannel	Mangrove Swamp	Algal Mat	Coral Reef
<i>Alleppeysporonites elsikii</i>			F		
<i>Alleppeysporonites</i> sp.				F	
<i>Alternaria</i> sp. 1	F				
<i>Alternaria</i> sp. 2		F			
<i>Alternaria</i> sp. cf. <i>A. bellus</i>	R				
<i>Asterinites tellezii</i>				F	
<i>Callimothallus pertusus</i>	F				
<i>Cercospora</i> sp.	R	R			
<i>Dicellaesporites bisariae</i>		F			
<i>Dicellaesporites foveolatus</i>				F	
<i>Dicellaesporites plicatus</i>		F			
<i>Dicellaesporites verrucatus</i>	F				
cf. <i>Endochaetophora</i> sp.	R				
<i>Exesisporites chandrae</i>			C		
<i>Exesisporites</i> sp.		R			
<i>Hypoxylonites</i> sp. 1		R			
<i>Hypoxylonites</i> sp. 2					R
<i>Hypoxynonites</i> sp. 3	R				
<i>Hypoxynonites</i> sp. 4	R			F	
<i>Inapertisporites kharei</i>	F				
<i>Inapertisporites foveolatus</i>	F				
<i>Inapertisporites kedvesii</i>			F		
<i>Inapertisporites microverrucatus</i>	C	F			
<i>Inapertisporites</i> sp. 1	R				
? <i>Inapertisporites</i> sp.		R			
<i>Inaperturate elongated fungal spores</i>			C		
<i>Laevitubulus laxus</i>	F				R
<i>Laevitubulus</i> sp.	R		R		F
<i>Monoporisorites jansoniusii</i>				F	
<i>Monoporisorites pattersonii</i>	F				
<i>Monoporisorites valdiyae</i>				F	
<i>Monoporisorites rotundus</i>				F	
<i>Monoporisorites</i> sp. 1				R	
<i>Monoporisorites</i> sp. 2	R				
<i>Palaeomycites robustus</i>	F		R		
<i>Palaeosclerotium</i> sp.	R				
<i>Papulosporonites multicellatus</i>			F		
<i>Pluricellaesporites mishrae</i>		F			
<i>Polyadosporites</i> sp.			R		
<i>Scolecosporites</i> sp.	R				
<i>Spinospororonites</i> sp.		R			
<i>Spirotremesporonites</i> sp.				R	
<i>Staphlosporites neyveliensis</i>		R			
<i>Tetraploa</i> sp. 1					F
<i>Tetraploa</i> sp. 2		R			
<i>Trichothyrites amorphus</i>		R			

Trichothyrites setifer	F	
Trichothyrites sp.		R
Cluster of fungal hyphae	C	F
Fungal Remain Type 1	R	
Fungal Remain Type 2		R
Fungal Remain Type 3	R	
Fungal Remain Type 1	R	
Sporangiun with spores	R	

4.4. Protists and Invertebrates

Foraminifers, thecamoebians and tintinnids are three groups of Protists that commonly occur in these assemblages. Benthic foraminifers are quite ubiquitous in brackish/marine environments ranging from intertidal zone to deep oceans and from polar regions to the tropics. Thus microforaminiferal test linings are found in all these environments. Thecamoebians, also known as agglutinated rhizopods or testate amoebae are benthic microfaunal groups that occur worldwide in bodies of fresh and brackish water. Tintinnids are present as tintinnomorphs that are part of the microzooplankton inhabiting primarily marine, but brackish and freshwaters as well.

4.4.1. Microforaminiferal Test Linings

Microforaminiferal test linings are the inner organic remnants of the benthic microforaminifera, commonly observed in palynomorph assemblages of marine and brackish water sediments. They are acid-resistant, chitinoid linings, usually <150 µm size. Mathison and Chmura [60] developed a qualitative classification of the physical condition of microforaminiferal test linings based on whether individual chambers were intact or damaged (split or torn), and if they were closely spaced (proximate) or the spacing of the individual chamber was open. Based on these criteria, sixteen microforaminiferal lining types were described as lining types 1 through 16 [16,17]. None of the specimens have any torn or split chambers in the present assemblages. Their distribution is shown in Tables 4 and 5. Microforaminiferal test linings generally occur as rare or few in most samples, however, occasionally they are common to very common in few samples (Tables 4, 5 and 7).

Microforaminiferal linings have been used as proxies for water pollution, ocean productivity and palaeoenvironmental studies [61]. Monga et al. [62] used various groups of microforaminiferal linings to delineate marine and terrestrial realms in the Paleogene sequences and facilitated better interpretation of the depositional environment. Mudie and Yanko-Holmbach [63] carried out concurrent palynological and micropaleontological studies to investigate the relationship between the morphology and abundance of these linings and benthic foraminiferal assemblages along the transects off the Danube River Delta, NW Black Sea. Al-Dubai et al. [64] published on the diversity and distribution of benthic foraminifera in the Al-Kharrar Lagoon, eastern Red Sea coast of Saudi Arabia. They defined five assemblages characterizing various sub-environments in the lagoon including intertidal assemblage *Quinqueloculina seminula* - *Q. laevigata* and *Affinetrina quadrilateralis*-*Neorotalia calcar* and a few other forms. It is not possible to relate these benthic foraminifers to the microforaminiferal linings of the present study.

A further study of microforaminiferal palynomorph assemblages was carried out to investigate palaeoenvironmental and palaeoecological utility of foraminiferal palynomorphs in absence of any foraminiferal data in marine and brackish water environments [19]. The study demonstrated 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. However, in the coral reef environments smaller benthic, both calcareous and porcelaneous forms were observed. 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.

Table 4.

Microforaminifera	Mangrove Swamp							Palaeochannel (Middle Holocene)							Algal Mat		Sabia Is.		Intertidal							
	M1	M2	M3	M4	M5	M6	M7	WH	WH	WH	WH	WH	WH	WH	WH	AM	AM	SI1	SI2	L1	L2	L3	L4	L5	L6	L7
								1	2	3	4	5	6	7		1	2									
Microforaminiferal test linings type 1 (Kumar 2020)	4	2	2	2		1	7															1				
Microforaminiferal test linings type 2 (Kumar 2020)																		7							1	
Microforaminiferal test linings type 3 (Kumar 2020)						4					1						5	14			1					
Microforaminiferal test linings type 4 (Kumar 2020)				1			3										6	4			1					
Microforaminiferal test linings type 5 (Kumar 2020)																					1					
Microforaminiferal test linings type 6 (Kumar 2020)																	2	14					1	1		
Microforaminiferal test linings type 7 (Kumar 2020)	3	2	2		1	1	3										9	5					1			
Microforaminiferal test linings type 8 (Kumar 2021)						1	10											1								
Microforaminiferal test linings type 9 (Kumar 2021)	2	3	2	1													2									
Microforaminiferal test linings type 10 (Kumar 2021)																	2	5								
Microforaminiferal test linings type 11 (Kumar 2021)																	1									
Microforaminiferal test linings type 12 (Kumar 2021)																		44								
Microforaminiferal test linings type 13 (Kumar 2021)																	1	3								
Microforaminiferal test linings type 14 (Kumar 2021)																		5								
Microforaminiferal test linings type 15 (Kumar 2021)																	3	2								

Microforaminiferal test linings type 16 (Kumar 2021)	11																			
Thecamoebians																				
<i>Arcella</i> sp.	1																			
<i>Centropyxis aculeata</i>	3			1		1	1			1			4	1	2	2				
<i>Centropyxis</i> sp.	3	2																		
<i>Cyclopyxis</i> sp.	2																			
<i>Diffugia</i> sp.		1	1																	
<i>Euglepha</i> sp.	1	1																		
<i>Geopyxella sylvicola</i>					1									1		1				
Thecamoebian type A (Kumar 2021)	3																			
Thecamoebian type B (Kumar 2021)		1	2																	
Thecamoebian type F (Kumar 2021)													2							
?Thecamoebians	2																			
Tintinnomorphs																				
Tintinnomorph type 9 (Kumar 2020)																1				
Tintinnomorph type 11 (Kumar 2020)														1		1				
Tintinnomorph type 12 (Kumar 2020)														1						
Tintinnomorph type 13 (Kumar 2020)														1						
Tintinnomorph type 14 (Kumar 2020)															1					
Tintinnomorph type 16 (Kumar 2020)															1		1			
Form taxa																				
<i>Katora arabica</i> (Kumar 2023)	1	1	4	2	18	10	14		1		4	7	12	30	1	7	5	2	3	1
<i>Katora oblonga</i> (Kumar 2023)	2	3	1			1	10	2				13	3	22		6	4	3	1	
<i>Katora twinmorpha</i> (Kumar 2023)	1		2				7													1
<i>Katora elongata</i> (Kumar 2023)		1					5	1					5	6		1	2	1		
<i>Mangrovia hallii</i> (Kumar 2023)				3			3	1				2								
<i>Mangrovia redseaensis</i> (Kumar 2023)		2	4			7	38	29				7	21							

4.4.2. Thecamoebians

There are only two published accounts of thecamoebians from the Red Sea coast of the Arabian Peninsula [16,17]. Further, a report on the acid-resistant Cretaceous thecamoebian tests from the Arabian Peninsula [65] is the only other publication on thecamoebian studies from this region. A useful illustrated key for the identification of Holocene lacustrine thecamoebian taxa [67] is widely used for thecamoebian studies. There is an extensive review on testate rhizopod (Thecamoebian) research that discusses the several aspects of studies on thecamoebians and their usefulness in paleoenvironmental and (paleo)limnological research [68].

Thecamoebian occurrence ranges between rare to common in these samples (Table 4). The taxa observed were *Arcella* sp., *Centropyxis aculeata*, *Centropyxis* sp., *Cyclopyxis* sp., *Diffugia* sp., *Euglepha* sp., *Geopyxella sylvicola*, Thecamoebian types A, B, F, and ?Thecamoebian [17]. *Centropyxis aculeata* occurs in almost every lacustrine environment; however, it prefers warmer waters above thermocline. Its morphology ranges from spiny to spineless. The occurrence of *Geopyxella sylvicola*, a soil testate amoeba was reported from the tropical coastal lowlands of southwest India [47]. Thecamoebian type A resembles *Arcella megastoma* [65] which is known from fresh-water lakes, coastal wetlands, mouth of the rivers, and the sewage drainage system in India. Thecamoebian type B resembles *Cyclopyxis* sp. [65] which is known from Nilarevu mouth of Godavari River, on the eastern coast of peninsular India [66]. Thecamoebian type F resembles *Centropyxis laevigata*.

4.4.3. Tintinnomorphs

Tintinnids are protists of complex eukaryotic organisms and are part of the microzooplankton (size ranges between 20 and 200 μm) that inhabit primarily marine, but brackish and freshwaters as well [69]. They produce a chitinous shell, called lorica with an oral opening at the anterior end, and the posterior end may be conical, globular, or tubular. The shape of the lorica is species specific. However, there are considerable intraspecific morphological variations related to the life cycle stages of these ciliates [70].

van Waveren [71] introduced the term 'Tintinnomorphs' to emphasize that palynomorphs resembling tintinnids cannot always be separated into loricae or cysts and may even represent cysts of other protozoans. Da Silva et al. [69] expanded the concept of 'Tintinnomorphs' for the group of palynomorphs resembling organic remains of tintinnids, which are not always identifiable as true lorica, cysts or pouch, and may even represent other structures of distinct organisms, such as rotifers and turbellarians. Many loricae and cysts occur in palynological preparations, especially in modern marine and marginal marine sediments (see references in 69) and were classified as zoomorphs [72].

van Waveren [71] described, illustrated, and categorized tintinnomorphs in an informal morphological system. Tintinnomorphs resemble organic remains of tintinnids, but are not necessarily identifiable as true lorica, cysts or pouch. In the present study, 34 tintinnomorphs types 1 through 34 [16,17] were described using the terminology of van Waveren [71]. Later most of these morphotypes were transferred to the newly proposed form taxa [18] except for Tintinnomorph types 9, 11, 12, 13, 14 and 16 described from the intertidal sediments (Table 4).

There is a possibility that tintinnomorphs described here might be *Neorhabdocoela* oocytes [73], because there is a morphological resemblance between them. Tintinnomorphs, as stated earlier, is a collective term for loricae, cysts and stalked pouches of Tintinnids and some of them appear morphologically like oocytes (egg capsules) of aquatic flatworms of the order *Neorhabdocoela* [73]. *Neorhabdocoela* oocytes are typically elliptical to spherical and of dark brown color, relatively larger in size (60 - 600 μm), but tintinnomorphs in contrast are usually cup-shaped, oval and of diverse shapes, pale yellow and of relatively smaller size. *Neorhabdocoela* oocytes occur predominantly in fresh-water environments, however, present assemblage is reported from the intertidal environment.

A high morphological diversity of tintinnomorphs indicates high diversity of Tintinnids in the southern Red Sea zooplankton; however, their numerical presence is usually rare in the intertidal sediments. Abu Zaid and Hellal [74] published an assemblage of modern tintinnids from the Hurghada coast of Red Sea in Egypt. However, it is difficult to assign a species or genus name to the tintinnomorphs just based on the shape of lorica or cyst.

Table 5.

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

4.4.4. New Form Taxa (18)

Palynological slides of Quaternary-Recent marine and brackish water sediments invariably comprise a variety of vase-shaped palynomorphs. They are of variable sizes, could be hyaline or agglutinated and their colour ranges between yellowish to dark brown, and sometimes greyish. Biological affinities of such palynomorphs are debatable, generally palynologists relate them to tintinnid loricae and cysts, thus known as tintinnomorphs. However, similar morphotypes are known from lacustrine sediments as well and considered to be oocytes or resting eggs (6-200 µm) of *Neorhabdocoela*, a small, soft-bodied flatworm belonging to class Turbellaria, phylum Platyhelminthes, found in freshwater environments all over the world. Sometimes their affinity has also been related to testate amoebae. Palynological literature reports occurrences of many such palynomorphs that were described primarily based on a variety of their shapes, such as vase, urn, flask, funnel, tube, spherical and shapes that could be morphological variants among them. Identification of such forms is confusing because there is no standard nomenclature to describe them. Although attempts to informally describe them in various morphological groups were made, confusion prevails in their identifications because they do not have any formal taxonomic identity as genus and species.

Kumar (18) proposed new form genera and form species from a large morphologically diverse population of tintinnomorphs recovered from the southern Red Sea coastal environments of Saudi Arabia [16,17]. From these assemblages two new form genera *Katora*, and *Mangrovia*, and six new form species *K. arabiaca*, *K. elongata*, *K. oblonga*, *K. twinmorpha*, *M. redseaensis*, and *M. hallii* were proposed. They occur in all the environments studied and their abundance ranges between rare to common (Table 4).

Table 6.

Invertebrates	Mangrove Swamp							Palaeochannel (Middle Holocene)							Algal Mat		Sabia Is.	Intertidal								
	M1	M2	M3	M4	M5	M6	M7	WH	WH2	WH3	WH	WH	WH	WH	WH	AM	AM	SI1	SI2	L1	L2	L3	L4	L5	L6	L7
								1		4	5	6	7	1	2											
Crustacean remains (unidentified)																				1	3	1		3	7	
Ostracod jaw cf. Leptocythere																						2		1	1	
carapace (ostracod)						3	2	7								1										
Scolecodont						2										3	5		4					2		
Crustaceant wing																									1	
Crustacean exoskeleton	65	45	42	49	35	51	96	6	5	13	10	9	13	9	44	63	6	33			1		1	3	1	
Copepod fragment																							1	1		
Crustacean antennae	5	29	>500*	33	8	12	11	>500*	>500*	>500*	119	165	132	141	52	57	83	88							2	
Crustacean hair	9	7	8	12	8	13	5	2	3	5	12	5	4	3	4	6	1	18								
Crustacean eggs	16	10	21	4	9	30	55								9	26	71	53								
Turbellarian worm		3	2					1		1	2		1		1					1			2	2		
Turbellarian egg	1							1			1		1					1								
Annelid palynomorph																	4	7	1		1			3		
Annelid jaw																								1	1	
Worms	1				1	5									8	27		5						2	1	
Annelid remains (unidentified)	77		18	3	9	11	17								7	20								1	1	
Mineral microfossils																										
Phytoliths																		Few	Few						Few	
Sponge spicules																		1								
Ascidian spicule type 1																	4	6								
Ascidian spicule type 2																	2	15								
Ascidian spicule type 3																	2	3								
Ascidian spicule type 4																		3								
Ascidian spicule type 5																	1	4								
Ascidian spicule type 6																	1									

4.4.5. Crustacean and Annelid Palynomorphs

The crustacean and annelid remain found in these palynomorph assemblages are diverse and occur in all samples; though their absolute numbers range between rare to few. A total of 17 forms including 12 crustacean and seven annelid occur in these samples (Table 6). A neoichnological study reported several biogenic traces that occur in the intertidal and supratidal flats of the same locality as the present study [75]. They were interpreted to have been formed by gastropods, land hermit crabs *Coenobita clypeatus*, ghost crab *Ocypode quadrata*, insects, beetles, sand wasps, and annelid species *Arenicola marina*, a large marine worm of the phylum Annelida; it is also known as lugworm or sandworm. Copepods (Subphylum Crustacea; Subclass Copepoda) inhabit the area of the present study as well. They are microcrustaceans (0.5-2 mm in size), normally occur in nearly every freshwater and saltwater habitat as planktic or benthic organisms. They have two pairs of antennae and a single red compound eye; are mostly crawlers, walkers, and burrowers in terrestrial environments, but still live where water is generally available [76].

It is suggested that chitinous remains of crustaceans and annelids observed in this study should most likely belong to these invertebrate animals. At present it is not always possible to relate such palynomorphs to their parent organisms. More work needs to be done on this matter.

4.4.6. Miscellaneous and Indeterminate Palynomorphs

1. Miscellaneous palynomorphs

Miscellaneous palynomorphs include tracheid, stomata; leaf epidermis showing stomata; charcoal; and phytoliths. They are rare or few in their occurrences and do not occur in all samples (Table 7). Leaf epidermis, probably of grass with stomata as well as phytoliths indicate the presence of family Poaceae in the region, but no Poaceae pollen was observed in these assemblages. The presence of charcoal indicates either natural forest fires or possibly wood burning due to human activity.

2. Indeterminate palynomorphs

A total of seven indeterminate forms were identified and informally named as A, B, C, D, E, F, and G. Most of these indeterminate palynomorphs occur rarely in the samples (Table 7). A tentative suggestion about their affinity is given wherever possible, within brackets. They are Indeterminate form A (may be worm oocytes with operculum); indeterminate form B (Algal spore?); indeterminate form C (Cyanobacteria?); indeterminate form D (Pseudoschizaea/Concentricystis sp.?); indeterminate form E (Crustacean egg?); indeterminate form F (Algal cyst?) and indeterminate form G (Fungal sporangium?).

4.4.7. Ascidian and Sponge Spicules

Ascidian spicules are mineral microfossils (calcareous) thus cannot be considered as palynomorphs. However, they occur in palynological slides along with other palynomorphs. Ascidians (Phylum Chordata, Class Ascidiacea), also known as sea squirts, are sac-like marine invertebrate filter feeders characterized by a tough outer "tunic" made of the polysaccharide cellulose. They are sessile animals that remain attached to their substratum, such as rocks and shells. They are found in all marine habitats from shallow water to the deep sea. Ascidians generate calcareous spicules (usually between 15 μm and 100 μm) of characteristic shapes that accumulate in their tunic or internal tissues. Spicule morphology is quite diverse, thus is significant in ascidian taxonomy [77,78]. A brief overview of the fossil record of ascidian spicules is provided [79,80].

The present assemblage contains forms that range in size between 26 μm and 38 μm . This size range compares well with the forms described from Quaternary piston core of muddy sediments deposited by turbidity currents from offshore Argentina [80] where average size ranges between 25 μm and 30 μm . The ascidian spicules described from Argentina are from shallow marine environments that were transported to deeper marine environments by turbidity currents.

Numbers of ascidian spicules in the present assemblage range between rare to few (Table 6). They are not identifiable with published forms; informal names were used to describe them [17].

Ascidian spicules were observed only in the Sabia Island coral reef assemblage. They were informally described using the terminology of Lukowiak [79] and Lukowiak et al. [81]. Ascidian spicule types 1 through 5 belong to the Didemnidae Family and the ascidian spicule type 6 belongs to the Polycitoridae Family [77].

Ascidian spicules type 1 has close morphological resemblance with *Didemnum*-like spicule A described from Miocene of Moldova [81]. However, the Moldovian specimens are significantly larger; their size ranges between 90 µm to 100 µm and has only 10 rays. Ascidian spicules type 2 has close morphological resemblance with *Trididemnum*-like spicule B described from Miocene of Moldova [81]. However, the Moldovian specimens are significantly larger; their size is 100 µm and has only 8 to10 rays. Ascidian spicules type 3 resembles *Didemnid* spicule type II described from Eocene of Australia [79]. However, the Australian specimens are larger measuring 60 µm. Ascidian spicules type 4 resembles *Didemnid* spicule type III described from Eocene of Australia [79]. However, the Australian specimens are larger measuring 100 µm. Ascidian spicules type 5 is triangular, Y-shaped form, with three long, slender, and conical rays with pointed ends. Length of each ray varies between 76-36 µm and maximum width at the center is 23.6 µm. Surface of rays is smooth. Ascidian spicules type 6 resembles *Cystodytes* cf. *dellechiaiei* described [79] from Eocene of Australia. However, the Australian specimens are 100-120 µm in diameter with a smooth central part. The present specimen is significantly smaller and has a granular internal surface.

One specimen of sponge spicule was observed in sample SI2.

4.4.8. Polychaete Chaetae

Rare specimens of setae of polychaetes were observed in the Sabia Island coral reef assemblage. chaeta (also spelled cheta or seta; plural chaetae) is a chitinous bristle found in insects, arthropods, and annelid worms. The Polychaeta or the bristle worms are generally marine annelid worms having a segmented body. Each segment has a pair of fleshy protrusions called parapodia that bear chitinous bristles called chaetae. Common Polychaetes are lugworm (*Arenicola marina*) and sand worm that were reported from this area in a neoichnological study by the author [75]. Chaetae shape and size vary considerably and are often species-specific; main types include capillary, compound, pseudo compound, hooked and many more [82].

Table 7.

TAXA	STUDIED ENVIRONMENTS OF SOUTHERN RED SEA COAST																								
	OF SAUDI ARABIA																								
	Intertida							Wadi Hali							Mangrove							Algal Mat		Coral Reef	
	I							Paleochannel							Swamp										
	L1	L2	L3	L4	L5	L6	L7	WH1	WH2	WH3	WH4	WH5	WH6	WH7	M1	M2	M3	M4	M5	M6	M7	AM1	AM2	SI1	SI2
Pollen and Spores																									
Angiospermous Pollen	F	F	C	R	R	C	R	R		R	R	R		F	F	F	C	F	R	R		R	R	R	R
Gymnospermous Pollen	R		R						R									R				R	F		
Spores						F					R	F	R	R	R	R	R					R	R		
Dinoflagellate cysts and Algal remains																									
Acritarchs																	R	R							R
Algal Remains (Indet.)	C	C	F	F	C	F			R					R	R	R	F	F	F	C	C	F	F	F	C
Botryococcus sp.	R	R	R																						
Concentricystis sp.		R				R		R						R	R										
Cyanobacteria	R					R																R			
Dinoflagellate cysts	R	R	R		R	R									R		R		R	R		R	R	R	R

This study describes palynomorph assemblages and their source from five different coastal environments of southern Red Sea, Saudi Arabia; they are mangrove swamps, Mid Holocene wadi

Hali paleochannel section, algal mat, and Sabia Island coral reef, and intertidal environment. Numerical distribution of palynomorphs from these coastal environments is presented in Tables 1–7, and percentage representation of palynomorph groups is shown in Figures 6–9. Provenance of various palynomorphs and palynomorph groups is discussed.

5.1. Mangrove Swamp Environment

Mangrove swamps in this region cover small patches of mangrove stands and the areas covered by them vary considerably. They are distributed in restricted, quieter environments, occasionally they also inhabit higher energy intertidal environments. The southern Red Sea coast has a relatively denser growth of mangroves than the northern coast. This is because of the tropical climate, more wadis, higher rainfall and nutrients, and less saline waters along this part of the Red Sea coast [83].

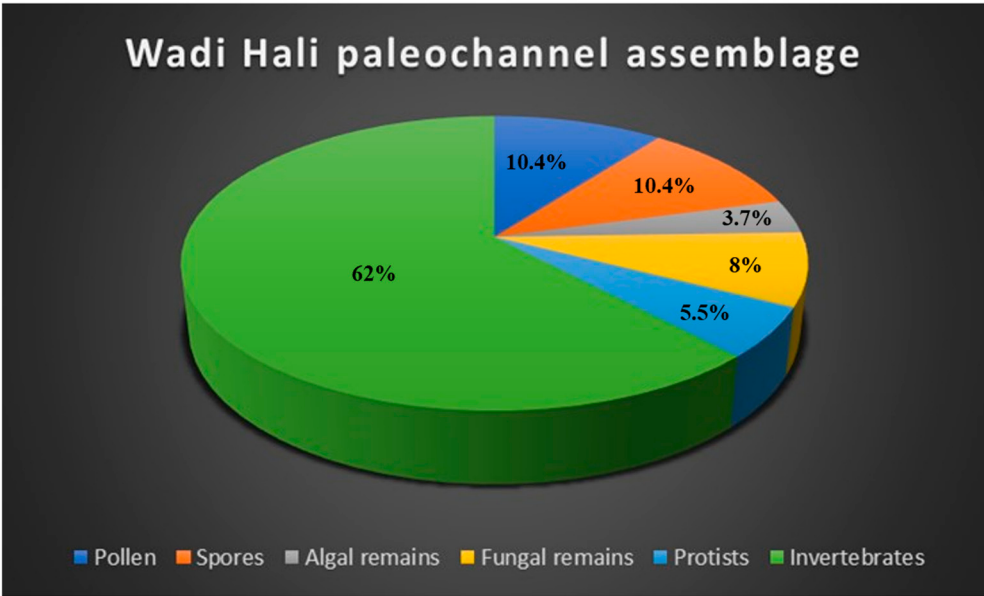
Palynomorph assemblages in the mangrove swamp environment show higher numerical abundance and diversity than the Wadi Hali paleochannel section and show closer similarity to the assemblages obtained from the intertidal samples [16]. Rare occurrences pollen and spores, which are mostly of angiosperm affinity except for the only gymnosperm *Juniperus* pollen were observed. The occurrence of dinoflagellate cysts is rare; however, four new types of dinoflagellate cyst types G, H, I and J were informally described. Only rare specimens of the new dinoflagellate cysts were observed. Algal remains are more or less similar to the assemblage described from intertidal environments, except that several algal remains could not be identified (indeterminate) and their representation in the assemblage ranges between few to common. This indicates a relatively higher diversity of dinoflagellate cysts and algal remains in the mangrove swamps than in the paleochannel section. The diversity and numerical abundance of fungal remains is higher and ranges between rare to common. Although the diversity of fungal remains is as high in the intertidal samples, their numerical abundance is lower and ranges between rare to few.

Generally, low numerical abundances and higher taxonomic diversity among the protists was observed in the mangrove swamp samples that included several types of thecamoebians, microforaminiferal test linings, and tintinnomorphs. Thecamoebian taxa found in these samples are like the intertidal samples, but five new types were informally described; they are Thecamoebian types A, B, C, D, and E. All these new forms occur as rare, but numerical abundance of thecamoebian type C ranges from rare to common. Several microforaminiferal test linings described from the intertidal samples occur in mangrove samples, and their numerical abundance ranges between rare to few.

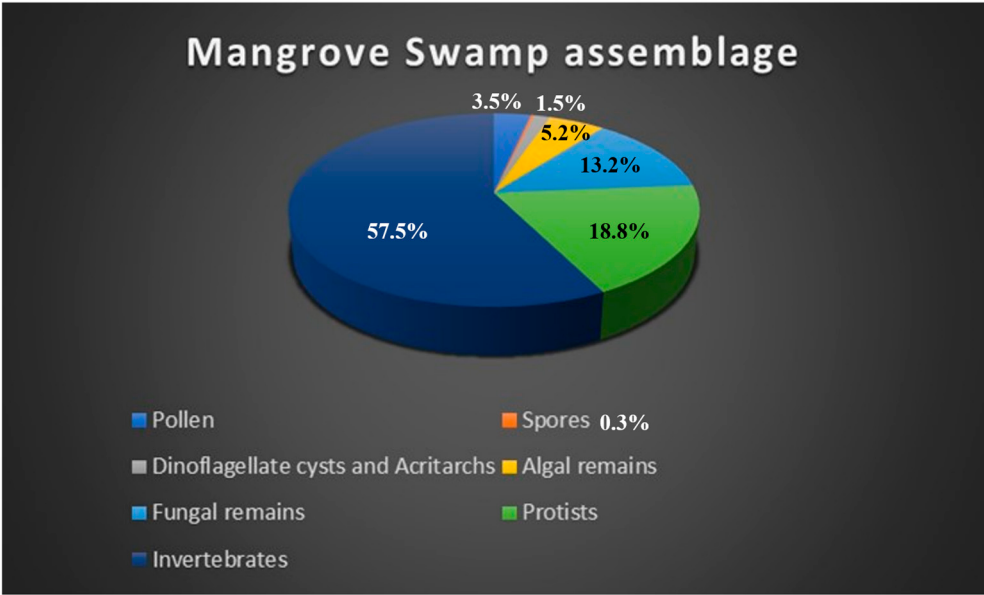
The six new form species *K. arabica*, *K. elongata*, *K. oblonga*, *K. twinmorpha*, *M. redseaensis*, and *M. hallii* occur commonly in this environment (Table 4). Numerical abundance of invertebrate remains is significantly higher than that of other groups of palynomorphs. These can be grouped into annelid, and crustacean remains. Their numerical abundance ranges between common to abundant. Rare remains of an ostracod species cf. *Leptocythere* sp. were observed in a few samples.

5.2. Wadi Hali Paleochannel Section

This section is possibly a mid-Holocene paleochannel deposit, is located about 2 km inland from the present-day coastline. There is no age control on these samples. However, geological, paleoenvironmental and paleoclimatic evidence provide certain clues to its age. In the Wadi Hali Quadrangle extensive flood plain deposits are present along the lower parts of major wadis. These deposits consist of silt, fine grained sand, and clay [29]. These clastic sediments were most likely deposited during the wetter conditions 6-9 ka BP in southern Saudi Arabia [84]. The middle Holocene wet phase has been dated to be 6.0 ± 0.6 ka BP [85,86]. Thus, it is suggested that the paleochannel deposit is most likely of middle Holocene age.



A. Percentage distribution of palynomorph groups in Wadi Hali paleochannel assemblage (crustacean antennae excluded).



B. Percentage distribution of palynomorph groups in mangrove swamp assemblage (crustacean antennae excluded).

Figure 6. Percentage distribution of palynomorph groups. A. Wadi Hali paleochannel assemblage (crustacean antennae excluded), B. Mangrove swamp assemblage (crustacean antennae excluded).

Wadi Hali is an example of an intermittent river [87]. Such rivers are dry most of the time, but they do discharge water during flooding events when they erode, transport and deposit huge amounts of sediment. The Wadi Hali paleochannel section may represent such a fluvial deposit. Mud cracks were observed on the surface of the outcrop along with traces of fossil plant roots in the section [75].

The percentage distribution of various palynomorph groups is shown in Figures 6A and 8A. The assemblage contains pollen grains, spores, algal and fungal remains, protists like thecamoebians and tintinnomorphs along with crustacean and worm remains. Except for crustacean remains, all other palynomorphs occur as rare to few. Only crustacean antennae are abundant in all samples. Pollen,

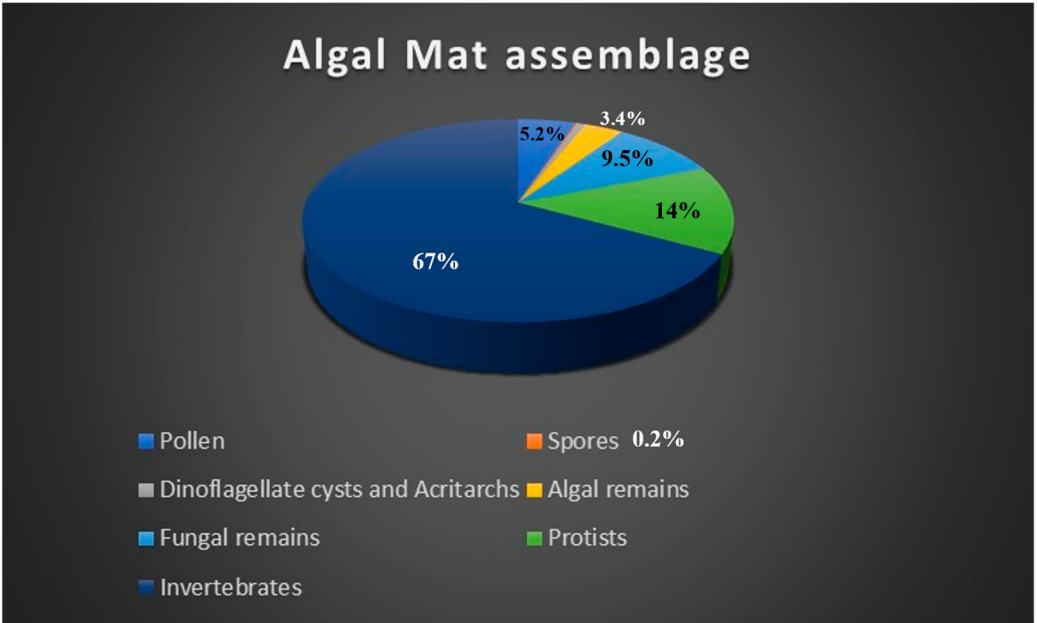
spores, algal and fungal remains are allochthonous that were transported by wind and water in this fluvial deposit. No dinoflagellate cysts and only one specimen each of microforaminiferal test linings and *Katora arabica* were observed.

The occurrence of thecamoebian taxa like *Arcella* sp., *Centropyxis aculeata*, *Diffugia* sp., *Euglepha* sp. and *Geopyxella sylvicola* in this section is problematic. Since these forms are benthic protists, they require a quiet standing body of water to survive. They are not expected to inhabit an intermittent river as described because they are dry most of the time and water moves extremely fast due to storm related flooding events [87]. Thus, it is suggested that during the Middle Holocene wetter climatic conditions, the Wadi Hali paleochannel section probably represented an isolated body of water such as a pond close to one of the channels of Wadi Hali. Few different taxa of thecamoebians inhabited this pond along with crustaceans and worms. The occurrence of abundant crustacean antennae in this section probably is due to their accumulation at a certain place because of sorting by waves within the suggested body of water. Isolated specimens of *Katora arabica* and microforaminiferal test linings are contaminants in this assemblage, and probably were brought in from the intertidal sediments during periodic storms that impacted this region [37]. A variety of tintinnomorphs and microforaminiferal test linings were reported from the intertidal sediments in this area [16].

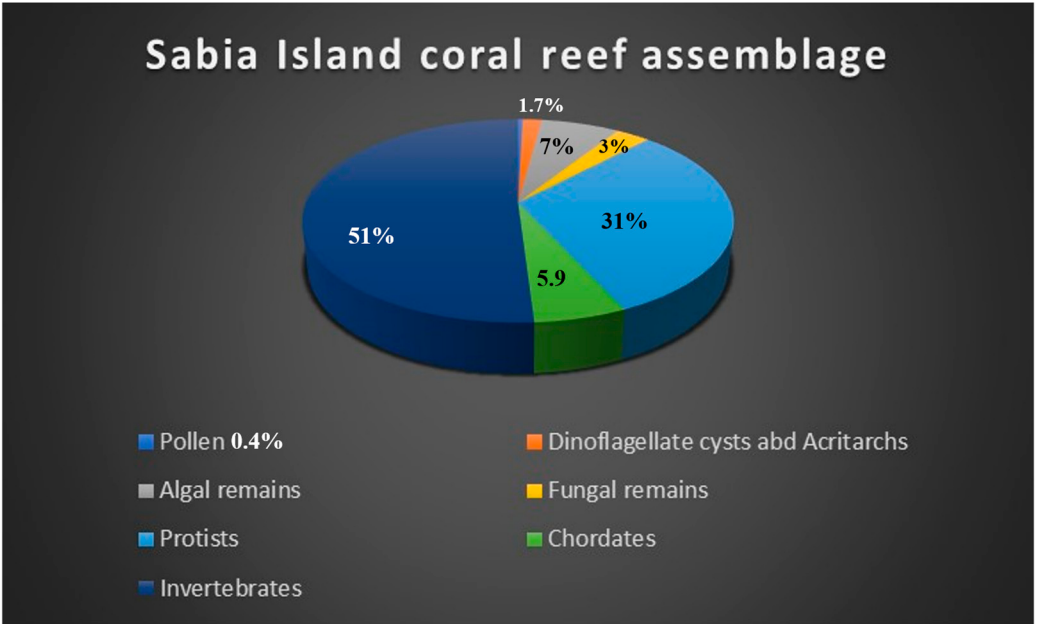
5.3. Algal Mat Environment

An algal mat is a sheet-like accumulation of microbial layer made of filamentous algae and/or cyanobacteria on marine or fresh water soft bottoms normally in the warmer regions. Usually, they occur in shallow marine subtidal to supratidal environments, as well as in lakes and swamps [87]. The numerical distribution of palynomorphs in this environment is shown in Tables 1–7. Figures 7A and 8C show proportional representation of palynomorph groups in this environment.

Palynological slides of these samples are characterized by the presence of abundant green filamentous, branched alga and numerous fungal filaments which are branched and unbranched, septate and aseptate. Pollen and spores occur rarely. Likewise, dinoflagellate cysts and algal remains occur rarely but there are a few occurrences of algal cells (indeterminate). The occurrence of form taxa ranges from rare to common, especially *Katora arabica*, *K. oblonga*, and *Mangrovia redseaensis* are common to very common. Diversity and numerical abundance of fungal remains vary between rare to common, and *Callimothallus* type fruit body and *Glomus* sp. are prominent among the fungal remains. The occurrence of Protists range between rare to common and only thecamoebians were observed. Crustacean remains are a significant part of the algal mat samples, and they range between few to abundant. Crustacean antennae and exoskeleton are major contributors to the palynomorphs of invertebrate affinity. Unidentified worm remains are important in the assemblage as well.



A. Percentage distribution of palynomorph groups in Algal Mat assemblage.



B. Percentage distribution of palynomorph groups in Sabia Island coral reef assemblage.

Figure 7. Percentage distribution of palynomorph groups. A. Algal Mat assemblage, B. Sabia Island coral reef assemblage.

5.4. Sabia Island Coral Reef Environment

This small island in the Red Sea, is about 20 km away from the nearest coast of Saudi Arabia and is surrounded by coral reefs. Present status of Red Sea coral reefs is discussed [88,89]. Palynomorph distribution is shown in the tables and Figures 7B and 8D show proportional representation of palynomorph groups in this environment.

Since these two samples represent the marine environment, unlike other samples that represented marginal marine environments, the palynomorph assemblages are quite distinct in them. As expected, rare specimens of only three pollen were observed, that must have been blown-in by wind from the mainland. No spores were observed. Dinoflagellate cysts and acritarchs occur rarely, but isolated specimens of informally described new dinoflagellate cysts were observed; they are dinoflagellate cysts K, L, M and N. Dinoflagellate cyst D earlier described from the intertidal samples [16] occur in this assemblage as well. Algal remains are a prominent group dominated by various types of algal cells and broken specimens of marine diatoms. Rare occurrences of fungal remains were observed, and their composition is like algal mat samples.

Protists are represented by a variety of microforaminiferal test linings. Their numerical abundances and diversity dominate the assemblage. There are no tintinnomorphs, but *Katora arabica*, *K. oblonga*, and *K. elongata* occur commonly. Thecamoebians occur rarely; that includes *Centropyxis aculeata*, *Geopyxella sylvicola* and an informally described form is thecamoebian type F. Presence of *Centropyxis aculeata* and *Geopyxella sylvicola* in this assemblage raises questions, because they are not known from the marine environments, instead they inhabit fresh to brackish water environments. *Centropyxis aculeata* is known to occur in a wide range of environments ranging from fresh to brackish water and prefers warmer waters above the thermocline [68]. *Geopyxella sylvicola*, is a soil testate amoeba found in tropical coastal lowlands in southwest India [47]. Thecamoebians were also reported from the Godineau River Estuary, Gulf of Praia, off the island of Trinidad [90], but none from the marine environments. It seems that the thecamoebian taxa that occur in these samples got contaminated and most likely were transported by storm winds from the intertidal environments.

The palynomorphs having affinity with invertebrates are once again dominated by crustacean remains, mainly antennae and skeleton, and their occurrence ranges between rare to abundant. However, annelid remains occur rarely. The most striking addition to this assemblage is the occurrence of ascidian spicules. Six types of ascidian spicules from type1 through type 6 were informally described [17]. Rare occurrence of sponge spicules and phytoliths were also recorded.

5.5. Intertidal Environment

Distribution of palynomorphs in these samples are presented in the tables. Palynomorph assemblage varies considerably among the samples. Generally, the occurrence of pollen and spores, dinoflagellates and algal remains, and fungal remains range from rare to very common in different samples. Protists like tintinnomorphs, thecamoebians, and microforaminiferal linings rarely occur. Crustacean remains are abundant and annelid palynomorphs are common to very common in various samples. *Katora* spp. occur as rare to common in these samples.

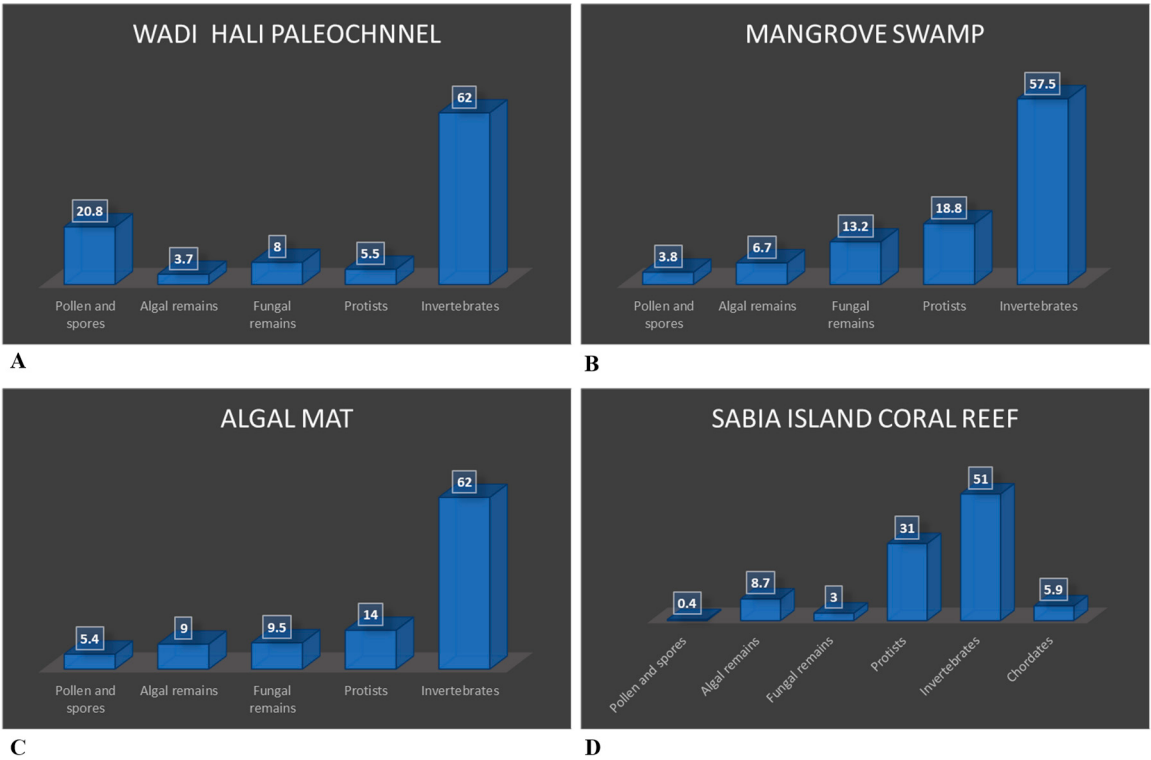


Figure 8. Percentage representation of palynomorph groups in various environments. A. Wadi Hali paleochannel, B. Mangrove Swamp, C. Algal Mat, D. Sabia Island coral reef.

Sample L1 has many microscopic remains of protists and invertebrates. Crustacean antennae and other remains are abundant in this sample. Pollen and spores, algal and fungal remains have only rare to few specimens. Palynomorph composition in samples L2 and L3 are very similar to sample L1. The assemblage of this sample is dominated by a few protists and invertebrates such as crustacean and annelid palynomorphs. Rare specimens of microforaminiferal linings occur in most of the samples. Palynomorph assemblages of samples L4, L5 and L6 have rare fungal hyphae, spores, and unidentifiable forms. Predominant palynomorphs in all these samples are derived protists and invertebrates. Crustacean antennae are either abundant or very common in these samples. Sample L7 is almost barren, has few cuticles, trachieds, fungal remains, and rare fragments of charcoal.

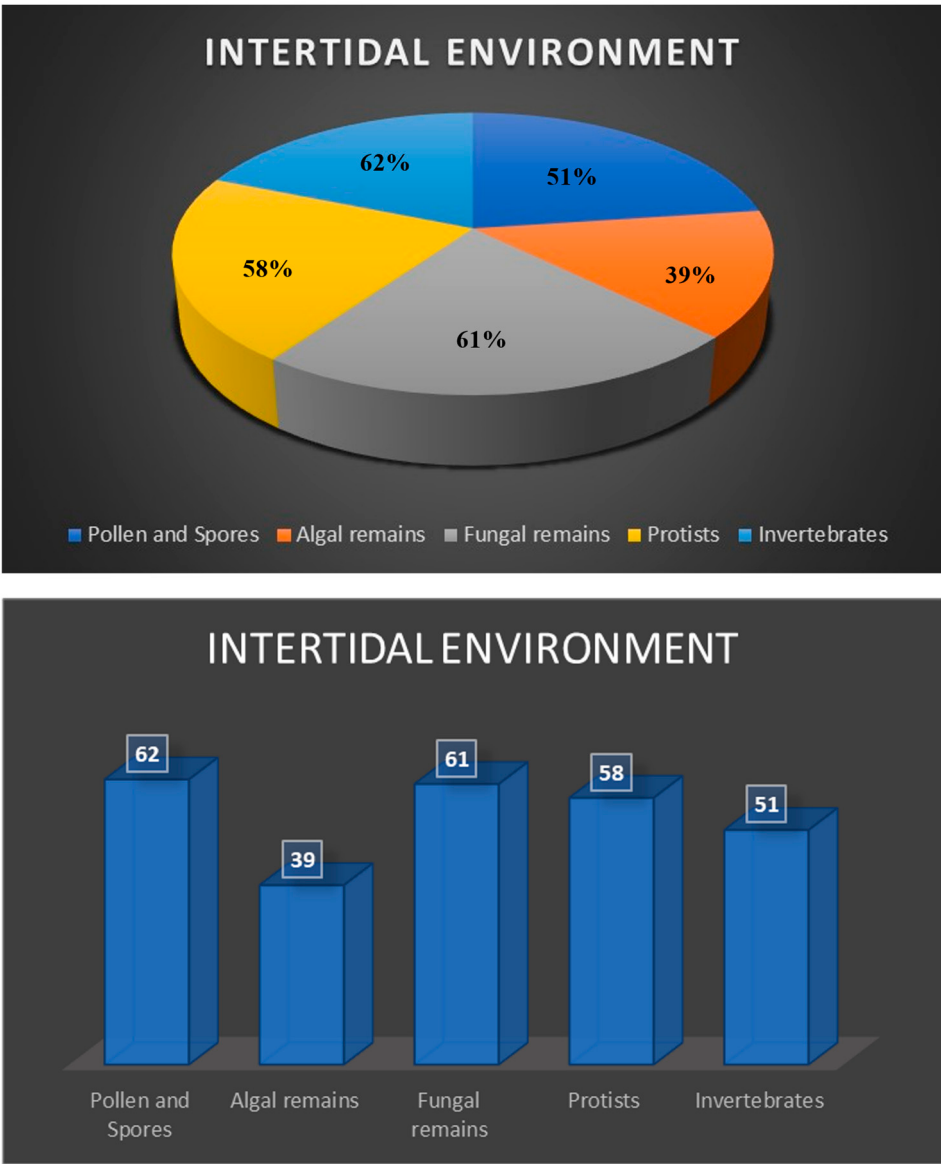


Figure 9. Percentage distribution of palynomorph groups in the intertidal environments. Data based on seven samples [16].

6. Conclusions

Table 7 shows the summary of relative distribution of palynomorphs and palynomorph groups in all the five southern Red Sea coastal environments. All five groups of palynomorphs occur in all these environments, however their relative abundances vary significantly among them (Figures 6–9). The intertidal environment is characterized by mostly rare occurrences of pollen, spores, dinoflagellate cysts and other algal remains (Figure 9). The same is true for fungal remains, except for fungal fruit bodies and few indeterminate forms that are common to very common. Palynomorphs having affinity with protists and invertebrates dominate the assemblage. The presence of tintinnomorphs, crustacean and annelid palynomorphs range between few to very common. The Mid Holocene Wadi Hali paleochannel section has an impoverished assemblages and has rare occurrences

of pollen, spores, fungal remains, algal remains and no dinoflagellate cysts. Among protists and invertebrates, only crustacean remains are common to abundant. Mangrove swamp environment has a relatively richer composition of palynomorphs compared with the intertidal assemblage. Pollen, spores, algal remains and dinoflagellate cysts occur rarely, but unlike intertidal assemblages, mangrove assemblages have a higher diversity and numerical abundance of palynomorphs. Distribution of protists and invertebrates is like the intertidal environment, where thecamoebians, tintinnomorphs and microforaminifera range between few to common. Crustacean and annelid remains are common to abundant. Algal mat environment is characterized by an abundance of filamentous green algae where fungal hyphae are the second most common form. It has rare to few occurrences of pollen and spores, fungal remains and dinoflagellate cysts and other algal remains. Protists and invertebrate palynomorphs are rare to few but crustacean remains are common to abundant. Sabia Island coral reef environment mostly has rare presence of pollen, spores, fungal remains and dinoflagellate cysts and algal remains. Protists and invertebrates dominate the assemblage; tintinnomorphs, microforaminifera and crustacean remains are few to abundant. No crustacean antennae were observed. Ascidian spicules occur only in this environment and are common to very common. A few specimens of phytoliths were also observed in this assemblage. *Katora* spp. occur as rare to very common in all the environments except for the paleochannel section. *Mangrovia* spp. occurs only in mangrove and algal mat environments. Few charcoal fragments occur in most samples.

This study provides comprehensive palynological baseline data about the southern Red Sea coastal environments indicating their flora and fauna that defines the present health of the coastal ecosystem. Study of palynomorphs occurring as fossils or subfossils in various coastal sedimentary settings represent local and regional climate, and environments.

Acknowledgments: I thank my former colleagues from King Fahad University of Petroleum and Minerals (KFUPM), Saudi Arabia: Lamidi Babalola, Michael Kaminski, and Khalid Ramadan, who joined me during the field trip and helped in sample collection. Asif Khan prepared the location map and Osman Abdullatif joined us to discuss various aspects of this project. I thank KFUPM for financial support for the field trip. I am thankful to Dr. Peta Mudie (Geological Survey of Canada), Dr. Francine McCarthy (Brock University, Canada), Dr. Kazumi Matsuoka (Kyoto, Japan), and Dr. Kenneth Mertens (Institut Français de Recherche pour l'Exploitation de la Mer, France) for helping me in few identifications.

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