Raised Coral Reefs and Sediments in the Coastal Area of the Red Sea

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Abstract

Along the Red Sea, narrow coastal plains ascend directly into fault-bounded blocks within a few kilometers of the shoreline. Littoral areas on both sides of the Red Sea are characterized by mixed sedimentation relating to a complex system of fringing and barrier reefs and alluvial fans. These marine sediments are uplifted to altitudes rarely exceeding 50 m. However, although terraces are well developed on both sides of the basin there is no apparent correlation, the possible exception being the youngest level situated about 2 m above present sea level. Raised coral reefs result from either the corrosive action of waves or from local erosion by occasional torrents creating low cliffs and exposures just above high-tide level. Each reef unit exhibits in a short distance lateral facies changes, which begin at the shore with the beach facies, mainly composed of siliciclastics, and end at the reef crest zone with transition to the fore slope made up of carbonate sediments. A strong similarity can be noticed between sedimentary facies of ancient Pleistocene sediments and those now present in modern fringing reefs. Reefs with their siliciclastic associations occur in the form of repeated cycles reflecting tectonic effects and/or sea level changes. Reef sequences exhibit different degrees of diagenetic alteration, which are reflected by a gradual change of skeletal particles and the early-formed cement, from aragonite and high Mg-calcite to low Mg-calcite. Tectonism controls the areal distribution of the depositional systems and influences the number, thickness, extension, and elevations of the reef sequences. Each sequence in each area can be uniquely correlated to the overall (global) population of dated terraces. Coastal areas of the Red Sea are under stress from a variety of human activities and many have experienced widespread degradation, especially around Hurghada and Jeddah. Hotel, resort and other developments along the coast of Egypt are growing rapidly, destroying raised reefs and threatening valuable coral reef ecosystems. Some areas along the coast suffer from construction problems that are associated with coral reefs. These problems include ground settlement and low bearing capacity which are mainly due to the low shear resistance and high porosity of reef sediments. These problems greatly affect the safe and economic land utilization of the coasts. Prediction of the future changes along the Red Sea coast would give guide lines to what will happen due to the varying nature of the coast. Such predictions would have implications for future social and economic development along the coast. Effective and integrated coastal zone management programs are critical to sustaining the natural resources of the Red Sea.

Introduction

Along the Red Sea, narrow coastal plains ascend directly into fault-bounded blocks within a few kilometers of the shoreline (Fig. 1). Along the shore there is a continuous band of

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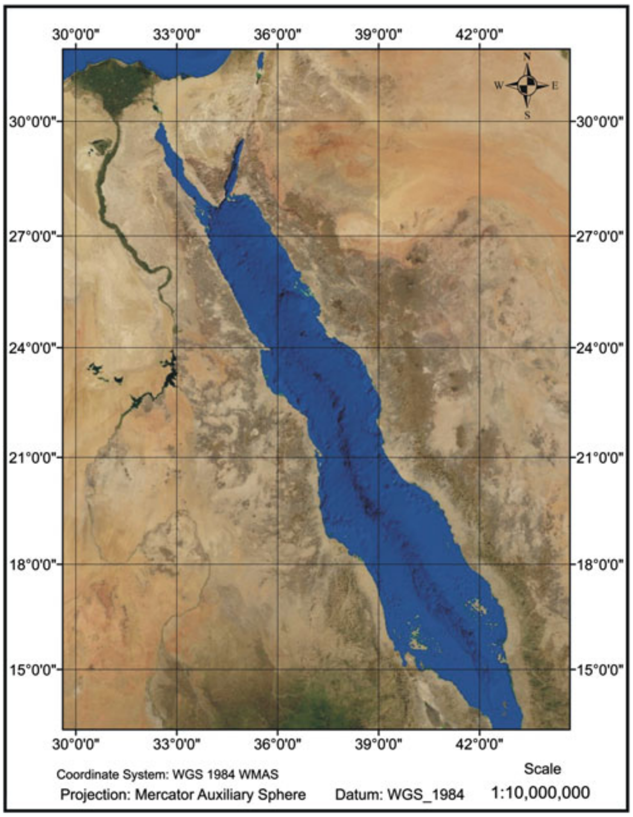

Fig. 1 Landsat image showing the narrow coastal plains that ascend directly into fault-bounded blocks within a few kilometers of the shoreline (Google map—2014 digitized by Arc map v.10)

emergent reef terraces and a sandy gravel surface which is inclined towards the sea, as described in 1888 by J. Walther, the founder of actuogeology. Littoral areas on both sides of the Red Sea are characterized by mixed sedimentation relating to a complex system of fringing and barrier reefs and alluvial fans. A series of raised fossil coral reefs higher than current sea level are one of the most striking features of the Red Sea coastline. There are at least two Pleistocene reef terraces; however, three are observed in several areas. Each exhibits a lateral facies development over a short distance, beginning at the shore with a beach of mainly siliciclastics, and ending at the reef zone with carbonate sediments (Mansour 2000a). Mansour (2000b) noted 6 terraces at Dishet El Dabaa (Fig. 2), south Hurghada. El-Asmar and Attia (1996) noted 4 terraces in the Sinai, and Guilcher (1988) refers to a series of 11 uplifted reefs on the Tiran Islands at the entrance of the Gulf of Aqaba extending vertically 320 m.

The Red Sea coastlines frequently extend out in the form of rocky headlands referred to, along the whole region, as Ras (e.g. Ras Banas, Ras Ghareb, Ras Hatiba). The coastlines and outlying fringing reefs are incised at irregular intervals by creeks known by the local people as Sharms (e.g. Sharm el-Sheikh). These creeks (or Sharms) are typically drowned discharge valleys. Recent coral reefs and elevated Pleistocene reefs terraces are also well developed along the coasts of the Red Sea.

The raised coral reefs and the sediments of the coastal area in the Red Sea are the main subjects of this chapter. Prediction of their future changes could be useful for the management and sustainable development of the coast. Several authors have discussed the ages and diagenesis of the Pleistocene reefs terraces along the Red Sea coast (Plaziat et al. 2008, with references therein; Manaa 2011).

Quaternary Coral Reefs

The Quaternary reefs appear strictly controlled by the Pleistocene cyclicity of ice ages which in turn modulate with the basin's hydrological conditions (Taviani 1998). It is proposed that the shallow-silled Red Sea basin was cyclically affected by more or less severe biotic turnovers as a consequence of periods of high environmental stress (temperature, salinity) during glaciations.

Raised coral reefs occur in the form of a ridge-furrow system, produced either by the corrosive action of waves or by local erosion by occasional torrents creating low cliffs and exposures just above high-tide level. Their thickness generally increases from north to south (Mansour 1993). Raised coral reefs are composed mainly of corals in their growth position and the preservation of corals is mostly good (Fig. 3).

Quaternary Coral Reefs on the Western Side of the Red Sea

The Quaternary sequences of the Egyptian Red Sea coast constitute a conspicuous belt flanking the Neogene succession in the NW part of the Red Sea rift. They include both alluvial fans and reefs. The former are the result of high basement relief and the presence of numerous scarps. Much of this detrital material is trapped in grabens formed by Quaternary and Neogene faulting (Purser et al. 1987). As on the Saudi Arabian coast, Pleistocene reefs may be uplifted to altitudes of about 50 m. The marine terraces along the Red Sea coast and the Gulf of Aqaba exhibit different elevations relative to the present sea level (Al-Sayari et al. 1984a, b; El-Asmar and Attia 1996).

The Pleistocene terraces are dissected by WSW-ENE trending dry wadis that act as conduits for coarse detritus to the sea only during flash floods. Reefs with their siliciclastic associations occur in the form of repeated cycles reflecting tectonic effects and/or sealevel changes. Pleistocene sequences comprise continental sediments and shallow-water carbonates and siliciclastics of different facies mostly similar to those of modern fringing reefs. However, this facies

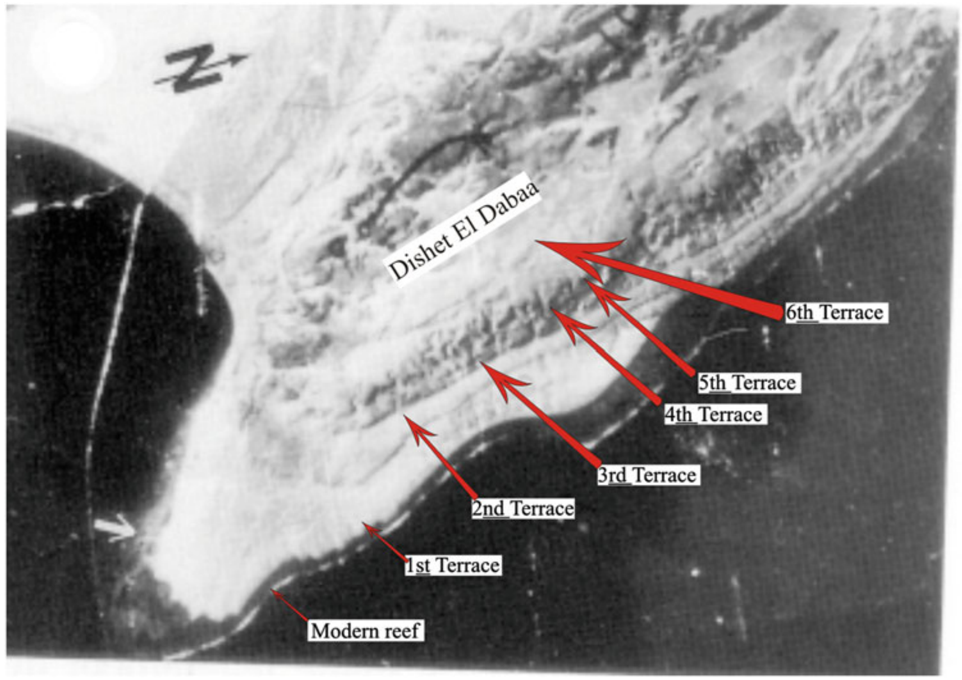

Fig. 2 Aerial photograph showing Quaternary reef terraces at Dishet El-Dabaa, 25 km south of Hurghada (Mansour 2000a)

Fig. 3 Raised coral reefs are composed mainly of corals in their growth position and the preservation of corals is mostly good

similarity probably reflects similar climatic conditions. All reef sequences reveal transgressive phases developed during the sea level rise, while the alluvial deposits are regressive sequences accumulated during the lowering of sea level.

Sequence boundaries of most reef units in most areas are depicted by an abrupt basinward shift of the coastal onlap. Other sequence boundaries are observed when alluvial channel deposits suddenly replaced coral reef (Mansour 2000a).

Fossil coral reefs, like the present fringing reefs, outcrop all along the Sudanese coast as well as everywhere around the Red Sea, except in the delta areas of the most important wadis, the Khor Baraka in the south and the Khor Dib in the north, where the silty alluvial deposits inhibit coral development. Generally narrow (a few hundred meters), the fossil coral reefs often form two or three parallel flat ridges, such as in the Marsas Fijja, Arus and lrayes areas.

Eastern Side of the Red Sea

Along the Red Sea coast of Saudi Arabia a sequence of marine and terrestrial terraces unconformably overlies Pliocene sediments. Alluvial fans relating to the mountainous hinterland and various fault scarps slope gently towards the sea. Partly reworked by wadi systems, they grade into coastal sabkhas developed as wide littoral plains or into reef assemblages along the narrower and steeper parts of the coast.

Caused mainly by eustatic sea level changes and only subordinately by vertical tectonics, three main terrace systems can be recognized (Al Sayari et al. 1984a, b; Dullo 1990; Dullo and Montaggioni 1998). The oldest terrace system whose reef platform is situated 30–50 m a.s.l. is associated with extreme coarse, boulder-like, alluvial fans. The second system, with elevations of 15–25 m, is often subdivided by a step situated at 15–18 m, and by another at 20–22 m. The terraces above 20 m are frequently tilted slightly, while the younger terraces generally are not tilted, though they may be affected by faults.

The third terrace occurs between 6 and 10 m and represents the last interglacial high sea level dated by uranium/thorium at about 95,000–120,000 years. A small terrace or wave cut notch located 2 m above modern sea level is related to the Holocene transgression. The terrace levels are relatively constant along the NW Arabian Red Sea coast confirming relatively minor vertical displacement during the Quaternary. However, larger deviations occur around the Midyan Peninsula, especially along the Gulf of Aqaba.

Facies Patterns of Recent Reefs

Beach

The beach is 3–8 m wide, a few cm to about 50 cm high and sloping 8–12°. The sediments are gravel and sand with abundant shell material swept up from the sea. Beach sediments at the mouths of valleys are mainly composed of quartz, feldspars and rock fragments. A few meters away from the mouths of the valleys, carbonate fragments are abundant in the beach sediments. Sometimes these materials are partly cemented by aragonite and/or Mg-calcite, transforming it into beach rock. The beach rocks exhibit clear color and coherence contrasts to beach sediments with a seaward dip. The beach sediments are flat with occasional heavy mineral concentrations, current shadows associated with bivalve shells, and various burrows of crustacea. At the valley mouths, beach sands extend and vary in width from a few tens of meters to a few hundred meters. The seaward margins of the sand facies grade into facies of the subtidal zone. Primary sedimentary structures of these sands include wave ripple cross-lamination. Crustacean burrows mostly destroy these structures and textures by mixing sediments.

Beach Rocks

Beach rocks are exposed in a narrow intertidal zone. They occur as conglomerate and/or sandstone layers at or just above the water table in the mouth of some wadis and in the furrows between coral reefs. They exhibit a typical appearance with a seaward dip of 10–20°. Field relationships suggest that these beach rocks are younger than the surrounding coral reefs.

Fringing Reef

Tidal flats are most widespread and conspicuous along the coast. In all cases they are rocky, built by coral limestone with a rugged surface. The contact to the subtidal zone is either gradational (e.g. at a valley mouth) or abrupt (e.g. away from valley mouths). The surface and its depressions are covered with a thin sand layer, sometimes with sparse seagrass growth (*Haloduleuninervis*, *Halophilastipulacea*) forming the sea grass zone. This zone is very rich with foraminifera, mainly Miliolida and Soritida which are a characteristic feature for this zone in the Pleistocene terraces. Ophiurids along with gastropods are abundant on hard substrates; massive occurrences of the Mytilid bivalve are also characteristic.

The Coral zone is a few meters wide and laterally increases on both sides of the valley mouths. It is characterized by a relatively even distribution of coral colonies. Corals grow on the margins of the channels just after a few tens of meters from the beach and become dense and variable seawards (Fig. 4). Leewards, the reef grades into a few meters wide intertidal zone. Seawards, the reef flat is sharply bordered by the reef slope, which is very steep (45–90°) leading to a complete disintegration of the reef and the development of a sandy bottom in the shallow parts grading into a coral carpet in the deeper (>15 m) waters. The reef flat is characterized by the common occurrence of the coral genera *Pocillopora*, *Stylophora* and other scleractinians such as *Favia*. The areas between the coral heads consist of a wavy, rocky bottom with a smooth surface covered by various calcareous (mainly coralline) and soft algae. At the reef slope, several species of the genera *Acropora* and *Porites* are dominant, and *Millepora* also exist. Some corals use dead coral heads as a substrate. Pools occur within the flat areas, which exhibit a dense cover of living scleractinians along their margins. The pool floor is covered by bioclasts from the reef slope during storms. A gentle inclined ramp and the abrupt onset of scleractinian growth characterize the reef crest. Within small fissures sea urchins thrive. Their thick spines are characteristic in the field and in thin sections for recognizing this zone in the Pleistocene terraces.

Facies of Pleistocene Reefs

The Pleistocene terraces occur in a narrow belt, with lateral facies changes, mostly parallel to the older Pliocene and the modern reef belt. The change of Pleistocene outline and topography in some places is due to the supply of clastic sediments during different climatic conditions. Based on field observations, sedimentological analysis and the distribution of fossils it can be stated that reef sequences comprise continental sediments and shallow-water carbonates and siliciclastics of different facies that mostly correspond to those of the modern environments.

Using this correspondence and the vertical and lateral succession in some areas along the coast (e.g. Wadi Guisses, Wadi Hamrawein) the distribution of rock units is clearly observed and each reef unit is represented by a facies association consisting of beach, back reef, reef crest and reef front (talus). This facies association is repeated in each terrace in the form of successive cycles, as was shown for the uplifted reefs on the Saudi Arabian coast by Dullo (1986, 1990).

Because of the commonly steep topography of the Red Sea coast, the sequence boundary of most reef units in most areas along the coast is depicted by an abrupt basin ward shift of the coastal on lap. This means that the sea level fall was extensive and rapid and falls below the physiographic sea margin and the entire coast may be exposed subaerially. Other reef boundaries unconformably resulted from the alluvial deposits. Sequence boundaries are clearly observed where alluvial channel deposits suddenly replace coral reef.

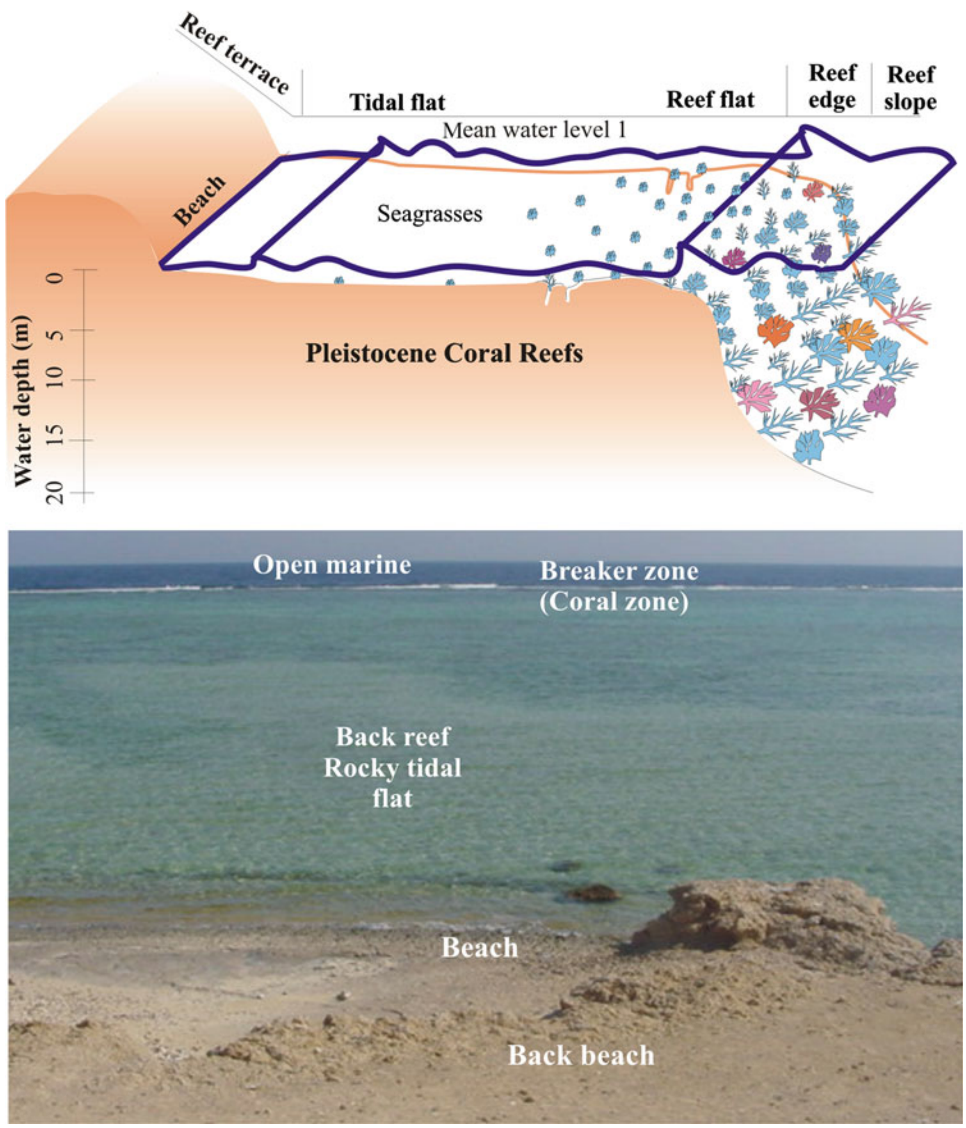

Fig. 4 Corals grow just after a few tens of meters from the beach and become dense and variable seawards (upper model, lower photo)

Genetically related sedimentary facies are attributed to various depositional systems. The various siliciclastics and carbonate depositional systems and facies are briefly outlined as follows.

Alluvial Fan

Impressive evidence of stream erosion and deposition exists in the areas of the Egyptian Red Sea and Gulfs of Suez and Aqaba (Issawi et al. 1971; Sellwood and Netherwood 1984). Infrequent rainfall and catchment areas of rocky desert highlands funnel flashfloods that build alluvial fans several square km in extent. Below the water surface submarine alluvial cones are formed, especially on the gentle slopes. On the extremely steep slope areas along the coast no subaerial fans are formed. Larger fans, alone or anastomosing, at the mouth of more than one wadi (e.g. Wadi Kid, Wadi Um Ghieg) have gentle slopes and finer particles, and sand grains and sand layers are more common than the gravels.

These fluvial sediments change upwards into beach sandstones which represent the older stratum of the Pleistocene sequences. It unconformably overlies carbonate Pliocene rocks and is marked by a basal conglomerate of clasts with sizes up to 30 cm in diameter, followed by clast supported polymictic poorly sorted conglomerates, up to 1.5 m thick, of subangular to subrounded cobbles and boulders grading upward into coarse grained lithic sandstones. Conglomerates are mainly composed of basement rock fragments, feldspars, quartz and some carbonate fragments. These fan deposits show a remarkable lack of maturity, indicated by the abundant detrital feldspar and little or no clay, implying a lack of chemical weathering. This demonstrates that arid climatic conditions prevailed at the time of initial fragmentation of the rocks. Moreover, their very poor sorting and lack of weathering suggests flashflood conditions, followed by drought, rather than permanent streams.

The Quaternary alluvial fan gravels are one of the preferred aggregates used for construction, buildings, highways, airport runways, and other structures. In different localities, most of them can be used as quarry sites due to their surface occurrence and proximity to roads. Deposits close to granitic rocks are very rich in feldspars, which can be used in ceramics. Alluvial fans are frequently excellent sources of ground water along the coast. The abundance of these coastal sediments can be useful in the development of the Red Sea area.

Beach

Successive fining upward deposits, 0.5–1.5 m thick, of a transgressive system dominate the beach. Its deposits change from conglomerate landwards to dominantly coarse to medium grained sandstones seawards. They show large scale unidirectional cross bedding dipping up to 5° seawards. The deposits are composed of quartz, feldspars, red-algal and foraminiferal packstones to grainstones and vary from intrasparite to biosparite rocks. However, in areas where beach deposits are in sharp contact with Pliocene sediments the dip angle of their lower contact is up to 15°. Upwards, they diminish progressively in dip which reaches 5° at their upper contact.

The beach facies of the intermediate reef (e.g. Wadi Hamrawein and Wadi Guisses) unconformably rests on alluvial channel deposits which form a siliciclastic foundation. This facies is 30–50 cm of conglomerates of cobbles and boulders of basement and carbonate rock fragments encrusted with calcareous red algae, and coarse to medium grained moderately sorted sandstones of carbonate rock fragments (red algae, foraminifera, echinoderm spines) with quartz and feldspars cemented by sparite and microsparite. Some voids are still free of cement.

The beach facies of the lower reef unit is mostly covered with coarse gravels. Its siliciclastic content is less than that of the intermediate and upper reef units. Generally, this content decreases from the older reef (averaging 57 %) to the modern beach (averaging 31 %), probably suggesting a decrease of uplift of the hinterland areas. According to Selley (1970) and based on the data available, the transgressional facies of the oldest terrace were accompanied by a moderate sediment supply, while the intermediate and youngest terraces attributed to transgression were accompanied by a low sediment supply.

Reefal Carbonates

Reef growth and its lateral seaward extension possibly reflect actual increments of subsidence or transgression of the sea. Lateral accretion continued initially without a significant break. The lateral facies variation leads to the recognition of three main parts. These are tidal flat or back reef, reef crest and reef front.

The back reef is subdivided into two main types

1. *Bioturbated-molluscan sandy limestone* is narrow (less than few meters) and is transitional from beach sandstones into dominantly carbonate reef deposits. It is 30 m wide and consists of a 1.5 m thick massive bed of pack stones composed of quartz, feldspars and biogenic clastics. Mollusks increase in amounts and size seaward. Field investigations, mineralogical composition, and petrographic study of samples collected along a profile of the older reef unit over a distance of about 30 m away from dominantly siliciclastic beach deposits show both the rapid decrease of siliciclastics (averaging 57–16 %) and the abundance of carbonate sediments and coral

Fig. 5 Reef front (talus) is clearly observed in the older reef in some areas (e.g. W. Hamrawein, W. Guisses and Ras Abu Soma). It is poorly bedded with unsorted reef fragments broken off by breaker erosion

heads. This rapid decrease of siliciclastics and the abundance of carbonate from the beach to coral zone are repeated in all reefs.

2. *Algal-molluscan limestone* is 15 m wide and is dominated by calcareous red algae with the appearance of a few small coral heads. Corals are locally encrusted by crustose red algae. The middle terrace still includes many calcareous algae and scleractinians, whereas the older terrace is poor in preserved fossils, many of which have been dissolved leaving molds filled with sparite cement, in which, of course, fossils have been present also prior to dissolution. Detrital fragments of carbonates, algal debris, echinoid spines, and anulids increase in size and amount toward the coral zone.

The reef crest (*coral zone*) is clearly observed in all reefs in most areas. It is a massive, wave-resistant zone about 10–15 m wide and about 3 m thick. It is dominated at the base by algal and coral debris and echinoid spines embedded in coarse bioclastics, followed upward by dominantly branched and domal corals in their growth position as well as calcareous red algae, mollusks and echinoids. Landwards of coral colonies, some corals use dead coral heads as a substrate. Seawards this coral zone interfingers with intervening talus reefal facies. Some geopetal fabrics of these coral colonies are filled with arkosic sand and skeletal debris.

The lower unit represents the biggest outcropping reef terrace with a higher diversity of coral species. It extends seawards and forms a steep wall bordering the present shoreline. Occasionally, the reef crest was eroded or tectonically subsided to the position of back reef. In some places it is bracketed by deep furrows, pits and pools occupied later by raised beach gravels and sabkha.

The reef front (*talus*) is clearly observed in the older reef in some areas (e.g. Wadi Hamrawein, Wadi Guisses and Ras Abu Soma). It is poorly bedded with unsorted reef fragments broken off by breaker erosion (Fig. 5). On the basis of clast sizes, a proximal and distal talus is present. The proximal part is dominated by angular coarse reef-derived detritus, with big reef blocks (50 cm) embedded in coarse bioclasts and algal debris, grading seawards into a distal part of finer coral-algal fragments (up to 3–5 cm), embedded in fine bioclasts and lime mudstone and siltstones. Rock types of biosparite range from wackstone at the base to grainstone, packstone and rudstone in the upper part. Terrigenous detritus may be mixed with slope reef facies.

Alluvial Channel

A progressive rapid fall of sea level terminated the deposition of the older reef terrace. This drop of sea level caused the incision of local channels into the pre-existing reefs by ephemeral fluvial streams. Detrital sediments filled local oval or semicircular channels about 10 m wide and 2 m high that unconformably overlie the distal part of the older reef (e.g. Wadi Hamrawein and Wadi Guisses). Channelized conglomerates of basement and carbonate detritus mark the lower contact of channels followed upward by fossil reef carbonate and coral fragments, embedded in pebbly siliciclastic conglomerates and algal bioclastics. This system can be interpreted as regression with a low sediment supply. High bioturbation is common in the upper part of this facies. Laterally on the margins of the channels, branched corals in growth position encrusted with calcareous red algae are common. However, floods of siliciclastics were enough to prevent coral growth along the axes of the channels.

Other Associations that Cover Coastal Pleistocene Reefs

During the last lowering of sea level erosional processes took place associated with tectonism. This resulted in the formation of a wide plain of gentle coastal morphology and occasional local depressions. Subsequently fluvial conditions prevailed in the area. This is demonstrated by large alluvial fans that funneled their loads of coarse clastics over pre-existing reefs. In areas where the paleo-shoreline is relatively far from the mountains there is a clear gradation seawards from dominantly alluvial fan deposits into beach conglomerates and sandstone sequences. In areas where the paleo-shoreline is near the mountains these coarse clastics were reworked by littoral hydrodynamics, as recorded by the beach gravels. Their gray color and coarse siliciclastics are a typical feature of these associations, which unconformably overlie and cut through the preceding Pleistocene reefs. Later on, parts of these coastal deposits were eroded forming lowland areas. These acted as pools filled by marine water, probably during flood episodes, which evaporated later under arid to semiarid conditions. This favoured the deposition of salt ponds and sabkhas.

1. *Alluvium* is represented by sporadic piles covering most parts of the reefs, and occasionally occurs on the low-lying Pliocene hills. The sediments consist of poorly sorted and immature large breccia and conglomerates (a few cm) intercalated with lenticular bodies of red sands and paleosol. It is believed that the sediments of this landward facies accumulated as proximal alluvial fans.
2. A *raised beach* is observed in some areas (e.g. Wadi Siatin, Wadi Hamrawein, Wadi Abu Hamra El Bahari and Wadi Guisses), and is absent in others (e.g. Ras Abu Soma and Dishet El Dabaa). It is a dark narrow belt and covers the upper part of the lower reef terrace. Seawards, this facies grades into conglomerates and sandstone layers. These deposits show a pronounced large scale cross bedding (8°E) suggesting an origin along gentle slopes. Closer to the shoreline, a prominent beach feldspathic sandstone is common.
3. *Evaporite facies or sabkha* occur on the upper part of the Pleistocene raised beach close to the sea, occupying small irregular depressions nearly parallel to the coast. The evaporites consist of about 0.5 m thick gypsum and anhydrite interbedded with calcareous fine muddy sands. The composition of the raised beach in some areas of less cemented gravel encouraged the formation of local erosional depressions during the subsequent lowering of sea level. These depressions were filled with evaporites as they become more restricted under an arid climate after a period of inundation. The restriction is probably related to the lowering of sea level or formation of beach barriers.

Composition of Pleistocene Reefs

Raised coral reefs are composed mainly of scleractinians in growth position and their preservation is mostly good (Fig. 3). The reef frame is usually massive and cavernous, with voids filled by marine cements and by internal sediment that is commonly perched on or within these cements. Skeletal remains of coralline algae, echinoderms, mollusks, and serpulids, with minor amounts of terrigenous materials constitute most of the sediments between corals. Raised coral reefs and beach rocks exposed along the coast of the Red Sea are generally composed of poorly sorted and well cemented framework grains. They consist almost exclusively of fragmented skeletal material derived primarily from corals, coralline red algae, echinoderms, mollusks and benthic foraminifera. Non-skeletal carbonate components such as ooids are very rare. Animal borings, mainly filled with brown sand to silt sized material also occur and are found to be continuous from the ground surface down to a few meters below the ground surface.

Patches of terrigenous materials with a lensoid shape within the raised coral reef horizon are also observed at two different levels at many places along the coast (Fig. 6). These patches are probably deposited in eroded areas created by wave action, and they are therefore younger than the surrounding coral reefs. These terrigenous bodies are few meters wide and few tens of centimeters thick and record the erosion history and the uplift of coral reefs at three different stages.

A comparison of the gross mineralogy of beach sands (Mansour 1991) and intertidal and marine bottom sediments (Piller and Mansour 1990) reveals that essentially the same constituents occur in both the beach rocks and raised coral reefs, but in significantly different proportions. The similarity of composition is explained by the derivation of most of these sediments from the adjacent coral reefs.

The mineralogy of the recent reef carbonates and Pleistocene reef sediments showed that the modern reef carbonates are composed of high Mg-calcite and aragonite with minor amounts of low Mg-calcite and traces of dolomite. On the other hand in the Pleistocene reef sediments low Mg-calcite, which is considered to have been formed by the meteoric digenesis of high Mg-calcite and aragonite, is the dominant mineral with varying proportions of aragonite (e.g. Dullo 1986, 1990). The carbonate content is more than 90 % and the non-carbonate material is dominantly quartz, minor

Fig. 6 Patches of terrigenous materials (*arrow*) within the coral reefs (Lower Terrace)

feldspar and heavy minerals in the sand fraction. Behairy (1980) recorded minor clay minerals and goethite in the clay fraction.

Diagenesis of Pleistocene Reefs

Detailed petrographic studies of thin sections of these reefs indicated that they are porous and slightly lithified skeletal limestone. Thin section investigations show similarities in mineralogical and petrographic characteristics as well as the distinct faunal assemblage of these sediments. Petrographic examination reveals the importance of cementation as a diagenetic process in the reef which contributes to the stability of reef structures. As mentioned before, in Pleistocene coral reef terraces along the Ras Mohamed-Sharm El-Sheikh coast (El-Asmar and Attia 1996) the petrographic examination reveals successive episodes of diagenesis from the younger to the older reef. Coral reefs of the lower terrace are cemented by carbonate of different textures. These are: (1) Calcareous mud matrix, (2) Cryptocrystalline high Mg-calcite (HMC) cement, and (3) Fibrous aragonite cement. The cement occurs mainly as micrite, and sometimes as microspar. Gypsum is present as cement, especially in the upper part of this reef. In the intermediate reef incipient transformation of Mg-calcite and aragonite into sparry calcite is recorded, whereas in the older reef sparry calcite is typically developed and all voids are filled with sparite cement.

Diagenetic cementation of sparry calcite is typically developed. The beach is characterized by well cemented calcareous sandstone with little porosity. Similar diagenetic effects were also observed in the upper parts of terrace three on the Saudi Arabian coast (Dullo 1986).

Calcareous mud matrix is the common cement in the lower reef, usually occurring as a groundmass in which the grains float and as cavity filling or micritic high Mg-calcite rims lining the interskeletal pore and the biogenic grains. Similar envelopes were observed in terrace "IV" of El-Asmar and Attia (1996), and in living corals from the Red Sea related to stage "II" of Gvirtzman and Friedman (1977). A cryptocrystalline submarine cement is precipitated within millimeters to centimeters of the surfaces of such high-energy deposits as reefs and beach rocks (Friedman 1985). Both intergranular and intragranular cryptocrystalline cement is common. Intergranular pores are seldom completely filled.

Diagenesis of beach facies records incipient transformation of Mg-calcite and aragonite into sparry calcite. Micrite rims are still present. The original high Mg-calcite of the micritic envelope becomes low Mg-calcite without a change in fabric. Any aragonite void filling that may have formed in the reef of the lower terrace is ultimately removed in this reef. Similar diagenetic observations were observed in terrace "III" of El-Asmar and Attia (1996) and the middle terrace (stage III) at south Sinai (Gvirtzman and Friedman 1977).

Another type of cement is the isopachous fringe of aragonite needle-like fibers nucleating the surface of the micritic envelope and/or the interskeletal pore forming palisade. In areas where cement fills a gap between parallel sides of two grains, aragonite laths grow on both sides parallel to each other and are closely interfingered. This fabric is presumably responsible for the hard and dense nature of the rocks (Khalaf 1988). In intergranular pores between more than three grains, aragonite cement is present as an isopachous fringe formed of interconnected laths growing from the surface of each grain towards the pore space. Similar diagenetic observations were observed in terrace "IV" (stage 2) of El-Asmar and Attia (1996) and the lower terrace (stage II) at south Sinai (Gvirtzman and Friedman 1977).

In the older reefs (upper ones) all voids are filled with sparite cement. Aragonite coral skeletons are transformed into a neomorphic sparry calcite mosaic. The neomorphic calcite crystals normally extend out of the original skeleton to fill partially the interskeletal pores, forming the cross-cutting calcite mosaic. This fabric is present either as a calcite cement crust of bladed dogteeth crystals characteristic of meteoric phreatic diagenesis, or as a micritic envelope of equant crystals of calcite growing on and lining the surface of the interskeletal pores. Similar diagenetic observations were observed in terrace "II" (stage 3) of El-Asmar and Attia (1996) and the upper terrace (stage IV) at south Sinai (Gvirtzman and Friedman 1977; Gvirtzman and Buchbinder 1978; Dullo 1984, 1986, 1990; M'Rabet et al. 1989; Strasser et al. 1992; Fathy 1994).

A thin hard layer of intraclastic beach rock observed only in the area north of Ras Gharib occurs at the surface of the intertidal zone. It consists of pelletoid sands, mainly faecal pellets, with quartz grains and smaller amounts of mollusks and foraminiferal shell fragments.

The occurrence of cemented fragments of pottery and glass artifacts in the beach rocks at sea level of the Red Sea suggests that lithification is currently active and rapid. Rapid lithification of beach rocks can be explained by the active growth of aragonite and high Mg-calcite crystals in the intertidal zone on the shore of the Red Sea (Mansour 1993).

Cryptocrystalline high Mg-calcite is the dominant cement, especially in the middle and upper horizons of coral reefs. The fibrous aragonite cement in the beach rocks and in the lower horizon of the raised coral reefs is common and concentrates in most areas of the rock. Aragonite cement in the raised coral reefs generally decreases upward and occurs only as small irregular aragonite patches in the upper horizon not concentrated in any particular part of the horizon. These details suggest that the dominance of high Mg-calcite in the upper horizon is due to the alteration of aragonite cement. The selective loss of aragonite over magnesium calcites has also occurred in Red Sea sediments (Friedman 1965).

Petrographic investigations do not show evidence for the alteration of aragonite to low Mg-calcite. Therefore, the relatively stable carbonates are believed to be of detrital origin, derived ultimately from ancient carbonates and calcareous rocks exposed along the Red Sea Coast. These detrital minerals are transported to the beach either by torrents or by winds.

Cements also play an important role in the mineral composition of beach rocks and raised coral reefs. The abundance of aragonite in the beach rocks and in the lower part of the raised coral reefs, although calcareous red algae of high Mg-calcite constitutes most of these rocks, is mainly due to the aragonite cement. There is a tendency for fibrous aragonite to occur more commonly in the beach rocks. According to Folk (1974), Milliman (1974), Bathurst (1975), Scholle (1978), Tucker and Wright (1990) and Montaggioni and Braithwaite (2009) the formation of such cement is favoured from pore water of marine composition. However, high Mg-calcite cement is more frequent in the coral reefs, especially above the high-tide level. The amount of cement generally increases in the coral reefs more than in the beach rocks.

Dating of Red Sea Raised Reefs

Much attention has been devoted to the precise dating of coral terraces in order to evaluate relative sea-level changes in regions considered tectonically "stable" or affected by a known and constant uplift rate. As mentioned before in Plaziat et al. (2008) the limited and episodic increase of rainfall and the relative tectonic stability of the shoreline suggest that the Egyptian reefs constitute an extremely favorable objective for a detailed study of the global climate and the instability of sea level during the late Quaternary highest stands (i.e. above Present sea level) for they were recorded by reef units referred to the Marine Isotopic Stages, MIS 7, MIS 5.5 and MIS 1 (= Mid Holocene Optimum) according to the $\delta^{18}O$ terminology (Martinson et al. 1987). Moreover, Plaziat et al. (2008) propose a nine stage diagrammatic reconstruction that illustrates the sedimentary results of around 200 ka of evolution of the Egyptian reefal shoreline (details in Plaziat et al. 1998a, b; Orszag-Sperber et al. 2001).

However, a general review of the dating of reefs on the coasts of the Red Sea, including those of Egypt, Jordan, Sudan, Eritrea, Saudi Arabia and Djibouti is given by Plaziat et al. (2008). A few Egyptian, Sudanese and Djibouti coral reefs were dated before 1980 (Butzer and Hansen 1968; Veeh and Giegengack 1970; Faure et al. 1980) while other dates have appeared in recent decades, many of them assigning an extremely wide range of ages to the lower reefs referred to as Late Pleistocene, from 150 to 50 ka. Because this lower reef unit is interpreted as being made up of "three onlapping reef cycles", Dullo (1990) suggested (his Fig. 21) that all the MIS (5e, 5c and 5a) high sea-level stands were appreciably above Present sea level. The lowermost Pleistocene "terrace", at +1.5 m, gave three ages (87.6, 86.6 and 57.6 ka) referred as a whole to the 5a substage (Plaziat et al. 2008). However, the last one is compared to a supposed stage 3 coral of the New Guinean record (Huon Peninsula, in Chappell and Shackleton 1986). Detailed studies of Egyptian reefs (Gvirtzman et al.1992; Gvirtzman 1994; El Moursi 1992; El Moursi et al. 1994) interpreted the younger dates as indicative of the probability that MIS 5c and MIS 5a reefs are a part of above sea-level outcrops, despite the absence of evidence of an adequate upheaval of the associated MIS 5e reef (Plaziat et al. 2008; cf. Reyss et al. 1993, Figure H2.35 in Plaziat et al. 1998a, b). On the other hand, an assumed tectonic activity during Holocene times (rift shoulder surrection or evaporate diapirism) in the pre-existing hemi-graben series induced Ibrahim et al. (1986) to mistake a late Pleistocene (5e) reef for a raised Holocene reef and to refer to gypsum residual tables of the same 5e substage (culminating more than 3 m above the Present littoral sabkhas) as Holocene salinas or sabkhas (see Orszag-Sperber et al. 2001). According to Manaa (2011) the reefs were probably formed during the major highstand of isotope 5e where the age of the upper reef is more likely to be 122.8 ka (MIS 5e), whereas the lower reef could be MIS 7 with no evidence of major tectonics in Rabigh area during the last 124 ka.

Reefs which formed during the interglacial period of isotope stage 7 (250,000–190,000 years B.P., Hays et al. 1976) have been identified by Gvirtzman and Buchbinder (1978) in Sinai, by Al-Rifaiy and Cherif (1988) in Jordan, and by Dullo (1990) on the Saudi Arabian side of the Gulf of Aqaba. According to Strasser et al. (1992), $^{230}Th/^{234}U$ dating in South Sinai places the older reef cycle between 350,000 and 270,000 years B.P., which corresponds to the interglacial period of isotope stage 9. The younger reef cycle has been dated between 140,000 and 60,000 years B. P. (isotope stage 5). At Zabargad Island, there are at least three systems of raised coral reefs (Hoang and Taviani 1991). The oldest terrace (>290,00 and 300,000 years B.P.) is found at +10 to +15 m. A 200,000 years B.P. high-sea stand is recorded by a terrace relict at +17 m on peridotite bedrock; the youngest system (125,000–138,000 years B.P.) is very well represented around the island, with terraces at about +6 to +8 m. Corals from Northern Brother yield ages of 132,000–135,000 and 204,000 years B.P. suggesting the existence of two systems of interglacial raised reefs. Both islands appear to have been tectonically quite stable since at least 125,000 years B.P. At Gebel e1 Zeit (southern Gulf of Suez rift basin), where terraces at elevations of +10 to 18 and +42 m have been radiometrically dated as 125 and 426 ka, respectively (Bosworth and Taviani 1996). However, as also mentioned before in Plaziat et al. (2008) most of the dates assigned to the raised reefs of the Red Sea may be considered much too imprecise, owing to the use of the α counting method and a loose selection of acceptable samples. The overall distribution of reef-growth ages may have been subject to the processes of rejuvenation that were invoked to interpret the broad deviations in the dates of Late Pleistocene 5e reefs on the Egyptian coast. A variable rejuvenation, related to local differences in the conditions that effected diagenesis, seems to be the key to the interpretation of the somewhat dispersed ages assigned to raised reefs.

Moreover, and as Dullo (pers. comm.) has added, most coral reef records have concerned sea-level high stands corresponding to the Last Interglacial period approximately 125 ka, and/or to the penultimate Interglacial (isotopic stage 7) from coral reef terraces exposed on the Huon Peninsula, Papua New Guinea (Chappell 1974, 2002; Bloom et al. 1974; Chappell and Veeh 1978; Stein et al. 1993; Chappell et al. 1996; Esat and Yokoyama 2006), Barbados (Mesolella et al. 1969; Edwards et al. 1987; Bard et al. 1990; Gallup et al. 1994; Potter et al. 2004), Sumba (Pirazzoli et al. 1993; Bard et al. 1996) and Mexico (Blanchon et al. 2009).

Impact of Civic Development on Coral Reefs

Coastal and marine resources are highly exploited in a non–sustainable way. The threats include habitat destruction, over-exploitation of living terrestrial and marine resources, environmental degradation from petroleum exploration and exploitation, significant risks from marine transportation, pollution from industrial activities, diverse environmental impacts from urban and tourism development and a series of emerging environmental issues associated with new types of economic development and uses of new technologies. Land reclamation and coastal road construction also affect shore zones and near shore waters. The impact of these activities can already be observed in areas subject to intensive use such as Dishet El-Dabaa (Fig. 7). Apart from areas of the sea that are lost, sediment loading of the water has increased and may affect coastal habitats in a similar manner to dredging (Aleem 1992; GEF 1997; UNEP 1997; Mansour 1999; Mansour et al. 2000a, b, 2005, 2011, 2013; PERSGA/GEF 2000, 2003; Madkour and Dar 2007; Madkour and Ali 2008; Madkour 2009, 2011; Madkour et al. 2012). Part of a highway to the north of Jeddah has been built on a reef flat, and any further building in this manner could cause serious losses to coastal habitats. Extensive coastline modifications have been carried out on an increasing scale in Hurghada and other areas.

Raised Coral Reefs and Construction Problems

The Red Sea coast is currently growing quickly due to flourishing diverse economic resources. Major harbours, cities and tourist villages in different countries along the Red Sea are built on these coral reefs (e.g. Hurghada, Safaga, Quseir, Port Sudan, Ashoaibah, Jeddah, and Rabigh harbours). The geological conditions and the type of foundations required are a key consideration in the structural and financial

Fig. 7 Coastal resources (e.g. raised coral reefs of Dishet El-Dabaa shown here) are highly exploited in a non–sustainable way

viability of a tall building. Within the coastal plain area the surface layer geology is primarily made up of coral reefs, sandy beach sediments, and other marine or alluvial deposits. Whilst these conditions do not prevent the construction of large hotels and tall buildings, they are not ideal. The hazards associated with the various ground conditions identified will influence the type and depth of foundations required (El-Shafie 2010). In the Marsa Ghaleb area along the Red Sea coast of Egypt some one floor buildings reveal many cracks (Fig. 8) and now whole buildings have been evacuated.

In recent years, however, the size of structures in some areas (e.g. Hurghada, Jeddah) has been increasing. Thus, evaluation of the engineering characteristics of the rock type has become an important issue for design and construction in this area. Construction problems associated with coral reefs include ground settlement and low bearing capacity, which are mainly due to low shear resistance and high porosity that are related to cavities in coral reefs and animal borings. Dewatering is a serious problem in these rocks due to their high porosity. These problems greatly affect the safe and economic land utilization of the coasts.

Ground improvement techniques such as compaction, deep compaction, using of stone columns, caissons, injection, and concrete piles are very important for construction in these areas. The selection of suitable methods depends on the economy and nature of the projects. However, adequate safety factors must be allowed for in the design of any construction founded on this rock type.

Predictions of Future Changes Along the Red Sea Coast

The population and economic growth in the coastal zone of the region has increased dramatically. A major contributor to growth in the coastal zone, with consequent impacts, is the rapidly expanding tourism industry. Prediction of the future changes along the Red Sea coast with its varying nature has implications for social and economic development along the coast. The associated land-use planning and mineral supply problems may be difficult to resolve. However, effective integrated coastal zone management programs are critical to sustaining the natural resources of the Red Sea.

The Red Sea is a very rich area from the resources point of view; it contains both living and non-living resources distributed over the terrestrial and marine sections. The data available on the resources of the area is scattered and mostly outdated. The scientific research on the natural resources and human impact is mostly at the national level and very few reports have been issued at the regional level. All types of habitat present in tropical coastal and marine areas are represented in the countries adjoining the Red Sea, with different degrees of distribution. All the threats to the natural resources arise from activities that are somehow related to the economic status of the countries.

Integration of planning, management and research in the coastal zone, on both land and sea is necessary to prevent pervasive degradation of the terrestrial and marine environments and to achieve ecologically sustainable use of coastal resources and conservation of these environments. All human activities if they are not done in a sustainable way can cause damage to the natural resources of the Red Sea area. The major factor that may reduce the damage from human activities is the increase in public awareness. The lack of laws and legal mechanism for implementation in most countries causes the environmental problems to build up and become disastrous. The lack of coordination between the countries may contribute in an indirect way to some of the problems. This demonstrates the importance of regional organizations such as Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA).

Fig. 8 One floor buildings on the lower terrace of Marsa Ghaleb area reveal many cracks

Because of the political and administrative differences between the countries in the area, the transfer of technology and experience between countries in the region is a way to ensure capacity building in the field of environmental protection. Cooperation between governments and owners of the land along the coast will solve many problems. The owners should be compensated for the damaged resources and the government should restrict property use to protect public health and for the safety and welfare of the people. Coastal and marine parks or even a zoning plan for controlling activities along the Red Sea are important and necessary in order to regulate the potentially damaging effects of development activities.

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