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REGIONAL SEAS

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A Review of the Geology of Coral Reefs in the Red Sea

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PREFACE

The Regional Seas Programme was initiated by UNEP in 1974. At present it includes twelve regions[1] and has some 140 coastal states participating in it. It is conceived as an action-oriented programme having concern not only for the consequences but also for the causes of environmental degradation and encompassing a comprehensive approach to controlling environmental problems through integrated management of marine and coastal areas. Each regional action plan is formulated according to the needs of the region as perceived by the Governments concerned. It is designed to link assessment of the quality of the marine environment and the causes of its deterioration with activities for the management and development of the marine and coastal environment. The action plans promote the parallel development of regional legal agreements and of action-oriented programme activities[2,3].

The Regional Seas Programme has always been recognized as a global programme implemented through regional components. Interregional co-operation among the various sea areas on common problems is an important element in assuming the compatibility of the different regional components.

The substantive aspect of any regional programme is outlined in an "action plan" which is formally adopted by an intergovernmental meeting of the Governments of a particular region before the programme enters an operational phase. In the preparatory phase leading to the adoption of the action plan, Governments are consulted through a series of meetings and missions about the scope and substance of an action plan suitable for their region. In addition, with the co-operation of appropriate global and regional organizations, reviews on the specific environmental problems of the region are prepared in order to assist the Governments in identifying the most urgent problems in the region and the corresponding priorities to be assigned to the various activities outlined in the action plan. UNEP co-ordinates directly, or in some regions indirectly through existing regional organizations, the preparations leading to the adoption of the action plan. All action plans are structured in a similar way, although the specific activities for any region are dependent upon the needs and priorities of that region.

The Regional Conference of Plenipotentiaries on the Conservation of the Marine Environment and Coastal Areas in the Red Sea and Gulf of Aden was convened in the City of Jeddah, 13-14 February 1982, at the invitation of the Government of the Kingdom of Saudi Arabia by the Arab League Educational, Cultural and Scientific Organization (ALECSO). The Conference adopted the Action Plan for the Conservation of the Marine Environment and Coastal Areas in the Red Sea and Gulf of Aden together with the following two legal agreements:

- Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment; and,[4]

- Protocol concerning Regional Co-operation in Combating Pollution by Oil and other Harmful Substances in Cases of Emergency.[4]

This document is one of a series of UNEP/Regional Seas Programme publications relevant specifically to the Red Sea and Gulf of Aden Regions[5,6,7] and which comes as a first publication of a new series of joint UNEP/PERSGA publications (see Forward).

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1 Mediterranean Region, Kuwait Action Plan Region, West and Central African Region, Wider Caribbean Region, East Asian Seas Region, South-East Pacific Region, South-West Pacific Region, Red Sea and Gulf of Aden Region, Eastern African Region, South Asian Region, Black Sea Region and North-West Pacific Region.

2 UNEP: Achievements and planned development of UNEP's Regional Seas Programme and comparable programmes sponsored by other bodies. UNEP Regional Seas Reports and Studies No.1, UNEP, 1982.

3 UNEP: UNEP-sponsored programme for the protection of oceans and coastal areas. UNEP Regional Seas Reports and Studies No. 135. UNEP, 1991.

4 Regional Convention for the Conservation of the Red Sea and Gulf of Aden Environment; Protocol concerning Regional Co-operation in Combating Pollution by Oil and other Harmful Substances in Cases of Emergency, UNEP, 1983.

5 IUCN/UNEP: Management and conservation of renewable marine resources in the Red Sea and Gulf of Aden region. UNEP Regional Seas Reports and Studies No. 64. UNEP, 1985.

6 UNEP: Action Plan for the conservation of the marine environment and coastal areas of the Red Sea and Gulf of Aden. UNEP Regional Seas Reports and Studies No. 81. UNEP, 1986.

7 HALIM, Y. et al: Regional Review on the State of the Marine Environment in the Red Sea and Gulf of Aden, UNEP, 1989 (Draft)

FORWARD

Since its initiation in 1974, the Red Sea and Gulf of Aden Environment Programme (PERSGA) has been working in close co-operation with related international organizations including UNEP which has supported the activities leading to the convening of the Jeddah Conference of Plenipotentiaries in February 1982, and continues to act in an advisory capacity on matters related to environmental assessment and management in the region.

Within the framework of this long-standing co-operation, and under an agreement between UNEP and PERSGA Secretariat, several projects were completed by institutions and individual scientists in the region in the context of the Red Sea and Gulf of Aden Action Plan.

The present publication is one of the products of these completed projects, supported by PERSGA and UNEP, and is published as a joint UNEP/PERSGA publication. Other similar documents are now being prepared as joint publications to appear in the near future.

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1. INTRODUCTION

1.1 OBJECTIVES

This review has been written in response to the rapid expansion of work on Red Sea reefs over the last two decades, and is an attempt to summarise our present-day knowledge about the kinds of reefs known in the Red Sea, and of their foundations and origins. This review cannot present the detail which is available in the source literature, but is intended to highlight the important literature and provide a useful starting point. One of the main problems of coral reef science in this region has been duplication of work caused by inadequate knowledge of the literature, and it is hoped that provision of such material in this single, summary document can also help to avoid this time-consuming and wasteful practice.

There has been some revision of knowledge in this area within the last two decades, and reviews (mostly biological in emphasis rather than geological) have examined this. Where such reviews exist, these are used as the source material here rather than the body of sometimes much earlier literature. One object of any review is to draw a new "starting line" for its subject matter; in the rapidly expanding scientific knowledge of the Red Sea today, any primary source literature over about 15 years old is likely already to have been assimilated into the body of understanding (or abandoned in many cases), and rarely is there much need to cite volumes of much older references.

Within the Red Sea (Figure 1), some areas have been much better documented than others. The Gulf of Aqaba in particular has been well studied, and to a lesser degree the areas around Jeddah and Port Sudan have been the focus of a reasonable amount of attention. Next, Yanbu in the central region, the Dhalak Archipelago in the far south, and the southern coast of the Arabian peninsula from south of Jeddah to Aden have also been surveyed to various degrees, although sometimes these surveys have been biological rather than geological. Together these add up to a fairly extensive area, but they are by no means comprehensive, and extensive parts of the Red Sea remain almost completely unexplored scientifically. The Gulf of Aden is less well documented, although the reefs of Djibouti have been the subject of some study.

The Red Sea is highly regarded above all else perhaps, for its fringing reefs. However, some of the literature has been misleading in respect to their distribution. Even some fairly recent summaries have remarked that fringing reefs line the entire banks of both sides, but this is incorrect. Fringing reefs are best developed in the northern half of the Red Sea proper and Gulf of Aqaba only, and while they do exist sporadically in the southern half, they are by no means continuous and are commonly weakly developed. The persistent, erroneous impressions derived from the fact that most visits to the region took place north of Jeddah, particularly in the Gulf of Aqaba, and extrapolation to the whole Red Sea was tempting and so perhaps inevitable until much better documentation became available (Sheppard and Wells 1988).

It is now known that the southern half is much more of a sedimentary basin, with gentle bathymetric gradients, seagrasses and mangroves, and is entirely dissimilar to the reef-fringed northern and central parts with their steep bathymetric profiles.

In the mid-1980's, a substantial barrier reef complex in the central section was documented, as were a series of remarkable algal reefs in the southern part, and also at this time the geology of the Dhalak Archipelago was documented in another series of studies. In the last 10 years, the region has emerged, in a marine geological sense, from a condition where more basic surveys were needed to one where a certain amount of synthesis is possible, and it is hoped that this document will help to provide a starting point for this phase.

1.2 IMPORTANCE OF RED SEA REEFS

Coastal coral reef formations of the Red Sea have long been used for recreation sites, sources of food and sources of material for building and crafts. In these respects they have been valuable to small local populations for at least 3,000 years. At the same time, they became known with much less favour to the increasing number of seafaring traders who navigated these reef-strewn waters. As the sea developed into an increasingly important trading and pilgrimage route, problems of unintended encounters with reefs increased too, so that from very early days, reefs of the Red Sea were well known, if not always appreciated. Horton (1987) reviews the human settlement of the Red Sea, and illustrates the importance of coral reef material, for example, in the construction of Port Suakin.

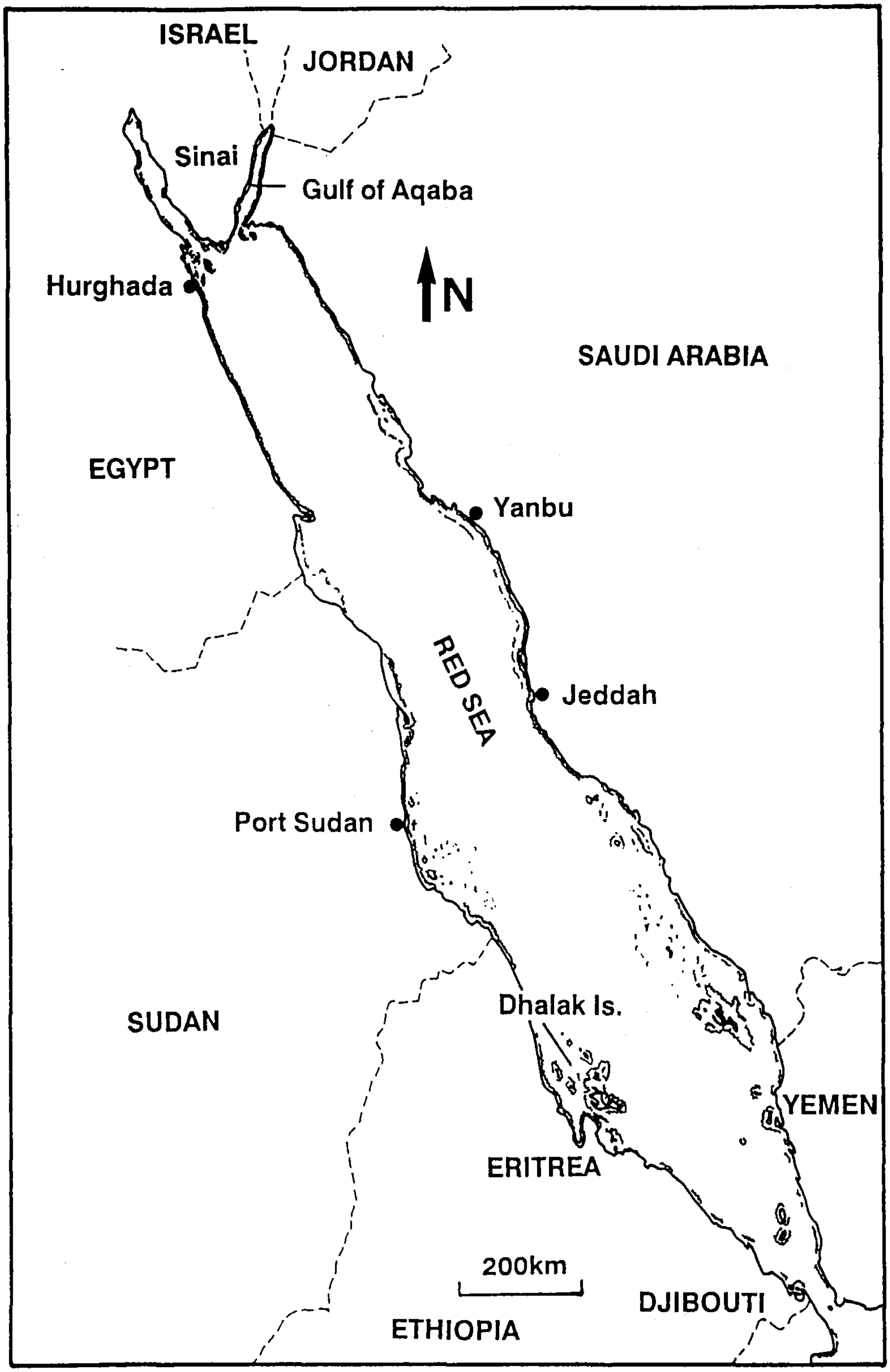


Figure 1: Red Sea and Gulf of Aden, showing major locations of reefs. Hatching indicates most studied areas.

For hundreds of years, reef resources of the Red Sea were used sustainably. There was nothing intrinsically different about the earlier cultures which allowed use to be sustainable, rather it came about from the low density of the populations living along the coasts. In the last few decades, increased population and the resultant increase of activities in the coastal areas, such as urbanization, industrialization and a growing tourist industry, have caused the damage of coral formations in many areas of the world, and the Red Sea is no exception, particularly near its major urban areas. Accordingly, the protection of coral reefs is becoming increasingly difficult, particularly of reefs near human settlements (Stoddart and Johannes, 1978).

New pressures also arise with shifts in human demands. The Red Sea is a major oil tanker route and coral reefs have been threatened by oil spills. Untreated sewage from urban areas, and unrestricted collection of shallow water marine life all add their deleterious effects. Landfill, which selectively encroaches onto reef flats and other shallow water areas, is a greater and still increasing problem. Corniche development along reef flats, landfill which extends municipal and private property, and shallow excavations associated with ports and more importantly perhaps, the provision of landfill material, all destroy reefs more or less permanently.

Despite the strategic setting of the Red Sea, being a link between the east and west, perhaps the main resources of the Red Sea are the coral reefs themselves. As expressed by Bemert and Ormond (1982) the coral reefs of the Red Sea provide a most valuable natural laboratory in which to further our understanding of life on earth. They are also especially beautiful, with highly diverse ecosystems. Their biological diversity, in fact, probably considerably exceeds that of the adjacent lands in an interesting inversion of the usual situation. With proper management, Red Sea reefs promise to be a source of great beauty and pleasure for generations to come.

The economic importance of reefs, where fossil coral reefs serve as reservoirs for petroleum, has been known since the beginning of the petroleum industry in the region. Much of the Middle East is a carbonate province with important hydrocarbon deposits. Reef complexes occur extensively from the Cretaceous and Tertiary, and some of these are coral reefs. For example, the Kirkuk field, Iraq, is a regressive Tertiary reef, with fore reef and a back reef facies; it extends for over 250 miles, ranging in age from Middle Eocene to Miocene.

The Red Sea itself has attracted reef researchers for many years. Many parts of it contain favourite sites for studying the growth of corals and formation of reefs. The Red Sea is characterised by markedly changing environmental conditions which span the entire range, from those which can support vigorously growing corals to those where environmental stresses exceed the tolerances of coral or reef growth. The Red Sea's varied bathymetry also provides excellent opportunities for researching modern carbonate reefal sedimentation.

Comprehensive reviews on ecological research on coral reefs of the Red Sea are given in Mergner (1984), Head (1987a) and Sheppard *et al* (1992). A chapter in the latter reviews available geological knowledge, though this is done mainly to provide a geological background to what is essentially a biological account. Braithwaite (1987) provides a valuable geological overview. Even so, geological aspects of this region have received less attention to date than biological aspects. Other reef geological reviews important to this region, though not necessarily concerned with reefs of the Red Sea specifically, are contained in Hopley (1982), Friedman and Krumbein (1985) and Schroeder and Purser (1986).

2. GEOLOGICAL OVERVIEW OF THE RED SEA

2.1 EARLY FORMATION

Today the Arabian peninsula occupies, more or less, its own tectonic plate (Figure 2), which appears to be a relatively newly separated fragment of the very large African plate. The separation zone is marked by the area of sea floor spreading which passes down the Gulf of Aqaba and Red Sea, through the Gulf of Aden to a point in the Arabian Sea at the Carlsberg Ridge. The Arabian Sea has rotated anti-clockwise relative to Africa by about 7°; the net result is that the Red Sea is widening at the rate of about 2 cm per year due to the associated spreading and rifting, while the Gulf of Aqaba is experience strike-slip rifting (Figure 3). The process of separation has been progressing for about 70 million years, though this has not been smooth or continuous. Episodes of marine sedimentation, vast alluvial flows, and extensive evaporation which left evaporite deposits over a kilometre thick, have all had marked effects on the present Red Sea region. Pauses in the rifting also saw important episodes of volcanic activity, whose remnants form important shallow substrata today. All of these events provide important foundations to today's reefs.

It is likely that the area now occupied by the Red Sea was land for most of the period from at least 600 million years ago (Ma) until about 200 Ma. Much of the rock is pre-Cambrian (the Arabian Shield), and very stable. Marine sediments from this period are found in Jordan, Carboniferous deposits are found on the Gulf of Suez, and in Sinai later deposits also indicate a few periods of submergence. Shales with fossil marine hemichordates suggest that some of eastern Saudi Arabia may have been submerged during this period too. However, these periods of submergence were relatively brief and limited to the margins of the Afro-Arabian continent. At this time the Red Sea depression did not exist.

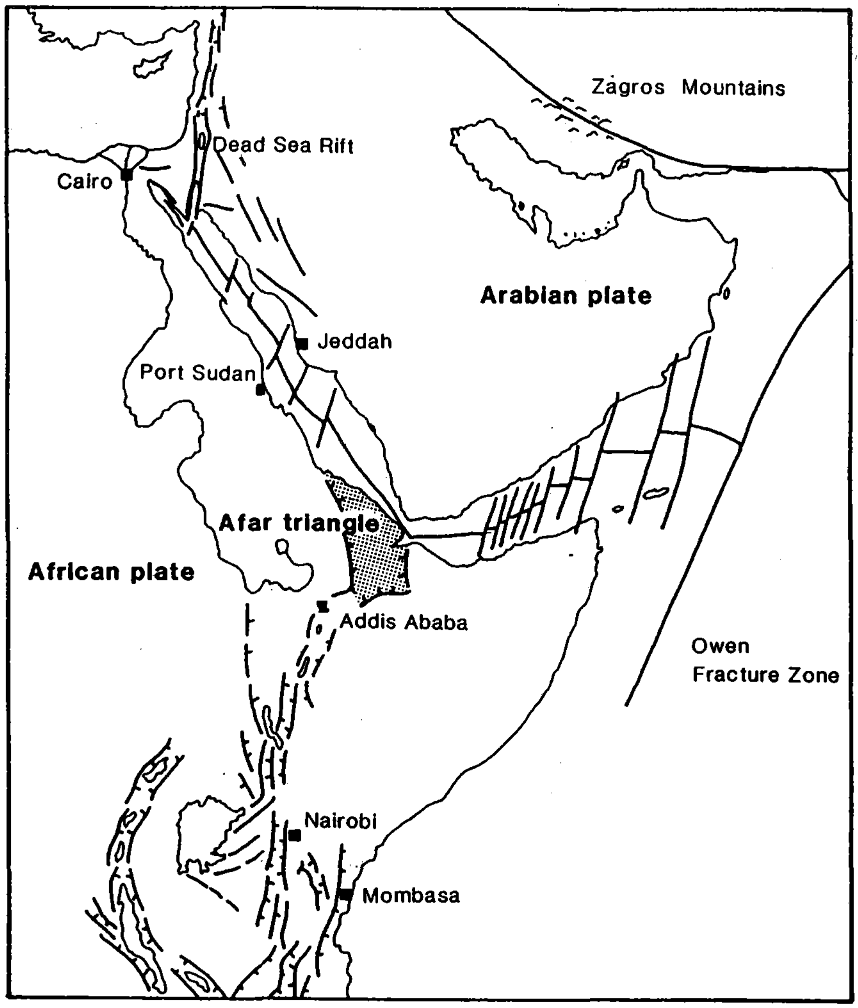


Figure 2: Arabian plate, showing main rifting and movement, and Afar Triangle

Source: Sheppard *et al* (1992).

In the Jurassic, it is thought that much of Arabia may have become submerged, although most of the present Red Sea area probably remained land, (Figure 4), with only the far southern part of the present Red Sea basin area being submerged. If so, a shoreline would have existed along the line of Massawa to Jizan. In early Cretaceous time, marine conditions existed across Sinai, and these marine conditions gradually extended over much of Egypt also, to about the Sudanese border. Towards the end of the Cretaceous, however, waters appear to have receded, leaving dry areas around high parts near the Gulf of Suez. At this time, this sea (the Tethys) also extended along the axis which later became the Red Sea.

The Oligocene is one of the important early stages in the region's history in the present context because of the intense volcanism which occurred. This poured basaltic larvas into the region. In northern parts, such as Egypt and Sinai, and southern parts, such as Yemen and Ethiopia, this sometimes exceed 1 km thick. Today, a chain of volcanic remnants and islands is an important, though fairly small feature of the Red Sea, especially in the south (Figure 5), where they act as substrate to some present day marine habitats, though they have also prevented the development of new fringing reefs (Sheppard 1985a).

This period was also probably a period of marine withdrawal and erosion. Crustal stretching caused the first outline of the Red Sea depression to appear. Faulting and downwarping both probably contributed to the formation of the depression, and during the Eocene and early Oligocene, widening probably occurred at the rate of 1.3 cm per year.

The widespread outcrops of Precambrian rocks on either side of the Red Sea show that there was only minor accumulation of marine sediments over a very long period around the edges of the Red Sea, and this contrasts with the massive accumulation of marine sediments in the rift itself since the Oligocene. Thus it is concluded that the Red Sea basin is lined by Precambrian rock which experienced little submergence, while the Red Sea trough (including the coastal plains) which developed much later, contains considerable marine deposits from the Oligocene onwards.

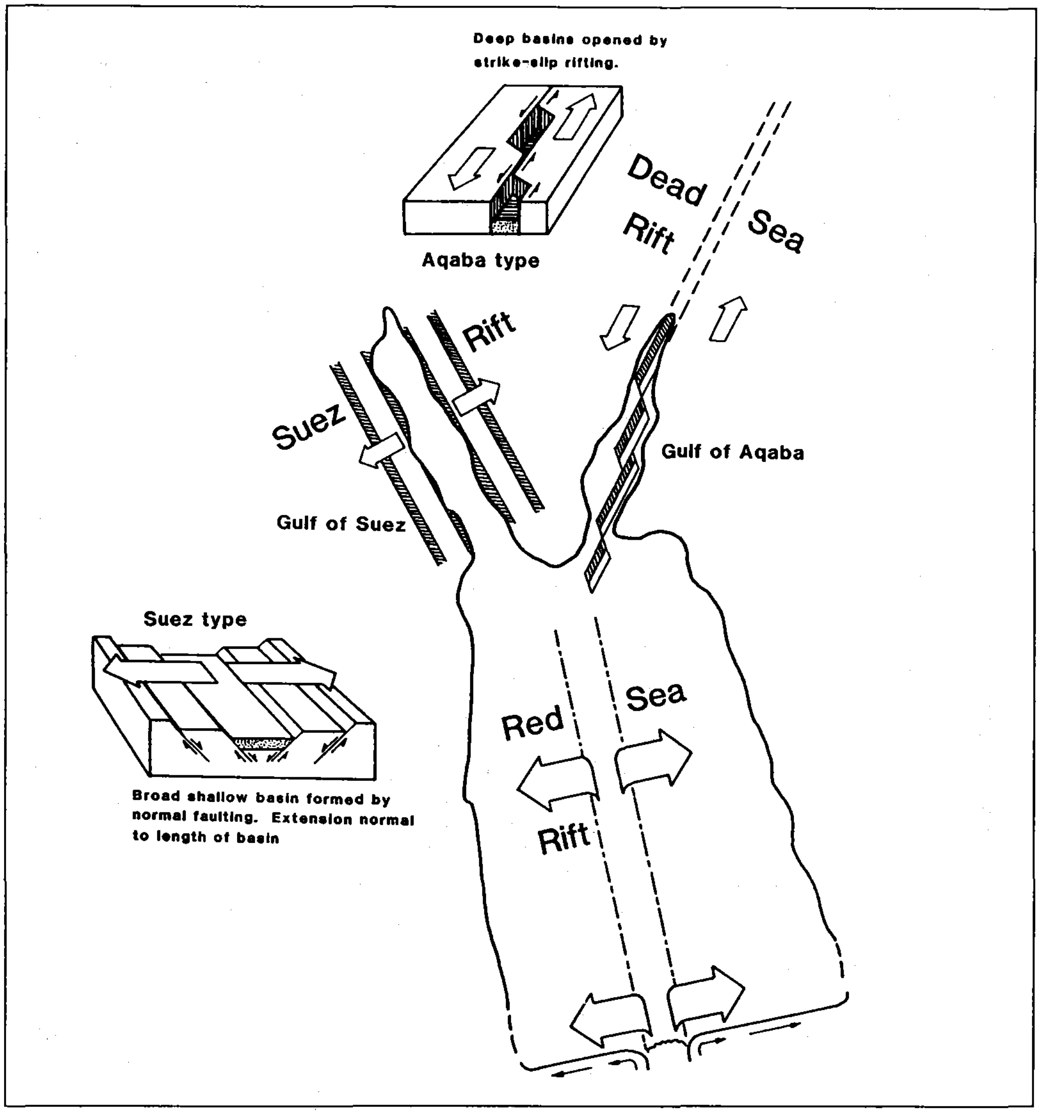


Figure 3: Tectonic framework of north Red Sea

Source: Friedman (1985)

Some of these deposits are salt deposits. These are widespread, from the Gulf of Suez to at least the Dhalak Archipelago. One example in the latter is 3.8 km thick, though commonly their lateral extent is not great and lateral thinning occurs. The northern deposits appear not to be as thick, but reach to nearly 1 km. These salt deposits are relatively mobile, and flow upwards, partly forced up by the denser, younger rocks which have accumulated on top of them, a process accelerated by the high temperatures found in the rocks of this region, which reach up to 180°C at depth (Braithwaite 1987). These salt diapirs, now rising, are important today.

The formation of these salt deposits from the Miocene required enormous evaporation. The fauna of the sea at that time was Mediterranean rather than Indian Ocean in character, and much is typically of shallow water type. The basin is likely to have become substantially isolated, and continuous evaporation and replenishment with sea water continued for a long time, maintaining water at salinities which allow sulphates and halites to deposit, but without total drying out. The evidence strongly suggests a shallow water environment, rarely drying out completely, but experiencing prolonged and intense evaporation. This possibly occurred over about 30 Ma during which time widening largely ceased, and it led to the thick deposits which now underlie much of the Red Sea and which are important to present surface features, including reef distribution.

About 5 Ma ago, widening began again at nearly 2 cm per year. This divided the existing deposits, and new seawater incursions promoted the deposition of sediments which covered the Miocene deposits. More recently still, connection occurred with the Indian Ocean, which introduced the Indian Ocean coral reef building biota too. This connection may not have been permanent due to substantial sea-level changes, but the biota of the Red Sea, unless extinguished temporarily, has been entirely Indian Ocean in nature ever since.

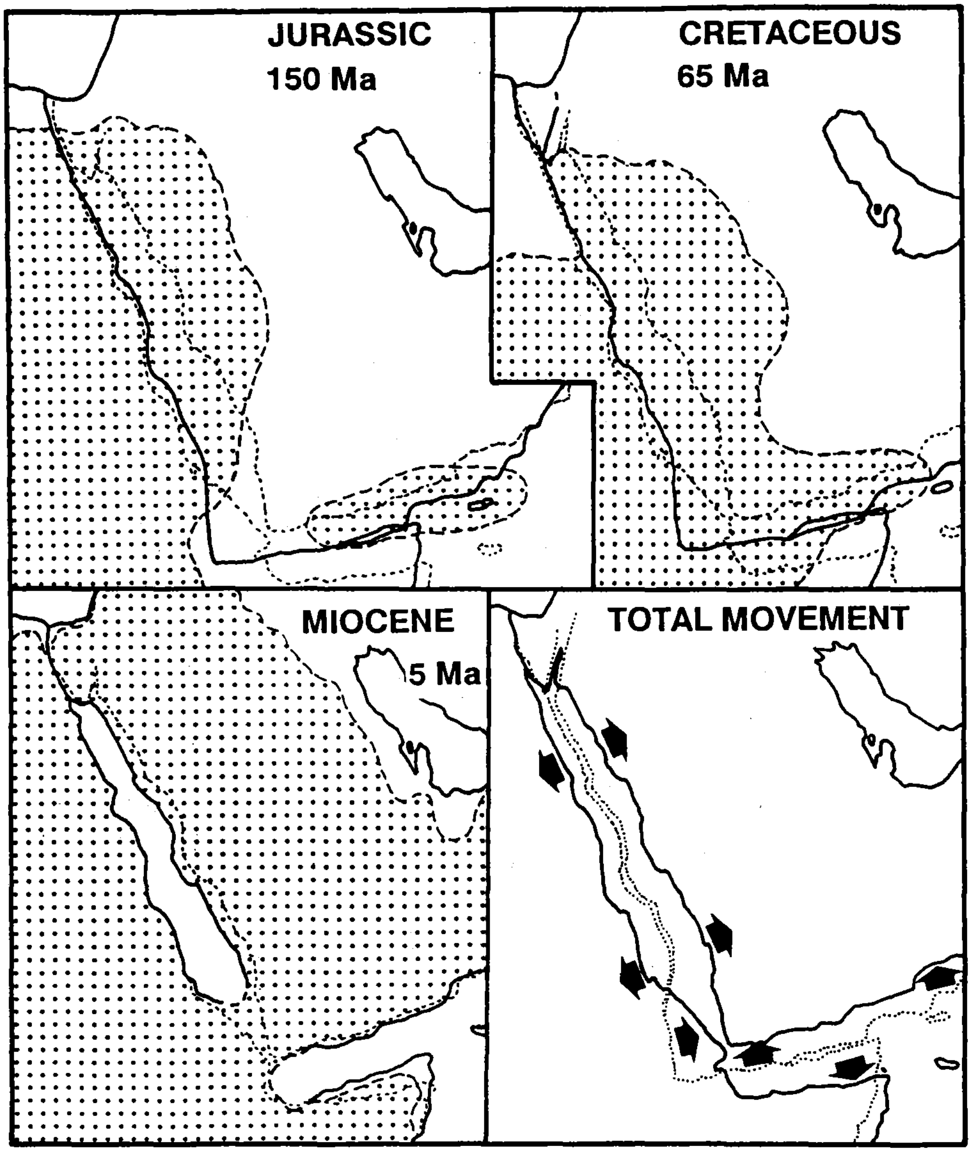


Figure 4: Palaeogeography of Red Sea in Jurassic, Cretaceous and Miocene Periods

Source: Braithwaite (1987)

In the Pliocene and Pleistocene, very different sediments were deposited over the older salt deposits. In part this was due to the connection now formed with the Indian Ocean and the removal of the connection with the Mediterranean. The latter was caused, probably, by gradual uplift in the Gulf of Suez area. The new sediments are found throughout the length of the Red Sea, and important components include shells of foraminifera and pteropods, and coccoliths. There is a substantial component of particles weathered from metamorphic rocks also, whose presence is not explained, and appreciable volcanic debris too, indicating the importance of continuing volcanic activity in the trough. The total thickness of the deposits from this much shorter time span is up to 300 m in several places, and nearly 1 km in some southern parts including the area of the Afar triangle.

Additional, substantial deposits from this time are those derived from alluvial flow at times of heavy rain. These deposits are the products of erosion of the surrounding hills, and in some places these deposits are 300-400 m thick. At the same time, reef growth occurred and, as described in more detail later, episodes of reef growth and alluvial flow sometimes alternated to produce vertical layers of each. Seismic investigations (see Braithwaite 1987) suggest that reef complex limestones deposited between the Pleistocene and today reach 200 m thick, and that these rest on the eroded Pliocene and older deposits.

Much of the detail is summarised by Table 1.

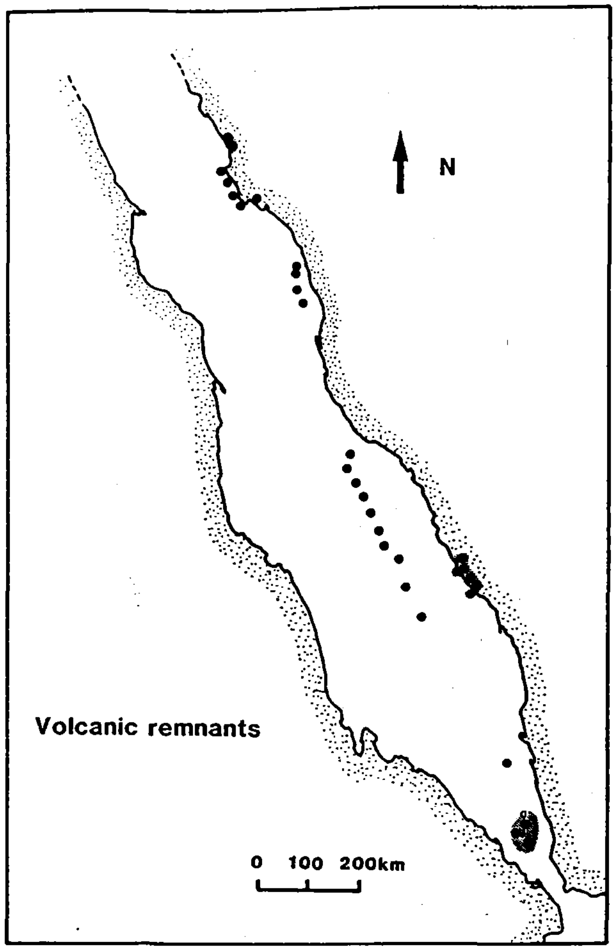


Figure 5: Location of important volcanic islands and coastal structures

Source: Sheppard *et al* (1992)

Table 1

Summary of geological events important to present Red Sea reef formation and distribution.

Age (Ma)	Period	Geological features relevant to present Red Sea reefs.
0 - 0.015	Holocene	Rise in sea-level from -135 m to present level. Growth of modern veneer of coral reefs on older foundations.
0.015 - 2	Pleistocene	Extensive sea-level fluctuations, mostly at -30 to -80 m below present sea-level. Substantial rain, karst formation and alluvial flows, with reef growth on shallow platforms; two reef growth phases in southern Archipelagoes. Uplift of older fringing reefs at margins, forming "terraces".
2 - 5	Pliocene	Rifting recommences, splitting earlier marine deposits. Connection with Indian Ocean, disconnection with Mediterranean. New Indian Ocean tropical deposits, including reef growth, alternating with large alluvial flows.
5 - 24.6	Miocene	Red Sea basin constricted, but not completely cut off. Substantial evaporation continues, producing salt deposits over 1 km thick. Widening stops.
24.6 - 38	Oligocene	Intense volcanism, creating basaltic larvas over 1 km thick. Marine withdrawal.
38 - 55	Eocene	Crustal stretching, widening at up to 1.3 cm/year, faulting and downwarping.
55 - 65	Palaeocene	Rifting commences.
65 - 144	Cretaceous	Red Sea depression starts. Tethys Sea covers Sinai and Egypt, and extends along newly developing Red Sea trough.
144 - 213	Jurassic	Present Red Sea area mostly land, though most Arabia is submerged, producing a shore line from Massawa to Jizan.
213 - 248	Triassic	
248 - 590	Permian - Cambrian	Area mostly land. No Red Sea rift. Some marine deposits in northern regions.
over 590	Precambrian	Arabian Shield made, which now surround Red Sea depression, and provides later gravel and sand deposits.

Source: Sheppard *et al* (1992)

2.2 IMPORTANT QUATERNARY EVENTS

During the early Quaternary, extensive carbonate depositions developed on the earlier formations outlined above, and provide the immediate foundation to the present living reefs. Two series of events are especially noteworthy:

(1) Quaternary climatic changes which particularly include sea-level changes and periods of heavy rainfall, and

(2) Uplifting along the margins of the Red Sea and in sections in the south.

Both of these series of events have had profound effects on present day reef substrate and positions.

Quaternary Climatic Changes

Two Quaternary climatic features are important to the present discussion. The first is the pattern of substantial changes of sea-level which occurred.

Two possible sea-level curves relevant to this region are shown in Figure 6. Between about 30 and 110 thousand years Before Present (BP), oscillations ranged from between -80 m to the present level. As with any coral sea, carbonate deposition occurs at, and just below, the existing sea-level. Thus, substantial limestone reef deposits developed at various intervals and depths, fringing the shores, around older volcanic intrusions, and on offshore areas of uplift which were shallow enough at the time. During the Pleistocene, therefore, much of the area which is currently between the surface to as deep as 100 m or perhaps more, was suitably placed for coral reef growth. Many of the features observed today, such as the barrier reef in the central Saudi Arabian section, are best explained by reference to huge limestone deposits which developed during this time.

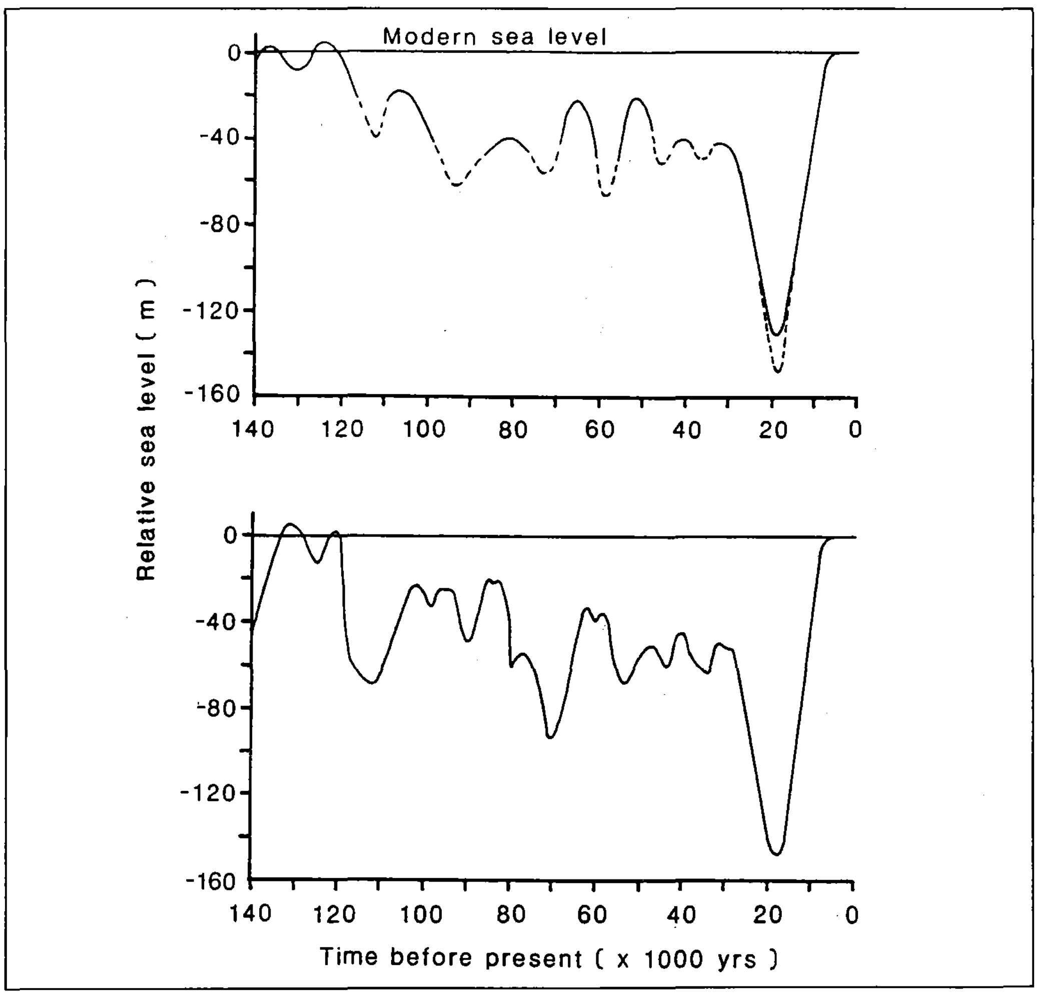


Figure 6: Sea-level curves in relation to time

Source: Sheppard *et al* (1992)

The second notable climatic feature was increased rain and alluvial flow. The effects of this had three aspects.

The first aspect of the extensive rain was direct solution. Solution caused important karst erosion of the emerged limestone. Braithwaite (1982) suggested that off Sudan, solution pits reaching 50-60 m depth were sculpted. Such pits also explain the "blue holes" including the well explored example in the Gulf of Aqaba, and karst erosion also explains several topographical features of present reef complexes seen throughout the Red Sea. In addition, they form important traps of recent sediments.

The second aspect was erosion from the increased alluvial flow. Extensive erosion occurred during several intervals, but when it occurred during the periods of lowest sea-level, it cut gullies through the elevated reefs down to the contemporary sea-level or possibly slightly deeper. This is the origin of many of the wadis or sharms seen today, and several examples demonstrate this process (Figure 7). The floors of these sharms are submerged again today, following the substantial sea-level rise to its present level.

The increased alluvial flow also caused extensive sheets of terrigenous material to flow into the sea, and this leads to the third important consequence of the increased rains. The large alluvial flow of this period caused substantial deposition of terrigenous matter in the Red Sea. Existing reefs were covered and killed, and the terrigenous matter formed a substrate for renewed reef growth in later episodes of higher sea-level. Only recently has the extent to which reefs can develop on mobile, loose substrate been fully appreciated, and that this occurs in the Red Sea is seen in several examples.

Said (1969) observed that the Pleistocene deposits of the Red Sea coastal plain include thick emergent sections made up of alternating beds of massive coral reefs and gravels. Akkad and Dardir (1966) described the presence of four coral reefs alternating with gravel beds along the Egyptian coastal plain. A similar succession is also recorded from the Sudan Coastal plain by Carella and Scarpa (1962) and in the coastal plain between Jeddah and Yanbu by both Behairy (1983) and Fugro (1977) (Figure 8).

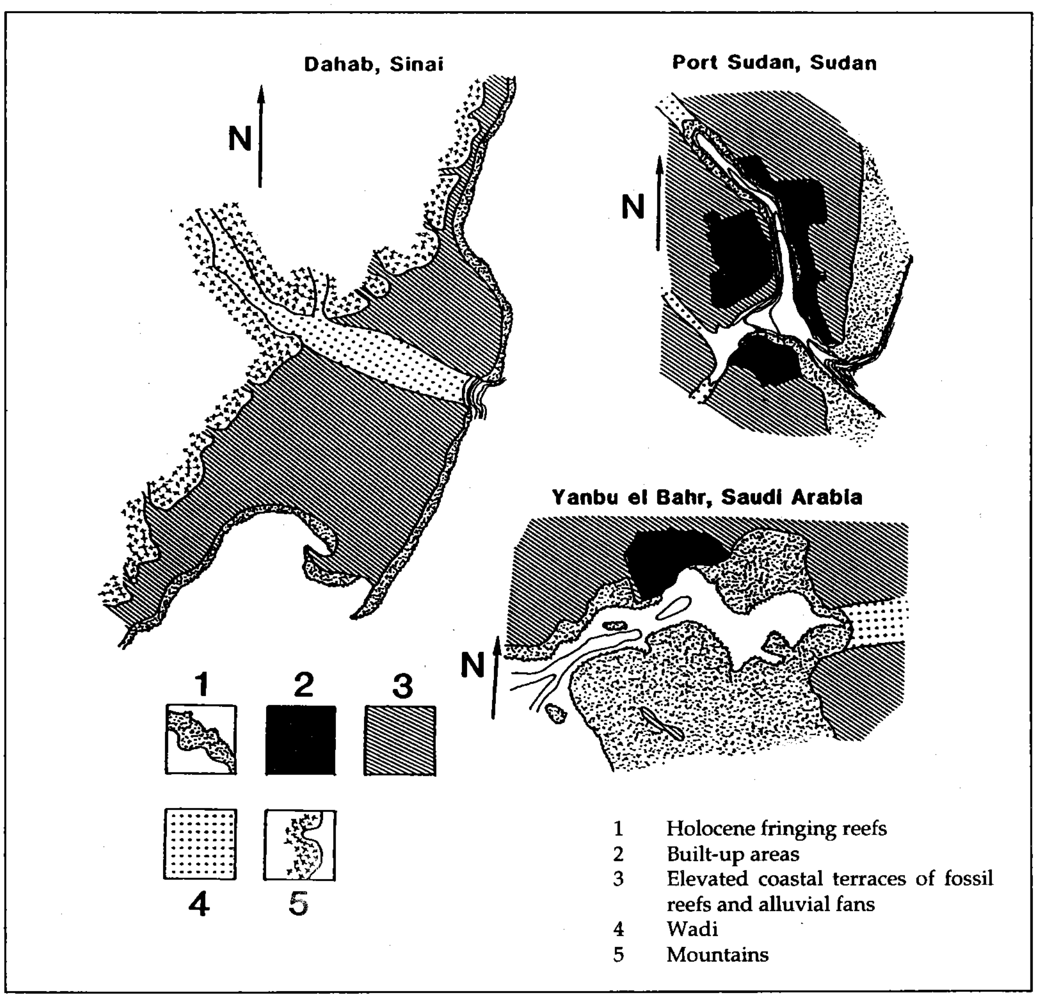


Figure 7: Sketches of three typical wadis, showing erosion patterns

Source: Sheppard *et al* (1992)

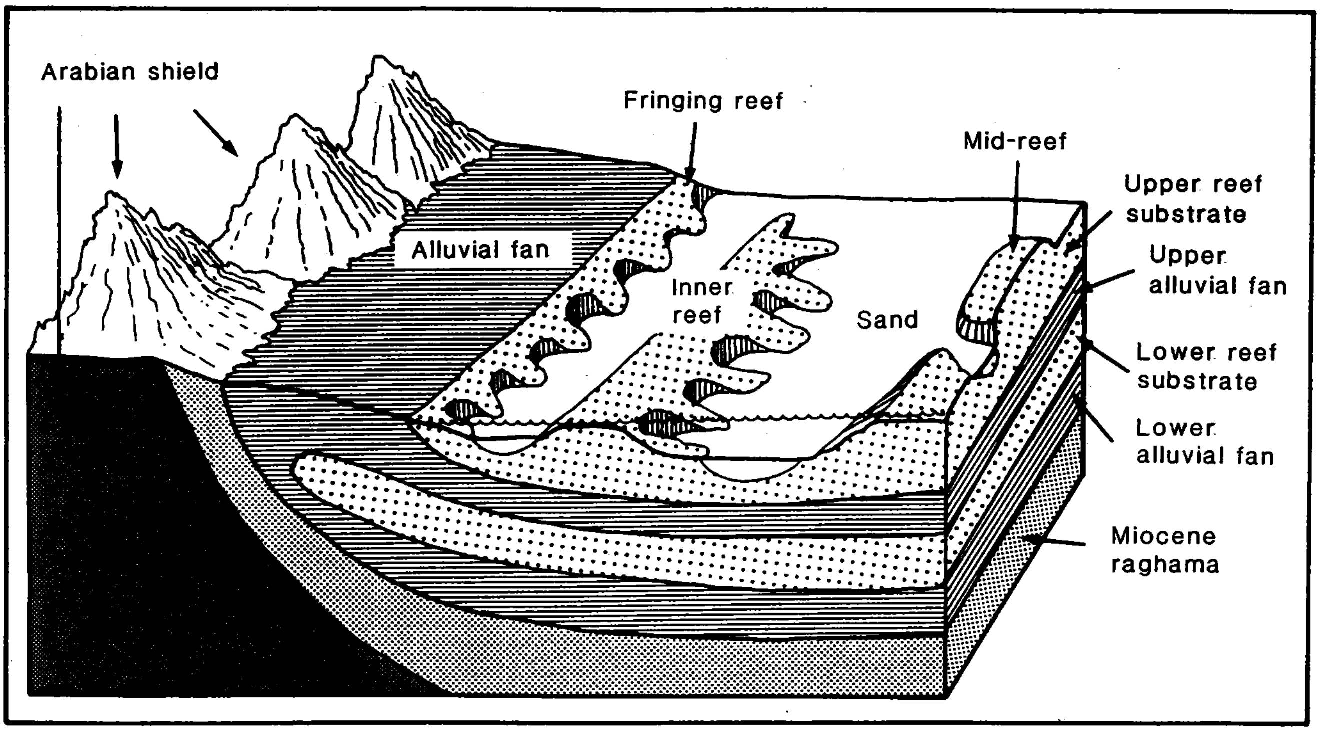


Figure 8: Section through alternating reefs and alluvial matter near Yanbu, Saudi Arabia

Source: Fugro (1977)

In summary, the period of 30-110 thousand years BP saw at least eight periods when sea-level was 30-60 m below present level, when reef accretion proceeded vigorously. The alternating episodes of submergence and renewed growth, and of erosion, had a substantial shaping effect, and this period has considerable immediate significance to reef distribution, thickness and lateral extent in the Red Sea.

Uplifting of Red Sea Margins

Several authors have noted series of terraces along the margins of the Red Sea. Earlier, some assumed that these were wave cut terraces, cut in times when sea-level was higher than today. However, Holocene sea-level is now believed to have risen only slightly above present levels, perhaps only 1 metre if at all, and it is likely that the terraces are uplifted sequences of fringing reefs.

Several series have been reported, shown in Table 2.

These series of raised reefs are one of the most striking features of the coastal plains of the Red Sea coastline. Even on the same shoreline, however, the heights vary appreciably. Some writers have felt that this lack of apparent conformity means that it is premature to attribute particular events to the uplifting pattern, but given the fact that these sequences are sometimes separated horizontally by over 1000 km, it is not surprising that the exact heights of the sequences differ. Figure 9 illustrates one of the sequences.

Additional support for direct uplift being the cause comes from the fact that the dates of the reefs sometimes places them as being older than the large sea-level changes which might have caused them. For example, in Series 1 (below), the highest fossil reef pre-dates both the regression and transgression, the middle reef terrace grew at the time of minimum sea-level and the lowest reef grew during the transgression.

Beneath present sea-level, in contrast, there are several series of wave cut terraces to depths of 60 metres. In addition, it has been suggested (Sheppard *et al* 1992) that many of the offshore patch reefs and the barrier reef are based on limestone surfaces, now at about 30-60 m deep, which were planed by waves.

Table 2

Elevations and dates of series of emerged fringing reefs.
k = thousand years. Heights in metres

Central Red Sea Saudi Arabia (1)		Gulf of Aqaba (2)	Gulf of Aqaba (3)		Gulf of Aqaba (4)
Height	**Age (Ka)**	**Height**	**Height**	**Age (Ka)**	**Height**
1	9.98				
		2.5			
3	18.1				
3	16.6				
			5-10	108-140	8-10
10	31				
		12.5			12-13
			15	140-200	
					15-17
		17			
					25
			30-35	>250	

(1) Behairy (1983)
(2) Dullo (1984)
(3) Klein *et al* (1990)
(4) Al-Sayari *et al* (1983)

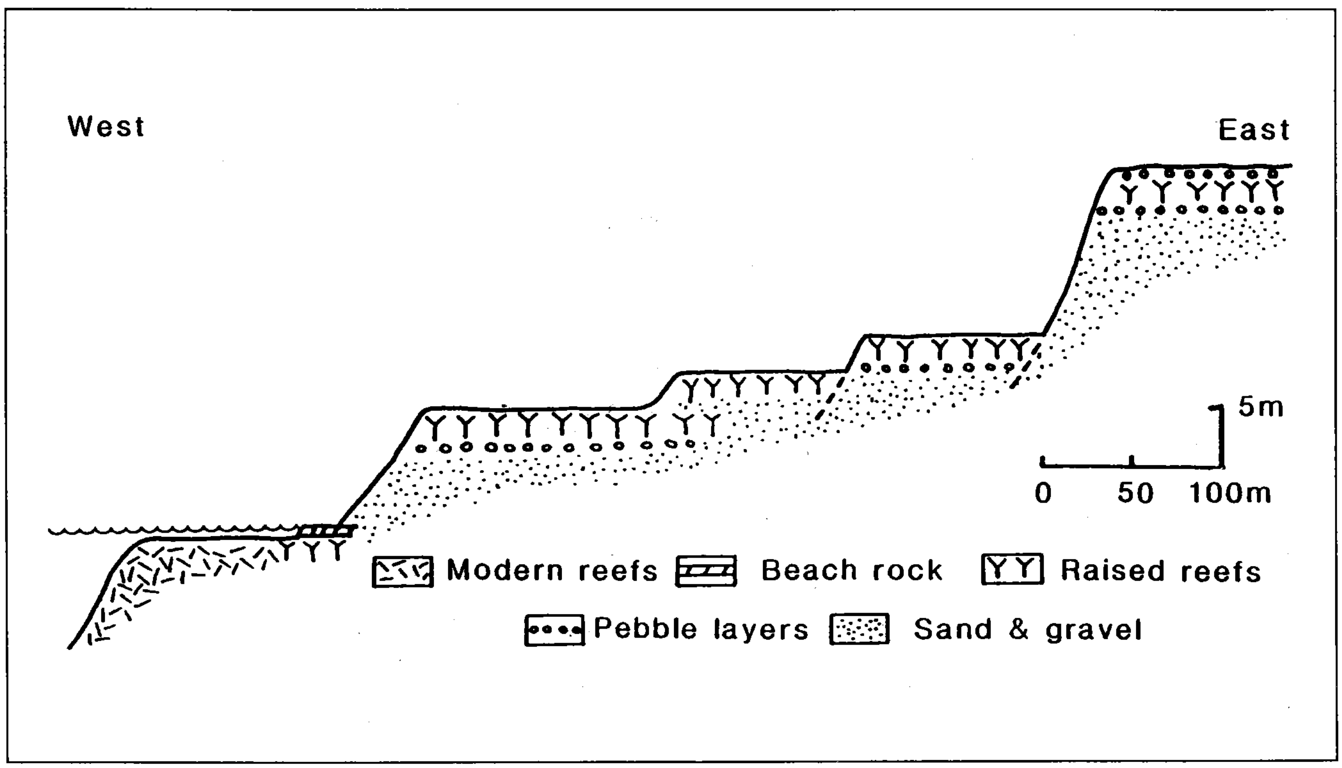


Figure 9: Sketch of series of uplifted reefs in Gulf of Aqaba

Source: Al-Sayari *et al* (1984)

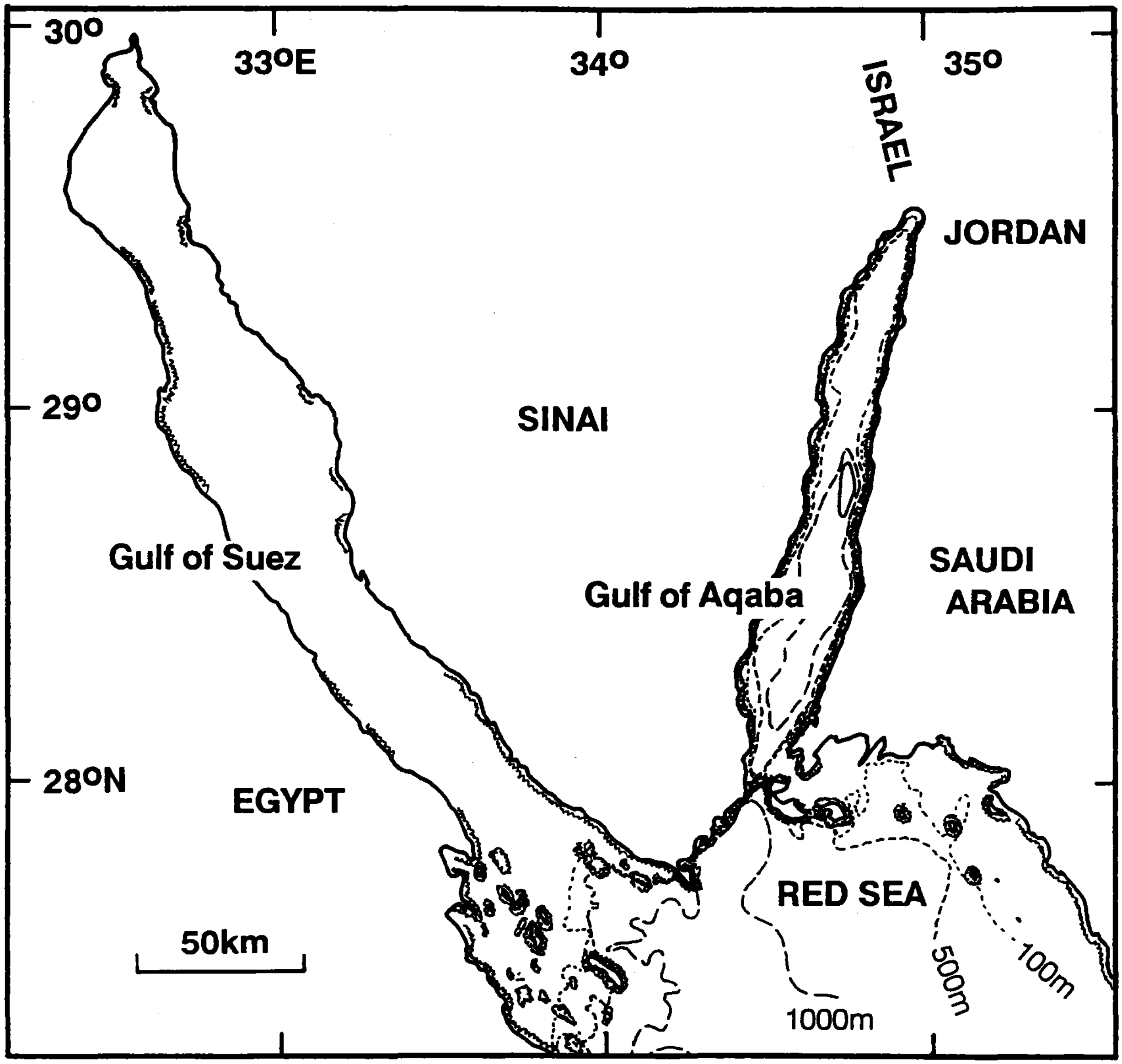


Figure 10: Reefs of the Gulfs of Aqaba and Suez

Modern reefs therefore are probably fairly thin films, grown during only the last 6-8,000 years, based mainly upon these older reef structures. While their present development and accretion owes much to this Quaternary history, it also is greatly influenced by present day oceanographic conditions in the Red Sea.

2.3 THE PRESENT CONDITION

The Red Sea is bounded by mountains throughout much of its length, set behind a narrow coastal plain. The mountains are not fold mountains, but are the product of uplift of the margins of the rift. The mountains reach their highest in Ethiopia where elevations reach 3,000 m and in the south Saudi Arabian - Yemen region where they reach 3,700 m (Braithwaite 1987). The greatest variation is near Port Sudan, where the escarpment exceeds 2,000 m and nearby brine pools at the bottom of the trough are 2,341 m below sea-level.

The result today is that the Red Sea is a narrow but deep oceanic trough (rift valley) extending for over 2,000 km, between Latitudes 13° and 28° N. In the north, the Red Sea is 180 Km wide and widens to about 350 km in the south. Further southward, it narrows to about 28 Km in the strait of Bab el Mandeb where it joins the Indian Ocean through the Gulf of Aden. At its northwestern extremity, the Red Sea bifurcates into the Gulf of Aqaba, which is the continuation of the rifting process, and the entirely different Gulf of Suez which extends northwest (Figure 10). The latter has a completely different geological character, occupying a wide valley bordered by plains with low relief. It appears to be spreading also, by normal faulting.

At its southern extremity, the Red Sea is at its shallowest, despite the fact that separation due to the Arabian plate rotation is considerable in this part. The depth near the entrance is only 130 m. This is due at least partly to the fact that the older, underlying salt domes, described earlier, are pressing upwards, leading to a general shallowing and also contributing to the formation of the Dhalak and Farasan Archipelagoes.

This formation is reflected in the bathymetry (Figure 11). This shows shallow reef-studded shelves of less than 50 m, followed by narrow marginal shelves of varying depth (100-500 m). A useful division by Head (1987b) quantifies this bathymetric profile (Table 3).

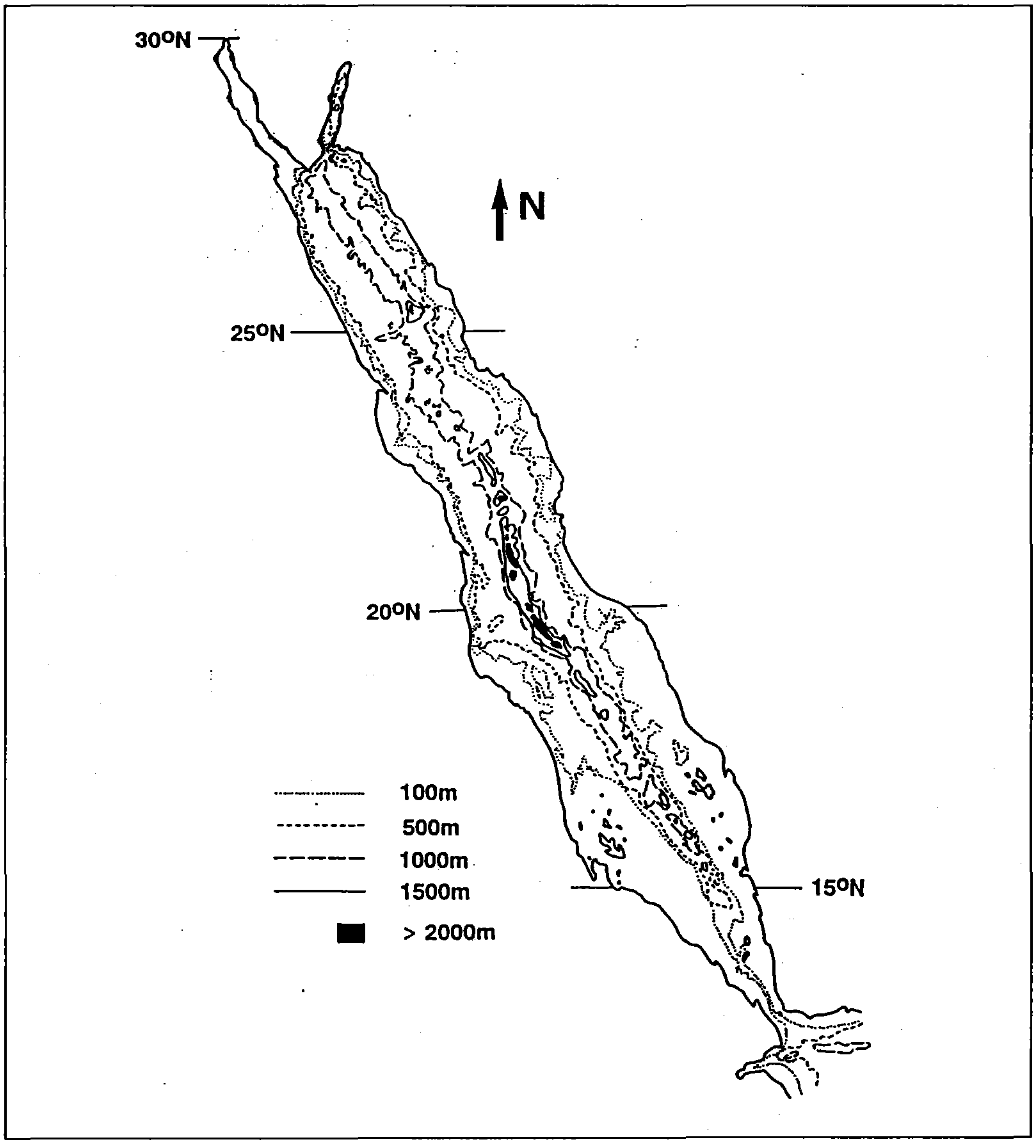


Figure 11: Major bathymetric profile of Red Sea

Table 3

Distribution of depth in the Red Sea

Depth Range (m)	Area as percent of total (%)
0-50	23.86
50-100	17.27
100-500	15.71
500-100	20.06
1000-1500	11.64
>1500	2.46

Source: Head (1987b)

The distinct main trough of the Red Sea is about 1,000 m depth, extending from the Zubayr Islands to the Southern tip of the Sinai Peninsula. The deeper or central part of this formation is the axial trough (maximum width 30 km, near 20°N) which reaches depths of about 2,000 m. The deepest parts along the axial trough form a series of isolated basins or deeps. According to Coleman (1977), selected topographic cross-sections reveal steep sided walls in the axial trough and a very irregular bottom topography.

The Red Sea may be viewed therefore as a great elongated depression which cuts across a huge dome of Precambrian basement rocks (Arabian-Nubian massif) flanked by epicontinental material of Miocene and younger age (Said 1969) and marine sediments (Picard, 1939). Relatively recent geologic maps by Said (1969) illustrate the pattern seen today (Figures 12 and 13).

It is notable, that the opposite sides of the Red Sea form an almost perfect "fit" with each other. This is unlike most seas, and is clearly the result of the rifting and widening. This fit is clear in the northern two thirds of the Red Sea, but in fact the fit is good in the south too when it is realised that the Afar Triangle, see Figure 2, is for the most part below sea-level, is volcanic, has major basaltic intrusions, and appears to be a section of oceanic sea floor which has substantial marine deposits upon it which reach nearly 1 km thick. If this part of oceanic floor was flooded, the correspondence between the two shores of the Red Sea would be extremely close in the south also. The importance of this area of land in the geological history of the region is noted as early as Wegener (1929) who considered the fit when developing his theory of continental drift.

3. CLIMATE AND OCEANOGRAPHY AFFECTING REEF GROWTH

3.1 WINDS AND RAINFALL

Winds, particularly those of storm strength, have controlling influences on the direction and extent of reef growth, and consequently are important in any discussion of carbonate geology. Red Sea climate and oceanography are extensively reviewed in Edwards (1987) and Sheppard *et al* (1992), and the key points are summarised here.

In winter two air flows exist; one from the Mediterranean flowing down the Red Sea axis to the central region, and one from the Arabian Sea flowing up the axis (Figure 14). These two meet in a region of low prevailing winds in the middle, and both flows are potentially rain bearing. In summer, prevailing air stream flows down the entire length of the Red Sea, but in this case it is part of an anti-clockwise circulation based over Arabia and Iran, and hence is not potentially rain bearing.

Several papers list rain data from cities in the region, sometimes tabulating it at great length (e.g. Crossland *et al* 1987) but all show very low values, and these annual totals, which average about 50 mm, are of little consequence. Much more important is the fact that the annual totals are usually deposited in a few hours, causing flash floods and enormous terrestrial run-off. This maintains alluvial fans, which may kill coral reefs. Only very rarely does the fresh water itself affect the growth and location of reefs, as can be inferred from the fact that most wadis or sharms contain reefs within them and at their mouths. This contrasts with earlier times when rainfall was much greater than it is today.

Probably more significant to placement and development of reefs are the daily temperature-induced sea breezes which build up in the summer to considerable strength, and which drive important high energy wave conditions. Their effect is most noticeable in the alignment of the reefs, whose general tendency to grow into prevailing waves makes them angle outward towards the waves wherever there is suitable shallow foundation for them to do so. Apart from occasional storms, these winds are the strongest experienced in the Red Sea and in the central part they induce a median wave height of 0.6 m along the unprotected outer edges of the barrier reef (Georeda 1982).

3.2 CURRENTS AND SALINITY

Surface water currents in the Red Sea are driven partly by these winds and partly by a density gradient which is established by heating and evaporation. Briefly, water entering the Red Sea from the Bab el Mandeb drifts northwards. The winds and high air temperatures result in evaporation of 1-2 metres per year, and this causes salinity to rise from about 38-39 parts per thousand (ppt) to as much as 42 ppt at the Gulf of Suez. These salinities are not in themselves limiting to coral or reef growth. However, the increasing salinity causes a small increase in water density.

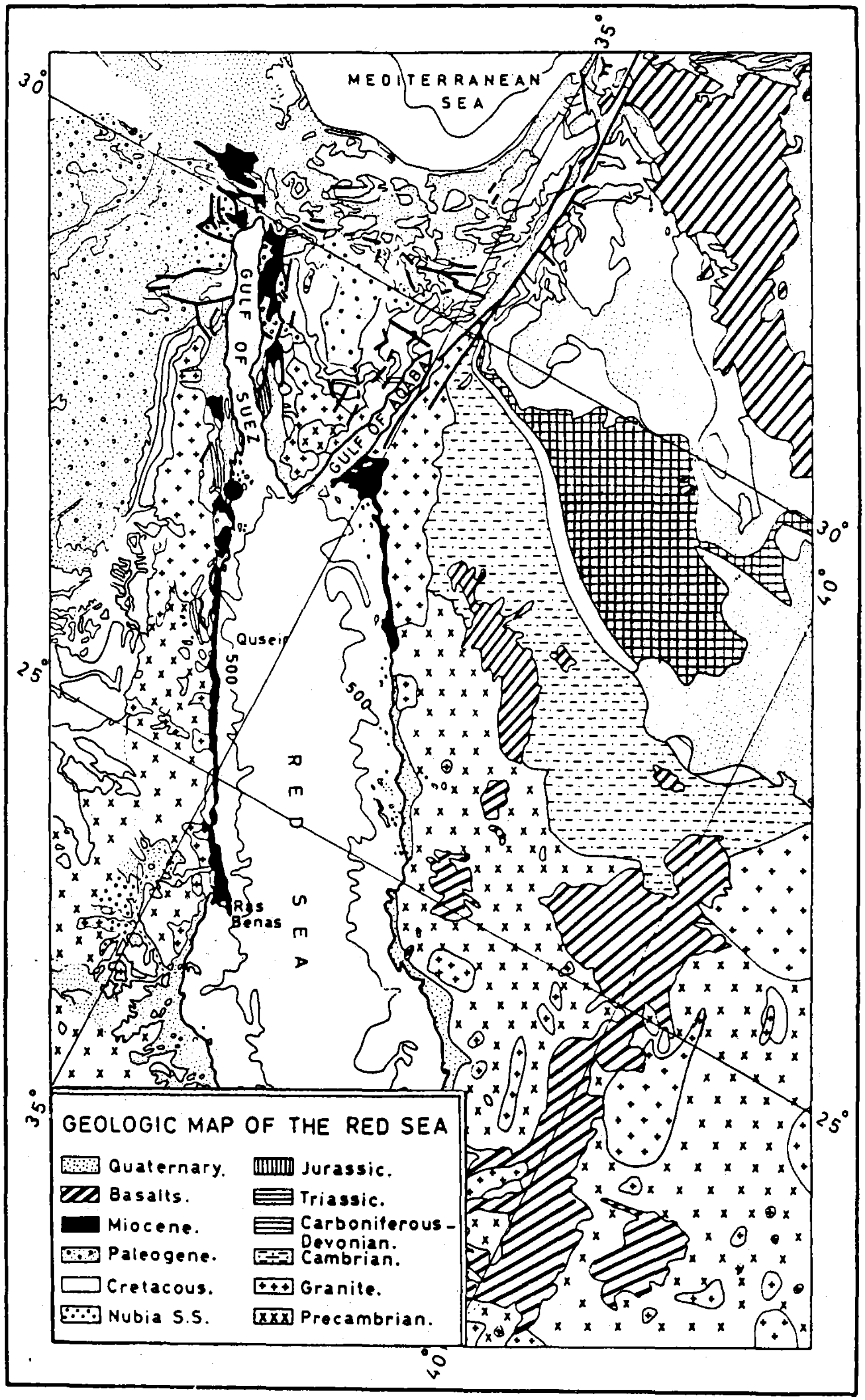


Figure 12: Geologic map of north and central Red Sea

Source: Said (1969)

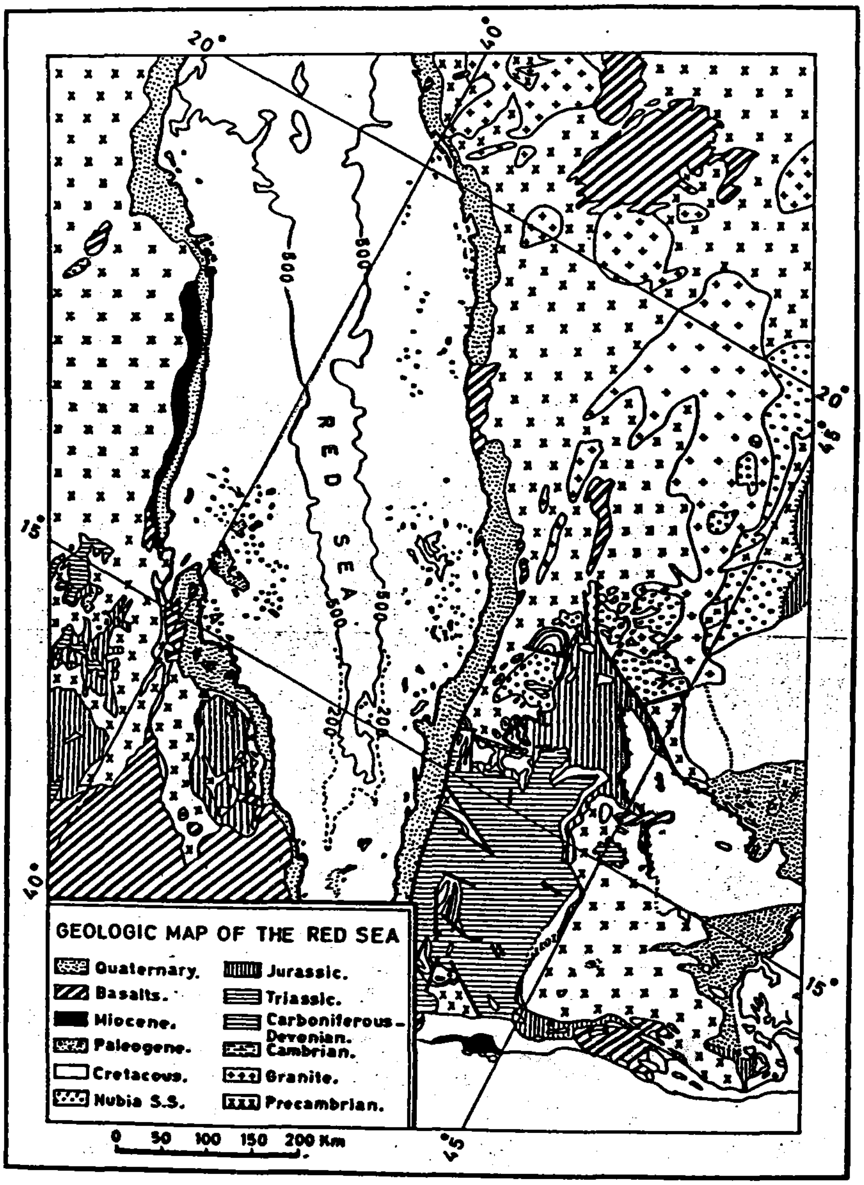


Figure 13: Geologic map of southern Red Sea

Source: Said (1969)

Winter cooling in the north, particularly in the Gulf of Suez, together with a possible addition of more salt from old salt deposits in the Gulf of Suez, further increases the seawater density, causing it to sink, turn underneath the northwards flow, and return southwards at depth (Figure 15). This "Suez Overfall" is probably the main key to circulation in this almost land-locked sea, as well as the main mechanism for water exchange with the Indian Ocean.

The consequences of this to reef geology or location are difficult to identify. Certainly the speed of the current itself has little effect. The evaporation and increasing salinity likewise seem to have little consequence; it has long been noted that both reef development and coral diversity are greatest in the north. However, the incoming water is relatively rich in nutrients, and this is likely to affect the southern region. It is known that reef development is retarded where nutrients are elevated. Values of dissolved nutrients are 3-10 times greater in the southern part of the Red Sea than they are in the north, and this may have contributed to the poor reef development seen in the south.

The temperature of the surface sea water in summer exceeds 31°C, while it varies from between 26.5°C and 24°C in winter, except for the Gulf of Suez, where temperatures commonly fall below 20°C in winter. As with salinity, temperature does not appear to have much controlling effect on reef development or growth, except in the northern Gulf of Suez, while high temperatures are important only in a few ponded areas with restricted water exchange, in summer.

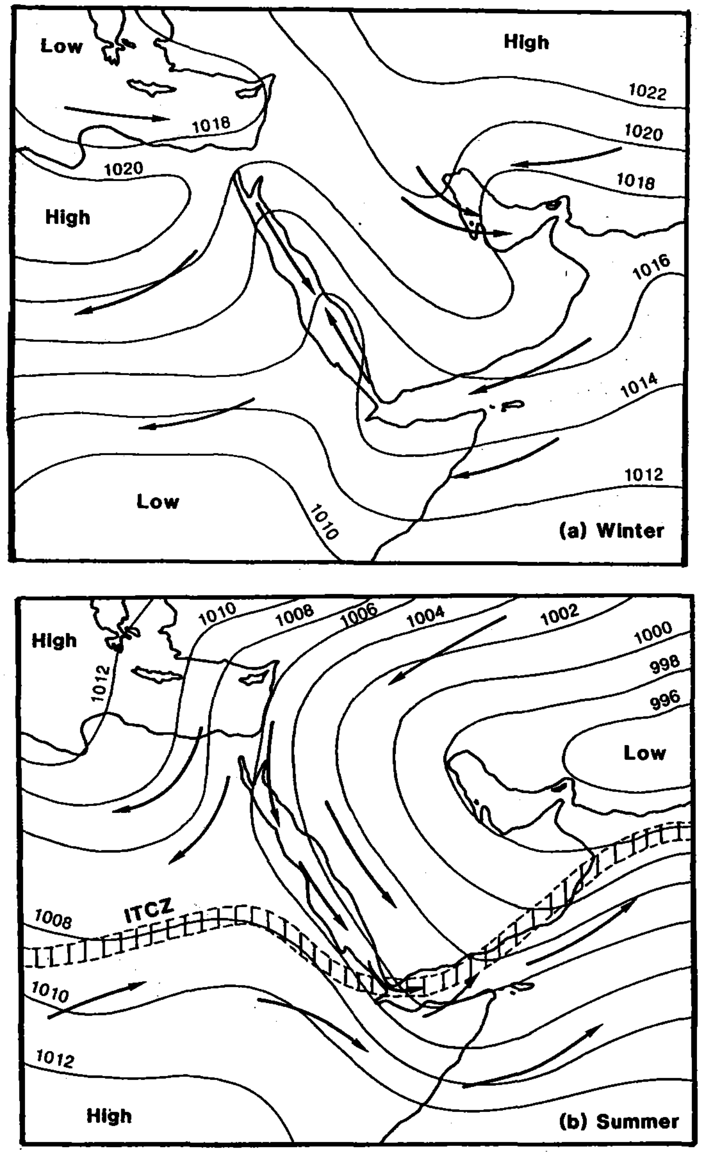


Figure 14: Winter and summer winds affecting the Red Sea (ITCZ = Inter-Tropical Convergence Zone)

Source: Sheppard *et al* (1992)

3.3 TIDES

Tides in the Red Sea are unusual. Morcos (1970) and Edwards (1987) describe the now well known oscillatory condition whereby the central part at latitude 20-21°N has almost no daily difference in tidal height but where the sea-level in the northern and southern ends oscillate, showing daily tidal differences whose range increases with distance from the central region. These ranges reach up to about 0.6 m in the north and 0.9 m in the south, but these are spring tide ranges and greater than the average. They are generally referred to as daily tides because they are a complex composite of both diurnal and semi-diurnal tides. The Gulfs of Suez and Aqaba continue this trend, and experience daily tides of 1.5 and 1.2 m respectively.

Superimposed onto this in the Red Sea is a seasonal tide of at least equal importance. In winter, mean sea-level is over 0.5 m higher than it is in summer. In the central region where there is no daily tide, this is therefore the only true tide. The change from winter to summer sea-level occurs fairly abruptly, over less than a month both in the spring and early winter. The mechanism causing this seasonal change is partly due to the greater evaporation in the summer, but is mainly the result of wind driven currents in the entrance to the Red Sea. The surface current in the Bab el Mandeb flows into the Red Sea in winter, and out of the Red Sea in summer, and this appears to be the balancing factor determining the seasonal rise and fall (Sheppard *et al* 1992) (Figure 16).

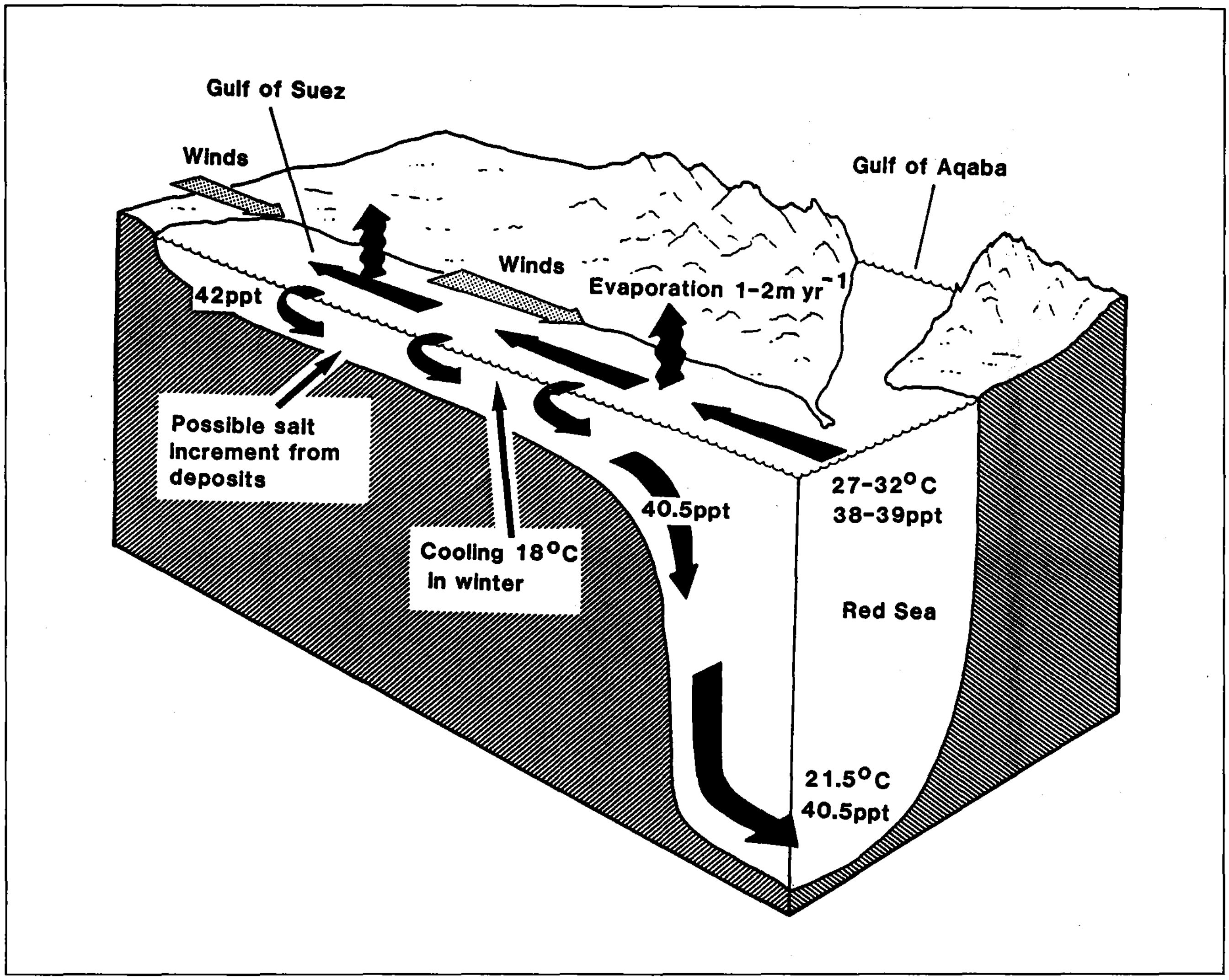


Figure 15: The "Suez Overfall". Density driven current near the entrance to the Gulf of Suez

Source: Sheppard *et al* (1992)

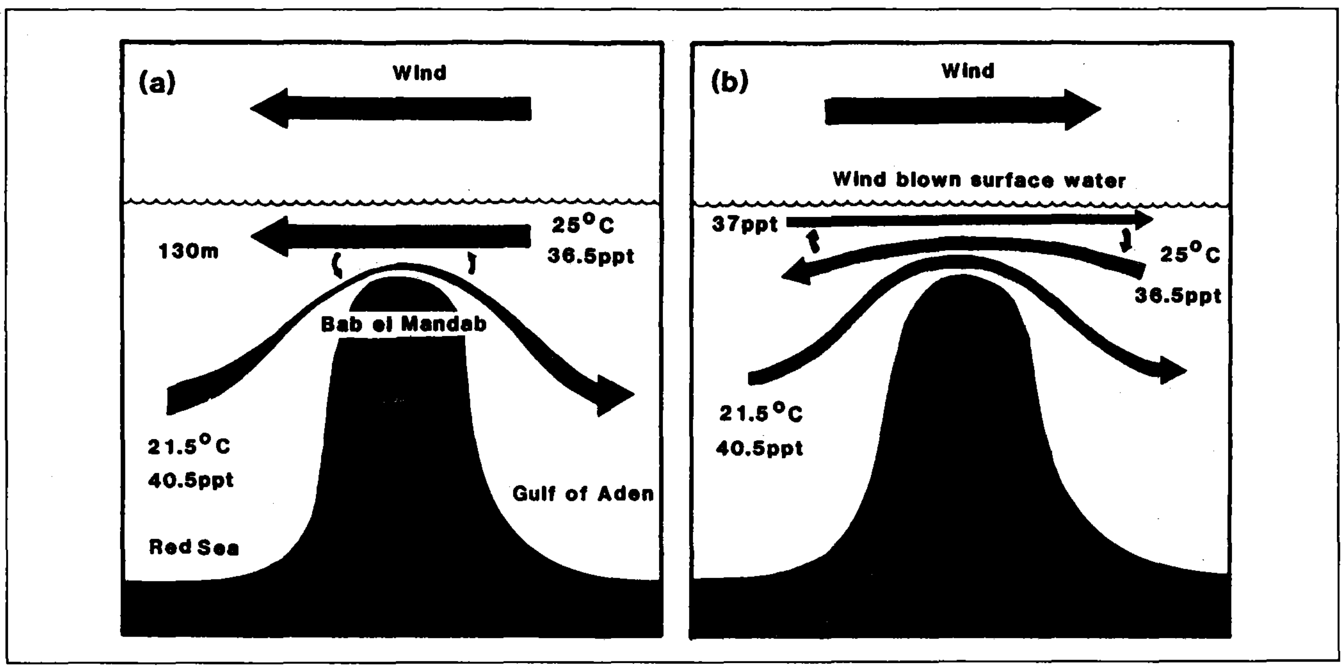


Figure 16: Sketch of winter and summer water flow through the entrance into the Red Sea

Source: Sheppard *et al* (1969)

Exceptional wind conditions have unusually important effects on Red Sea reef growth and distribution. While the overall level of winds is low compared with many coral sea areas, the summer breezes are commonly strong enough to lead to exposure of reefs. The coral mortality arising from this is such that reef growth is arrested at a level which appears to be slightly lower than might be expected from the position of mean low water.

Winter winds may also have considerable consequences. Morley (1975) describes water temperatures as low as 14.7°C in January 1973 in Jeddah, which lasted several days following a period of low air temperatures. At the end of this period, warmer winds and rapid mixing caused a rapid temperature increase to 25°C, leading to massive mortalities. Similarly, in the Gulf of Suez, cold winds cause local severe temperature depressions with consequent local mortalities, which also limits reef development.

Nutrient levels in the Red Sea (Weikert 1987) are generally low, which favours coral reef growth, though it is markedly higher in the southern part, as noted above. Dissolved oxygen is always near to, or above, saturation, in all parts.

4. REEF TYPES AND DISTRIBUTION

Misunderstanding still pervades the literature in connection with the types of reefs in the Red Sea, and their distribution. In part, this is because very few people have studied more than small sections of it, and many citations are perpetuated of earlier work which was incorrect. The most notorious example of this is the often repeated statement that fringing reefs line both banks of the Red Sea for its entire length, whereas in reality this is true only for the northern half. Further south, the different, highly sedimentary regime mostly excludes any reefs, especially fringing reefs. The south is more a province for soft substrate, mangroves and seagrass beds with occasional reefs in locations which are favourable to corals. A description of reef distribution is fundamental to understanding many aspects of their geology, and the following description of Red Sea reef distribution is taken from Sheppard *et al* (1992).

4.1 RED SEA REEF DISTRIBUTION

Northern Gulfs

The most northerly reefs of the entire Indian Ocean are those near Suez. This Gulf is shallow and sedimented, and is not part of the main, deep Red Sea rift system. On the eastern shore, the most northerly reefs include small coral patches with elevations of 1-3 m, lying on calcareous sandy and silty substrate from 1 to 5 m deep. They experience winter temperatures as low as 18°C and salinity as high as 41 ppt. The latter factor is not especially limiting to coral or reef growth, so the main constraint on coral reef development probably comes from exceptionally low winter temperatures, and especially from high sedimentation. The morphology of the corals dominating these reefs supports this view, being composed of stagshorn *Acropora* and an unusual form of similarly-branching *Stylophora*, both of which have ideal shapes for passively rejecting sediment in low energy conditions.

Reefs on the western coast of the Gulf of Suez are better developed in general than those on the east. This is particularly so in the far north where relatively well-developed fringing reefs exist to within 50 km of Suez. This marks the beginning of a long stretch of fringing reef running southward. At Ein Sukhna, the reef-flat extends 30-40m offshore and is followed by a gentle slope to a sandy bottom at 4-5m deep. The outer slope supports flourishing coral growth with up to 15 genera present. Communities are dominated by *Porites, Acropora* and *Stylophora.* Only patch reefs lying offshore are found at the same latitude on the eastern side, such as at Ras Sudr which itself is a small promontory projecting away from highly mobile beaches.

Extensive reefs first appear in the southern Gulf of Suez, both on Sinai and around the Ashrafi islands on the African shore. This region lies at the point where the northerly surface flow of Red Sea water dips under to return southward at depth and, being shallow, has extensive illuminated substrate, something which is greatly limiting in most of the northern Red Sea. As a consequence, the reefs here form some of the largest of all northern Red Sea reef complexes.

Northern Red Sea

At Ras Mohammed on the southern tip of the Sinai, the bathymetric profile changes abruptly into that of the main Red Sea system, which includes the Gulf of Aqaba. Water in most of the latter is over 1,800 m deep. The entrance to the Gulf of Aqaba has a broad sill less than 200 m deep where extensive shallows of soft substrate provide a complex, fertile area of reefs and seagrass. In most of the rest of the Gulf of Aqaba only a narrow fringing reef finds a foothold on the steep cliffs. For most of its length, fringing reefs line both shores; they are usually narrow, and have been termed "contour reefs" (Fishelson 1980), but they extend outward to as much as 1 km in embayments and old wadi systems.

The term contour reef has not taken a strong hold, as it merely denotes particularly narrow fringing reefs. Their narrowness means that they do exhibit features of great interest, however. They can be seen in many places to have "split" so that the underlying basement rock can be seen, (an excellent example is the famous cleft on Ras Mohammed, Sinai) and they show the manner in which fringing reefs conform to their basement contours.

The classical fringing reefs for which the Red Sea is famed extend southward along both the east and west sides of the northern Red Sea to 18-20 °N. Mostly they are narrow, extending only a few tens of metres from shore. Figure 17 illustrates profiles of this and several other major forms of reef. In much of the northern Red Sea, only a very limited proportion of the total area is shallow enough to fall within the illuminated zone, and hence only a small area is even potentially reef-bearing. Restrictions on the physical growth of fringing reefs are expected under such conditions, and this is indeed seen to be the case. Present fringing reefs are undoubtedly maintaining themselves at present sea-level, but are themselves founded on vertical series of much earlier reef structures. In the case of fringing reefs, most have reached the surface, and hence have kept up with or caught up with Holocene sea-level rise. Some offshore patch reefs arising from platforms, however, have not done so. In the case of fringing reefs, the outward, or lateral, growth of many is now also restricted by the fact that there is no shallow substrate for them to "expand" on to. This is manifested by the vertical slopes which characterise these reefs and whose dramatic "drop-offs" have attracted many recreational divers. Indeed overgrowth and overhanging is common, and in many areas outward extension over very deep water has been followed by fracturing and slumping of the new outgrowths.

Shores here, like the Gulf of Aqaba, contain raised fossil reefs. As discussed earlier, they have arisen from tectonic uplift and complex changes of sea-level relative to the land, and are likely to have been fringing reefs at different times in the past 120,000 years.

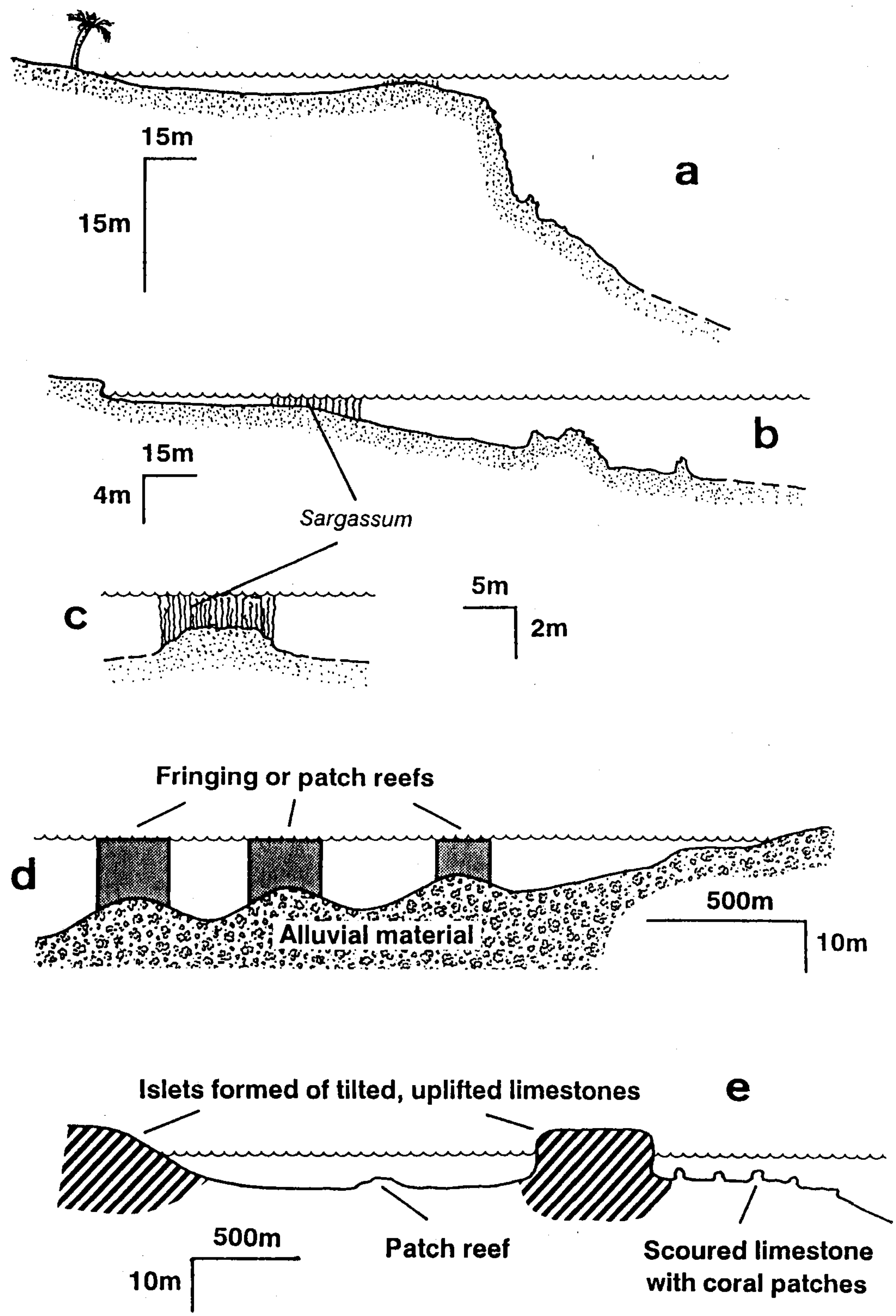
In areas, especially further south, the fringing reefs commonly extend 1 km to seaward. Throughout this region, the alluvial plain may be broad, and alluvial deposits on top of the basal substrate have elevated the substrata to depths which fall within the illuminated zone where coral growth is possible. Where old wadi systems are present, vast amounts of debris form shallow fans up to 1 km from the shore. The larger fans were mainly created during the Pleistocene and may extend 3 to 4 km along the shore, while both large and smaller ones may still be highly active (Hayward 1982). Beaches here are well developed, and many fans are characterized by large back reef lagoons which develop shoals parallel to the shoreline. Series of "fringing reefs" are found on the edges of these alluvial fans, though possibly these should be termed series of patch reefs instead. Thus the alluvial fans are an important influence on reef growth in such areas.

Offshore in the northern Red Sea lies the Wedj Bank and its islands. These contain extensive seagrass, reefs and mangroves (Ormond *et al* 1984 a, b & c), Al-Muhandiss and Al-Ruweissy, 1984). Also offshore, from Wedj to Jeddah, is an extensive series of submerged limestone platforms which form the foundation for a chain termed the "Little Barrier Reef" (Sheppard 1985b). Coral communities on this are the most exposed, varied and vigorously growing known in the Arabian region. This barrier reef is described in more detail later.

In Egypt, a series of patch reefs and fringing reefs around Hurghada, now an important tourist site, have been studied since Cyril Crossland founded a marine biological station there in 1930. Further south is Quseir, which was the Carl Klunzinger's base during two periods between 1863 and 1875, whose studies are a landmark in coral reef science generally. These two naturalists revealed the extent of fringing and patch reef systems of the northern part of the Red Sea.

Central Red Sea

Further south on the west coast is 500 km of little-studied coast. It has been explored by Edwards *et al* (1981), Gubbay and Rosenthal (1982) and Barratt (1982) enough to suggest that it is similar to the Arabian side, with probably one remarkable exception. In a section under joint Sudanese and Egyptian control, a mountainous region including Gebel Elba lies close to the coast. The marine environment remains mostly unknown, though the fact that the fringing series of reefs here swing almost 70 km offshore indicates that they rest on a vast alluvial fan.



(a) Classical Red Sea fringing reef
(b) Southern fringing reef
(c) Algal reef of far southern region
(d) Series of reefs on extensive alluvial fan
(e) Reefs of Dhalak Archipelago

Figure 17: Sketch of main Red Sea reef types

Source: Sheppard *et al* (1992)

The central Red Sea is widest in the region of Jeddah and Sudan, and supports a correspondingly wide range of reef morphologies. The character of the reefs is broadly similar to that of the north, though reef flats begin to broaden in this area and to develop more and larger lagoons, and sedimentary environments supporting mangroves begin to assume greater importance along the mainland shoreline. The barrier reef is well developed and coral communities and reefs still flourish, especially offshore.

The Sudanese coastline covers 750 km between 18° and 22° N. At Dunganab 160 km north of Port Sudan there is a very large sedimented embayment which is considered to contain a unique marine biotope in the country, with characters which may be similar to those of the Gebel Elba region noted above. Sanganeb Atoll, also located in this region, is well studied, and several similar, circular or annular reef structures form part of the barrier reef system on the Arabian side as well. Most work has, and continues to be done, on the Towartit reefs and in the Suakin Archipelago near and just south of Port Sudan.

On the Arabian side, fringing reefs become much reduced in size south of about Al Lith at 20° N. The continental shelf becomes broader in this area, and the floor slopes more gradually so that the reef base meets soft substrate in increasingly shallow water. The steady increase in muddy substrate and mangroves causes significant reef development to be pushed out further from shore, where there continues to be large expanses of limestone platform. Fringing reefs diminish and have a reduced coral diversity, and in many places there is a complete replacement of fringing reef by broad and thick stands of mangrove.

Southern Red Sea

Sand shores and sandy sublittoral habitat with no coral or mangrove growth increase southwards. These conditions reach their maximum extent opposite the Farasan islands, and extend into Yemen and the Gulf of Aden. The lack of reefs appears to be due to sedimentation in some cases, and to high exposure on the sandy beaches further south. There is an unusual development of reefs constructed almost entirely by calcareous red algae on extensive, sublittoral sand in the south.

Only rudimentary reefs occur on the continental shore of Ethiopia. The east and west mainland coasts of the Red Sea appear to mirror each other as far as Bab el Mandeb, and this mirroring extends to the two offshore island groups: the Saudi Arabian Farasan archipelago and the Dhalak archipelago of Ethiopia, described in more detail later. In the south, volcanic intrusions are more common, as are uplifted fossil limestone platforms, forced upwards by rising salt domes. Fringing and patch reefs are common around both these limestone and volcanic components.

Anecdotal information (Wainwright 1965) suggests that sublittoral algal and coral populations of the Farasans and offshore reefs are similar to those of the mainland shore, though compared to some of the reefs further towards the central axis of the Red Sea they are clearly richer in corals. Throughout the southern area, fossil reefs occur above sea-level along the mainland coast, and these have a higher generic diversity than do the present living reefs, possibly suggesting more favourable conditions in the past.

The shores of the Red Sea converge and shallow at the Bab el Mandeb. About 25% of the Yemen coast in the Red Sea and Gulf of Aden is fringed with shallow reefs or coral communities, found mainly around headlands on remnant fossil reef substrate. High energy sandy beaches dominate the coastline on the Arabian side.

The Gulf of Aden is worth including in this context. Djibouti on the African coast has a few reefs, but little work has been done on them. There is even less information for Somalia. It is likely that Somalia has no reefs and only scattered corals, due to upwelling water, a condition which continues down the Indian Ocean coast of Somalia for at least 500 km. The upwelling causes large brown algae to dominate hard substrate, while seagrasses are abundant on soft substrate. Darwin (1842) reported a small reef near the tip of the Horn of Africa, but otherwise there is apparently no significant coral growth until the southern part of Somalia, Kenya and beyond. On the north side of the Gulf of Aden, information is also sparse. It is known to be strongly affected by the Arabian Sea upwelling. Scheer (1971) visited the Abd el Kuri Island in the east of the Gulf of Aden and found sublittoral hard substrate dominated by large algae, with few corals. In the Gulf of Aden therefore, the extremely sparse data suggests that reefs are largely or completely absent, but that scattered coral communities occur amongst the macroalgae.

4.2 IMPORTANT AND UNUSUAL REEF TYPES

Coralline Red Algal Reef Construction.

Two main types of algal reef constructions are now known for the Red Sea. These are complete opposites in their environmental requirements, although they may superficially appear similar due to the similarity of their constructing biota.

- Spurs

Where wave energy is sufficiently high, spur and groove systems tend to develop. These are reef crest structures whose projections (spurs) point into the prevailing waves, and whose channels (grooves) carry water at rapid velocity. The water oscillates in the grooves such that outgoing swashes collide with incoming waves, resulting in dissipation of energy. The term "spur and groove system" has been applied to structures of this shape on reef crests over a wide range of scales; those of the northern Red Sea are growth features, made by red algae.

The spurs are usually constructions of the coralline algal genus *Porolithon*, as is the case for the whole Indo-Pacific. In very exposed locations, the algae also develop massive algal ridges from which the spurs project seaward, though to date, no location has been found in the Red Sea which has such a high exposure and such structures. To construct the spurs alone requires strong water movement and high aeration (Doty 1974, Littler and Doty 1975). Growth is enhanced by sediment forced into cavities by strong wave energy (Ginsburg and Schroeder 1973). The resulting spurs form a strong, dense limestone which may persist for thousands of years; spur and groove structures may persist at depths of 50 m on drowned reef crests (Sheppard 1981), and are known also in elevated fossil reefs.

In all cases, the tops of spurs are at the approximate low tide level at their landward end, and dip downwards to seaward. They have steep sides, usually with a scoured appearance. The widths of the spurs and grooves in any one series are similar both with each other and throughout their length, and at their seaward ends spurs fade out at a depth where average wave turbulence is diminished.

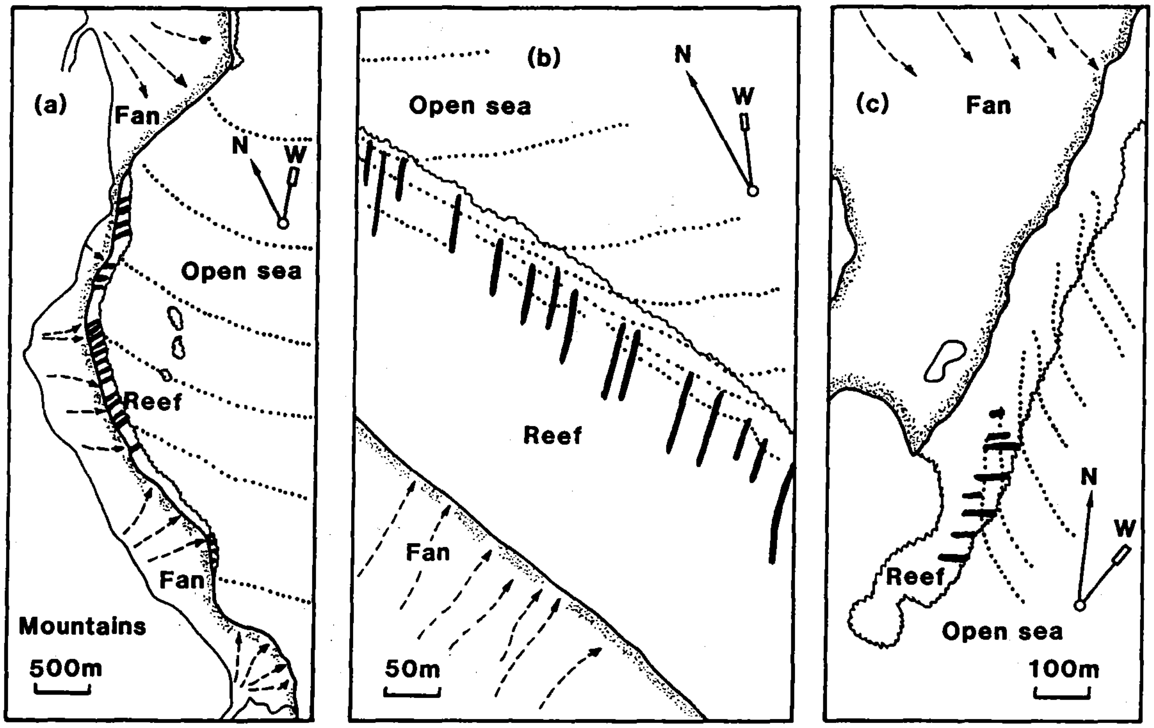
The fact that they are strong and persistent structures gave weight to earlier arguments that grooves are inherited from erosional features cut into pre-existing limestone platforms (Hopley 1982). That etching to this degree and greater is possible is clearly shown by wadi systems which are cut into limestone to depths of tens of metres. As pointed out by Hopley (1982), however, Red Sea spur and groove features are aligned at angles of up to 25° from perpendicular to the reef front in response to wave refraction, which by itself supports the hypothesis of spur growth rather than erosion as the dominant process in the Red Sea. It now seems clear that features of this dimension (i.e. 1-2 metres wide and about 10 metres long) are almost exclusively growth features, and that pre-Holocene erosion explains only the wadi fan formations and associated canyons which are larger by orders of magnitude.

Series of such algal constructions exist in the Gulf of Aqaba (Friedman 1968, 1985, Sneh and Friedman 1980) and on the African side of the Red Sea between the southern Gulf of Suez and Quseir, as well as on the barrier reef which runs down the northern Red Sea (Figure 18). In the Gulf of Aqaba such structures are important in limited areas, but this is far from universal. The Gulf of Aqaba can present some long fetches in northerly or southerly winds which are sufficient for spur formation, and these areas add considerably to the range of exposure and habitat experienced in the region.

- Algal reefs

In the southern part of the Red Sea an entirely different reef type is encountered in sheltered conditions, which appears to be formed from the same, or very similar crustose coralline algae that forms spurs in the north. These are termed "algal reefs" (Sheppard 1985a). They appear to be analogues of the crests of true coral reefs, but they exist in the absence of coral reefs, and all examples seen are found in low energy conditions in the southern part of the Saudi Arabian Red Sea, where coarse sand extends several kilometres to seaward. They arise from sandy substrata nearshore where water is 2 to 4 metres deep, and develop steep sides which reach to the low tide level. A profile of a typical example is shown in Figure 17. The reefs support very few and sparse corals, and are conspicuous from shore because they are covered in dense *Sargassum* whose fronds float in thick mats at the water surface. Notably, the very few corals present include *Siderastrea savignyana* which is extremely tolerant of sedimentation, high temperatures and high salinities.

This region appears to be unfavourable for coral reef growth today, although there are fossil reefs present which suggest that fringing reefs of high diversity have occurred before. The algal reefs are more than just a curiosity, however. Outside the Caribbean, living examples of algal reefs such as this are rare, and in this region, which includes several hundred square kilometres of shallow water, they provide most of the limited amount of biogenic limestone.



(a) El Hibeiq (b) North Dahab (c) South Dahab

Spurs marked by heavy lines. Wave fronts marked by dotted lines.

Figure 18: Sketch of spur systems in the Gulf of Aqaba

Source: Friedman (1985)

Barrier Reef

For at least 500 km between Wedj and Jeddah, a chain of reefs and shallow water runs nearly parallel to the Saudi Arabian coast, about 5-20 km offshore. It is broad and irregular, with several gaps deep enough to allow shipping through. Various parts of it have been studied individually both in the centre (e.g. Sheppard and Sheppard 1985) and south (Behairy and Jaubert 1984), but it has become apparent that these isolated reefs are just part of one large chain. The actively growing components which reach the surface are numerous enough to be uncounted, and they are all based upon what appears to be a limestone platform whose upper surface is at present mostly between 30-50 m deep. This platform itself rises from very deep water to seaward, and is separated from the shore with its fringing reefs by water usually well over 100 m deep (Figure 19). The density of the reefs on this platform are similar to those which are collectively termed the Great Barrier Reef of Australia, and hence the term "Little Barrier Reef" (Sheppard 1985b) is increasingly used for this structure.

Both as a whole and in its separate components, it is a very poorly studied part of the Red Sea reef system. Only recently, perhaps, has it been viewed as a single, large element, but if this is indeed appropriate, it is probably the largest single shallow carbonate component of the central Red Sea, extending as it does for about 500 km, and having a width of 1-7 km. The limited evidence available suggests that the bulk of the reef is limestone, whose surface mainly lies around 30-50 m deep. Its thickness is unknown, but it appears likely that it represents older periods of reef growth. The many reefs upon it which reach the surface today appear to be of recent origin, and may themselves be based on older projections of the main mass. The interpretation has been made that the present reef structures grow upwards from a Pleistocene platform (Sheppard and Sheppard 1985). Conditions for corals are amongst the best in the Red Sea, with clear, well mixed water, and hence coral growth is amongst the most prolific of the Red Sea. Numerous depressions, which have been attributed to karst erosion features, are filled with carbonate (mainly coral) sediments.

Similar profiles have been shown elsewhere in the Red Sea, most intriguingly off Port Sudan, suggesting that a similar structure along the African coast may mirror that off the Arabian coast (Schroeder and Nasr 1983). While this is possible, it is not well documented.

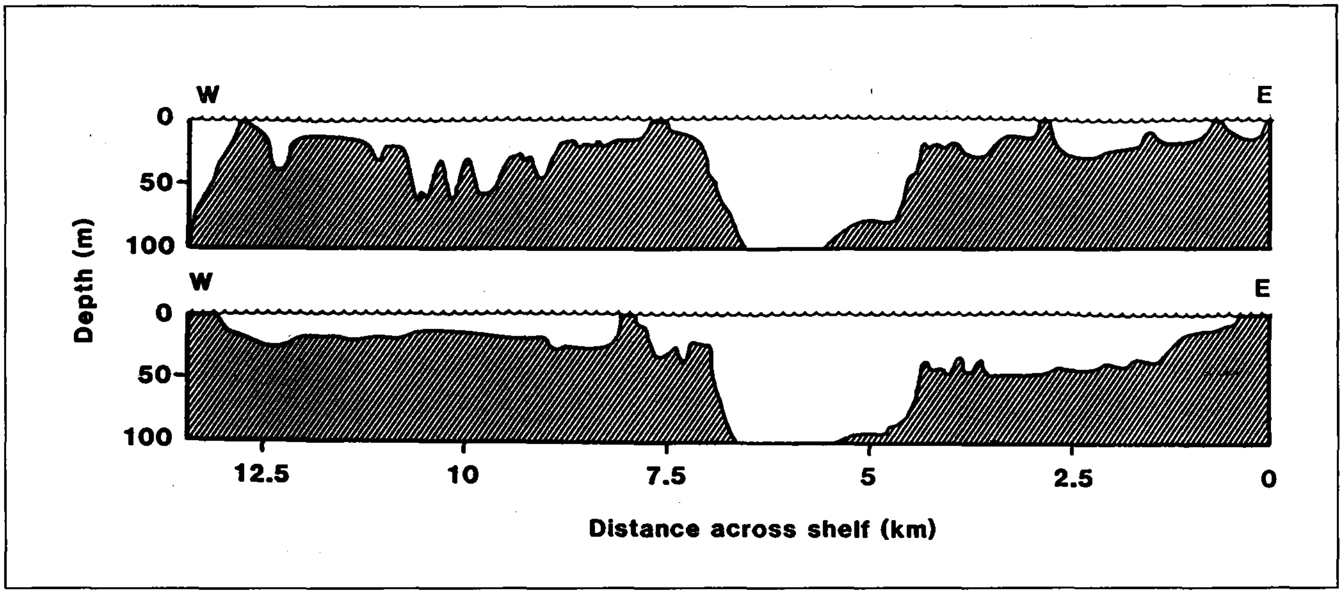


Figure 19: Echo-sounder traces across Barrier Reef at Yanbu, Saudi Arabia

Source: Sheppard *et al* (1992)

Ridge Reefs and Atolls

Guilcher (1988) defined a "new" type of reef structure called a ridge reef for the Red Sea, which occurs in both fossil and Recent form from the Sinai, Farasans, Jeddah and near Port Sudan. In fact reef structures with the same appearance are abundant along much of the Saudi Arabian Red Sea coast, although they are not usually referred to by this name. The reefs so defined are longitudinal ridges lying along the axis of the Red Sea, and probably result from a combination of normal faulting from the progressive opening of the Red Sea, and of upward movement of underlying salt deposits (diapirs) along these faults. Those on the Sinai appear to have only a veneer of coral capping the ridges, while others such as off Port Sudan may have thicknesses of tens of metres of limestone. In cases where the limestone cap is presumed to be thick, a later subsidence of the substrate is invoked, and the latter has to occur after the initial formation of the ridge.

However, it is neither necessary nor desirable to invoke a new class of reef for this, especially as the modern tendency is to recognise the gradation of reef development, and to recognise that Darwin's classic forms mark only points along a sometimes complicated continuum involving substrate movement, sea-level movement and limestone biogenesis. In the same vein, Guilcher (1988) remarks that the only atoll described from the Red Sea, Sanganeb off Port Sudan, rests on a ridge reef, suggesting that the latter is both a ridge reef and an atoll. There is no reason why a reef cannot be viewed as two different "kinds" at once, since it has a foundation formed from rifting and salt deposit uplift, and it is simultaneously a ring of reef resulting from progressive subsidence over a long period. Both events may occur sequentially.

Sanganeb atoll (Figure 20) is the best described atoll in the Arabian region. However, these oval shaped reef structures, enclosing lagoons with depths of tens of metres, are not usually described as atolls. Numerous examples occur along the Little Barrier Reef. If the definition of an atoll requires growth on top of progressive subsidence (as classically it does), then there is little evidence that any of these structures are true atolls; they could equally well be formed from upward growth of reef from the pre-Holocene reef substrate described earlier and, as pointed out by Guilcher (1988), confirmatory drilling into enough representative sites has yet to be done. The cross-sections of the barrier reef off Yanbu, shown in the preceding section, were particularly broad, yet they show how the outer and inner edges of the platform reach the surface, in a manner identical to Sanganeb atoll.

The gradations of the classical reef types, and their validity in an area as active geologically as the Red Sea, are discussed later.

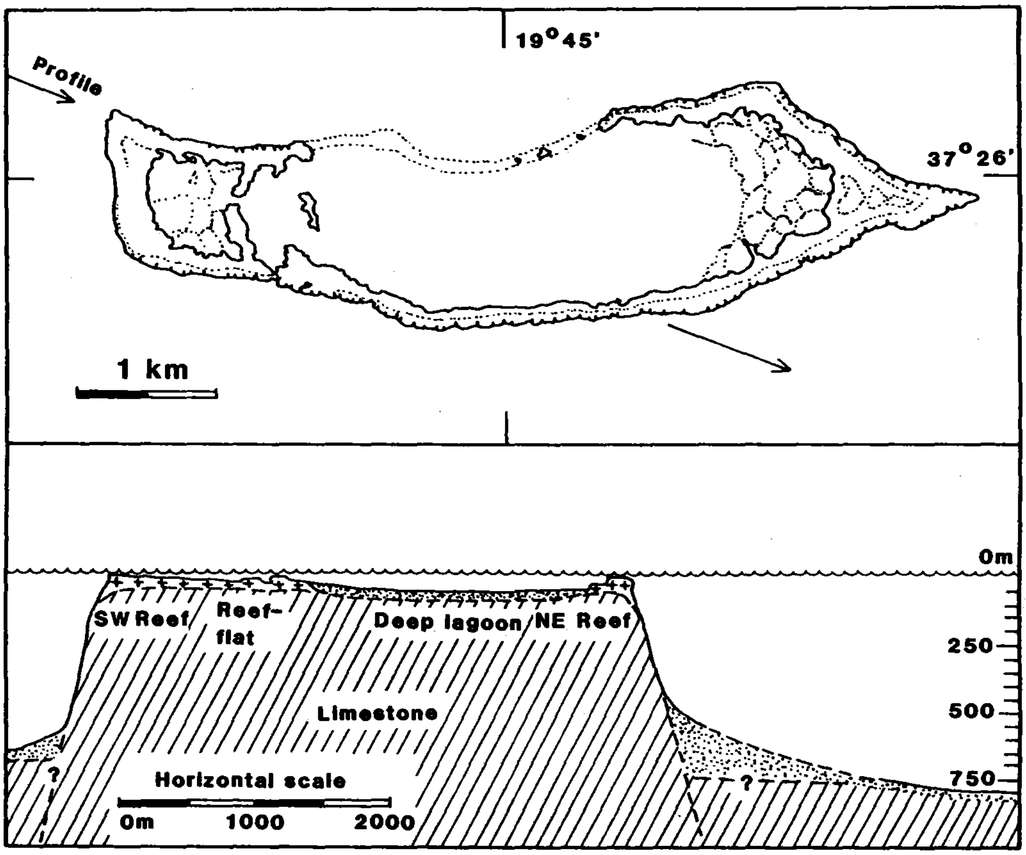


Figure 20: Sanganeb atoll, Sudan

Schumacher & Mergner (1985)

Reefs of the Farasan and Dhalak Archipelagoes

Both of these are low-lying groups near the southern end of the Red Sea, being located on much broader carbonate platforms. The Farasans remain poorly documented geologically, despite the considerable attention they have received from wildlife and conservation interests, and from television documentaries. Geological features of the Dhalak group have been much studied (Angelucci *et al* 1980, 1982a,b, 1985, Civiteli and Matteucci 1981). It is very probable that the two archipelagoes share common origins and have similar foundations.

The Dhalak Archipelago is the relict and uppermost layer of a larger carbonate platform, which grew between the Pliocene and Pleistocene (Angelucci *et al* 1980) on top of Upper Miocene evaporitic deposits. These underlying salt structures with their distending and collapse effects, control to a degree the distribution of the present sedimentary environments. This platform, according to Angelucci *et al* (1985) was split by the spreading tectonics of the Red Sea, and also underwent irregular uplift from the rising salt domes beneath. The result is a very articulated pattern, whose depressions act as extensive sedimentary traps. Around the emerging areas, reef complexes developed, and sedimentary deposits grew, so that today both new reefs and sabkha carbonate environments exist. The reefs, however, appear to be merely thin fringing types, growing on abraded carbonate substrate. Bioclastic sands are the most common type of deposit. Dating has given two dates of the raised reefs; 160-170,000 years before present, and again at 120,000 years BP (230 Th method, Angelucci *et al* 1980).

During the fluctuating sea-level changes of the Quaternary, substantial karst erosion is also assumed to have taken place, creating wide erosion channels which sometimes reach to the middle of the present islands. The work of Angelucci *et al* (1985) suggested that the patterns of sedimentation are much more connected with Quaternary tectonic and sea-level changes than with straightforward paleogeography of the platform.

At present, inner parts of the Farasans are poorly colonised with corals, and substantial stretches lack any modern reef growth. Islands and submerged areas more distant from shore, however, do support fairly luxuriant coral (Sheppard and Sheppard 1991), though there is no indication at present whether these lie on accreting reefs. A typical cross section is given in Figure 17.

4.3 REEF CLASSIFICATIONS

For 150 years, the classical progression of fringing reef, barrier reef and atoll has been widely used, and more recently patch reefs have been added. Where these are merely labels they provide convenient terms for describing kinds of reefs. However, there is a tendency to attribute functional or structural attributes to them (the latter in terms of the way in which the reefs arise, for example), and this raises problems in areas such as the Red Sea. In the Red Sea, newer terms such as contour reefs and ridge reefs have also been proposed, to explain structures which appear to be different, or which arose in a different way, to the classical types.

It cannot be doubted that a tectonically active coral sea which experiences tectonic uplift, spreading, faulting and upward movement of salt ridges, will provide complex combinations of substrate type. In the Red Sea, faulting, ridge formation and uplift all appear to have occurred sequentially in many places. Where this occurs, it is not realistic to assign simple labels to the reefs.

The most uncomplicated reef structure is probably the contour reef, being a thin fringing reef closely hugging the shoreline. Examples of this type in the Gulf of Aqaba (from where the name was coined) can never become broad since they adjoin very deep water, and additional outward growth results in fracturing and slumping of the newest growth.

The fringing reefs themselves, for which the Red Sea is well known, are rarely as simple as either the contour reefs or as the classical term used to suggest. Many fringing reefs have developed on the continental shoreline, but equally, many have developed on alluvial deposits, sometimes repeatedly in the same place, building layered structures where reef alternates with terrigenous deposits.

The barrier reef type is basically straightforward, in that it is, in the Red Sea context at least, a generic term for an offshore series or system of reefs. They may all be based upon a single, unifying platform whose upper surface is 30-60 m deep, but even this is not certain at present. Elements of the platform may be primarily caused by uplifted "ridges", but it is possible that not all of it is, especially where components in the north appear to grade towards large alluvial fans, and may be based on them.

The term ridge reef describes the mechanism of how substrate is elevated to depths which permit coral reef growth, and because of this appears to be a legitimate addition to Darwin's original terms. However, whether or not the underlying mechanism of uplift is particularly important can be argued, especially as subsequent subsidence of the initially uplifted segment is more important.

In fact, many of the ridge reefs of the Red Sea also support annular patch reefs, and an annular patch reef which comes about by subsidence is commonly called an atoll. Sanganeb atoll is one of a large number of similar structures, and those which lie off the central Saudi Arabian shore collectively fit the definition of barrier reefs in the classical sense too (see above). Some also have coral islands or at least sand banks as well, and these are commonly rimmed by fringing reefs.

While there may be value in retaining the classical names in general, these overlaps and complexities make them of less value in the Red Sea, and it is clear from some literature that their retention has occasionally misled. There is perhaps, more overlap in the classical "kinds" of reef in the Red Sea than in most parts of the world, due to the fact that it is tectonically active. What is clear is that reef substrate in the Red Sea have moved vertically upwards by both tectonic activity and salt dome movement, and vertically downwards by faulting, by tens or even hundreds of metres. In addition to this, there has been substantial lateral spreading and lateral extension of colonisable substrate by alluvial fans. Also, the pre-Holocene low sea-levels allowed substantial reef platforms to develop at levels now 30-60 m deep. Together these have resulted in what is probably a greater complexity of present reef foundation than in most coral seas. This complexity is one factor which makes this region of especial interest to carbonate geology.

5. CORALS AND REEF BUILDING PROCESSES

5.1 CORALS

The main reef building corals are the Scleractinia, though some *Millepora* species (Hydrozoa) are very important in shallow water. The important reef building members of both groups contain zooxanthellae, or symbiotic algae, within their tissues. The greatly enhanced metabolic efficiency and calcification which arises from this association is the foundation for the success of these coelenterates, and is the basis of their substantial limestone production.

Several taxonomic investigations have been carried out on reef building corals in the Red Sea, though much less work has been done in the Gulf of Aden. The long and often complex history of coral taxonomy has been enriched by numerous visitors to the Red Sea. The work, while pioneering and essential, has nevertheless been superseded to a great extent and much is of mainly historical interest. Coral taxonomy of the region is summarised, synonymised, revised and reviewed in Scheer and Pillai (1983), Sheppard (1987) and Sheppard and Sheppard (1991) and need not be repeated here. Table 4 lists all confirmed reef building coral species for the Red Sea and Gulf of Aden, taken from the latter work, which should be referred to for authorities and synonyms of each species. As with the taxonomy of all difficult groups, changes and additions to the following table are to be expected, especially following future work in the less well visited areas of the Red Sea.

The Red Sea appears to contain the richest diversity of corals west of India, and in part this is due to biogeographical reasons whereby the Red Sea acts as a trap for larvae which flow with the winter currents through the Bab el Mandeb (Sheppard *et al* 1992). Several of the above species are endemic to the Red Sea, suggesting speciation since the Holocene transgression, and several common species show different morphological ranges, suggesting effects of prolonged isolation.

The corals in the above table are all zooxanthellate, meaning that they contain symbiotic algal cells and have enhanced metabolic and calcification rates as a result. Although some groups, especially the *Poritidae, Faviidae* and *Acroporidae,* include important reef builders, it is now well known that the previous use of the term "hermatypic" (or reef-building) for all zooxanthellate corals is thoroughly misleading, a point discussed frequently during the 1980's (e.g. Sheppard 1982, Schuhmacher and Zibrowius 1985). Looking beyond this now obvious point, the role of corals in reef building is now known to be not as simple as previously imagined.

5.2 CORAL AND REEF GROWTH

It is increasingly clear that as environmental conditions become more severe from the point of view of the corals, that the processes of reef building and coral growth become "uncoupled" (Sheppard *et al* 1992). It appears that the processes required for reef growth fail before the point where these reef building corals cannot survive. This is seen in many parts of the world where turbidity, salinity or temperature gradients lead to local extinction of the corals, and in these areas corals form communities without forming reefs. This was perhaps first documented in the southern part of the Red Sea itself, by Wainwright (1965), who reported coral communities which did not appear to be associated with reef growth.

Whereas it was once universally thought that growth of reefs equated with growth of corals, it became clear once examples of coral growth without reef growth began to accumulate, that the concept of "corals growing on corals" was far too simplistic. Most of the matrix or fabric of both living and fossil reefs was seen, for example, not to consist of coral skeletons at all, even though numerous coral skeletons could be seen embedded in it. The term "framework" accommodated the observations better, and is sometimes used to refer to the matrix of coral colonies which trap sediments, allowing the latter to consolidate into the bulk of the reef fabric over much longer periods of time. Obviously limestone production by corals is important, but without other aspects which involve the consolidation of limestone sediments, the result would remain merely coral skeletons with sediments, not a durable reef.

Simplest Reef Formation

There is a special case where coral reefs are formed in the simple "corals on corals" way, and this is important in several parts of the Red Sea. In sheltered areas, such as back reef areas, lagoons, parts of deeper water amongst the vast alluvial fan formations, and in several areas of the southern Red Sea, coral diversity is generally low. Here, reefs of the simplest kind develop, from aggregations of enormous coral colonies of great age. These are almost always based on *Porites*, though some *faviids* may add significantly to this. Massive colonies develop on the shallow substrata where numerous adjacent colonies of the same species tend to fuse together, forming a structure whose cross-sectional profile is identical to that of a small reef. No sediment binding processes are necessary for their formation. In their simplest form, they may be only a single colony of *Porites*, several metres across, reaching the low tide level and hence having a flat top.

These very simple "corals on corals" are important in limited areas, but they are not the important Red Sea reefs. The latter, like reefs in the rest of the Indo-Pacific, develop in much more complex and little understood ways. These ways involve, principally, the consolidation and transformation of limestone sediments into new reef fabric. The fabric forms around many coral colonies which may therefore remain within the reef in the position of their original growth, and such conditions can be observed in most parts of the elevated reef terraces bordering the Red Sea, for example.

Table 4

Tabular summary of the reef building corals of the Red Sea and Gulf of Aden

	1	2	3	4		1	2	3	4
Stylocoeniella guentheri	+	+	+		*Alveopora ocellata*	+	+		
Stylocoeniella armata		+			*Alveopora spongiosa*	+	+	?	
Pocillopora damicornis	+	+	+	+	*Alveopora tizardi*		+		
Pocillopora verrucosa	+	+	+	+	*Alveopora viridis*	+			
Seriatopora caliendrum	+	+	+		*Siderastrea savignyana*	+	+	+	+
Seriatopora hystrix	+	+	+		*Pseudosiderastrea tayamai*				+
Stylophora pistillata	+	+	+	+	*Anomastrea irregularis*				+
Stylophora mamillata	+	+			*Psammocora contigua*			+	+
Stylophora wellsi	+	+	+		*Psammocora explanulata*	+	+	+	
Madracis interjecta	+				*Psammocora haimeana*	+	+	+	+
Montipora aequituberculat	+	+	+	+	*Coscinaraea monile*	+	+	+	+
Montipora circumvallata	+	+	+	+	*Coscinaraea columna*		+	+	
Montipora danae	+	+	+	?	*Craterastrea levis*		+		
Montipora digitata				+	*Pavona cactus*	+	+	+	
Montipora informis	+	+	+		*Pavona decussata*	+	+	+	
Montipora monasteriata	+	+	+	+	*Pavona diffluens*		+		+
Montipora spongiosa		+	+		*Pavona duerdeni*	+	+		
Montipora stilosa	+	+		+	*Pavona explanulata*	+	+	+	
Montipora tuberculosa	+	+			*Pavona maldivensis*	+	+	+	
Montipora venosa	+	+	+	+	*Pavona varians*	+	+	+	+
Montipora verrucosa		+	+		*Leptoseris explanata*	+	+		
Acropora clathrata	+	+	+	+	*Leptoseris foliosa*	+	+		
Acropora cytherea	+	+	+		*Leptoseris hawaiiensis*	+	+	+	
Acropora danai	+	+	+		*Leptoseris mycetoseroides*	+	+	+	
Acropora digitifera	+	+	+		*Leptoseris scabra*	+	+	+	
Acropora eurystoma	+	+	+		*Leptoseris yabei*	+	+	+	
Acropora formosa	+		+	+	*Gardineroseris planulata*	+	+	+	+
Acropora granulosa	+	+	+	+	*Pachyseris speciosa*	+	+	+	
Acropora hemprichi	+	+	+		*Cycloseris costulata*	+	+		
Acropora horrida	+		+	+	*Cycloseris cyclolites*	+			
Acropora humilis	+	+	+		*Cycloseris doederleini*	+	+		
Acropora hyacinthus	+	+	+	+	*Cycloseris marginata*	+	+		
Acropora nasuta	+	+	+		*Cycloseris patelliformis*	+	+	+	?
Acropora nobilis		+	+		*Diaseris distorta*	+	+		?
Acropora pharaonis	+	+	+		*Fungia (Fungia) fungites*	+	+	+	+
Acropora polystoma			+		*F. (Danafungia) corona*	?	+		
Acropora robusta		+	+		*F. (Danafungia) horrida*	+	+		
Acropora squarrosa	+	+			*F. (Danafungia) klunzing.*	+	+		
Acropora valenciennesi	+	+			*F. (Danafungia) scruposa*	+	+		
Acropora valida	+	+	+		*F. (Danafungia) valida*		+		
Astreopora myriophthalma	+	+	+		*F. (Verrillof.) concinna*	+	+	+	
Porites compressa	+	+	+		*F. (Verrillof.) granulosa*	+	+		
Porites echinulata	+	+	+	+	*F. (Verrillof.) repanda*		+		
Porites lobata		+	+	+	*F. (Pleuractis) moluccen*	+			
Porites lutea	+	+	+	+	*F. (Pleuractis) paumoten.*	+	+		+
Porites nodifera		+	+		*F. (Pleuractis) scutaria*	+	+	+	
Porites solida	+	+	+		*Ctenactis echinata*	+	+	+	
Porites (Synarea) rus	+	+			*Herpolitha limax*	+	+	+	
Goniopora djiboutiensis				+	*Podabacia crustacea*	+	+	+	
Goniopora columna	+	+	+		*Galaxea fasicularis*	+	+	+	+
Goniopora minor	+	+			*Galaxea astreata*				+
Goniopora savignyi		+	+		*Echinophyllia aspera*	+	+	+	
Goniopora somaliensis	+	+	+	+	*Oxypora lacera*	+	+	+	
Goniopora stokesi	+	+			*Mycedium elephantotus*	+	+	+	
Goniopora tenella		+			*Blastomussa merleti*	+	+	+	
Alveopora allingi	+	+			*Cynarina lacrymalis*	+			

Locations Col 1 = North Red Sea, Gulf of Aqaba and Suez
Col 2 = Central Red Sea, Yanbu, Jeddah and Sudan
Col 3 = South Red Sea
Col 4 = Gulf of Aden

Source: Sheppard & Sheppard (1991)

Table 4 (continued)

	1	2	3	4
Acanthastrea echinata	+	+	+	+
Acanthastrea hillae				+
Symphyllia erythraea	+	+	+	
Symphyllia radians		?		+
Lobophyllia corymbosa	+	+	+	
Lobophyllia hattai		+		+
Lobophyllia hemprichii	+	+	+	+
Hydnophora exesa	+	+	+	+
Hydnophora microconos	+	+	+	
Merulina scheeri	+	+	+	
Caulastrea tumida	+			
Erythrastrea flabellata	+			+
Favia stelligera	+	+	+	
Favia laxa	+	+	+	
Favia favus	+	+	+	
Favia pallida	+	+	+	+
Favia speciosa	+	+	+	+
Favia lizardensis		+		
Favia matthai	+	+		
Favia rotundata	+	+		
Favia wisseli		+		
Favites abdita	+	+	+	
Favites chinensis	+	+	+	
Favites complanata	+	+		
Favites flexuosa	+	+	+	
Favites halicora	+	+	+	
Favites pentagona	+	+	+	+
Favites peresi	+	+	+	
Goniastrea australensis	+	+	+	
Goniastrea edwardsi	+	+	+	
Goniastrea pectinata	+	+	+	+
Goniastrea retiformis	+	+		+
Platygyra crosslandi	+	+		
Platygyra daedalea	+	+	+	+
Platygyra lamellina	+	+	+	
Platygyra sinensis		+	+	
Leptoria phrygia	+	+	+	+
Oulophyllia crispa	+	+	+	
Montastrea curta	+	+	+	
Montastrea magnistellata		+		
Plesiastrea versipora	+	+	+	+
Diploastrea heliopora	+	+	+	
Leptastrea inaequalis	+	+	+	+
Leptastrea purpurea	+	+	+	
Leptastrea transversa	+	+	+	
Cyphastrea microphthalma	+	+	+	
Cyphastrea serailia	+	+	+	
Echinopora gemmacea	+	+	+	+
Echinopora lamellosa	+	+	+	
Echinopora cf fruticulosa	+	+	+	
Euphyllia glabrescens	+		?	
Plerogyra sinuosa	+	+	+	
Physogyra spp.			+	+
Gyrosmilia interrupta	+	+	+	
Turbinaria mesenterina	+	+	+	
Turbinaria peltata				+
Turbinaria reniformis			+	?
Heteropsammia cochlea				+

Non-scleractinian hermatypic species:

Millepora dichotoma
Millepora platyphylla

Several examples exist in the Red Sea and Arabian region where coral reefs do not develop into reefs, and these perhaps will be the areas where future research tackles the problems of reef growth.

Consolidation processes

The trapping and transformation of sediments into durable reef is an essential part of most reef formation. Corals are a major provider of sediments, and the calcium carbonate material produced by the scleractinian corals is almost entirely aragonite. There is some evidence that growing tips may also produce some calcite, which is produced by several other reef dwellers, both plant and animal. It seems likely that some analyses performed on coral skeletons which have shown various combinations of aragonite, calcite and high magnesium material, have not sufficiently differentiated between true skeleton and external sedimentary material trapped into the skeleton; the latter may take place through dead, exposed surfaces of the coral, or by active incorporation by polyps onto which such extraneous material has fallen.

Diagenesis is defined by Eicher *et al* (1984) as "any post-depositional chemical reactions between grains of sediments and the solutions around them," and by Bates and Jackson (1980) as "All the chemical, physical, and biological changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism."

The latter definition specifically includes biological changes, and this implies, amongst other processes, changes induced on grain surfaces by microorganisms after binding and stabilisation by biota, such as sponges and algae. In addition, inorganic precipitation of carbonate also occurs. This results from the fact that shallow reef waters are commonly supersaturated with respect to calcium carbonate, and microbial changes alter the chemistry, pH and other aspects of the micro-environment, leading to precipitation of limestone cement. These processes are very well reviewed in Hopley (1982). Most of the work relates to reefs other than in the Red Sea, where little in this field has taken place (though see Dullo 1986, Aissaoui *et al* 1986).

These processes occur relatively readily in the pores and interstitial spaces of reefs and of coral colonies, because trapped sediments are retained in an immobile state for the required, long, periods of time. This contrasts with sand bodies where mobility is such that the growth of cement is disrupted (Schroeder and Purser, 1986). In some senses, especially quantitatively, the most important function of corals on coral reefs is the provision of aragonite sediment which is slowly transformed to durable, solid calcite. However, the stable environment of the reef framework, also made by corals, is of course essential.

Several other factors affect the consolidation process. Highly saline interstitial waters that periodically seep through upper levels, such as may occur in back reef conditions in the Red Sea, may alter the tiny grains of deposited calcium carbonate to the mineral dolomite, $CaMg(CO_3)_2$. Where there is evaporation of occasional seawater incursions, such as on large horizontal expanses immediately behind reef flats, evaporite deposits such as gypsum, $CaSO_4.2H_2O$ and NaCl occur too. These processes are important in the Arabian Gulf (Eicher *et al* 1984). Similar environmental conditions occur in many parts of the Red Sea, especially in the south, and it is expected that these additional processes occur there too. Expanses of gypsum are already known from Red Sea shores (e.g. Sheppard *et al* 1992).

Given the wide range of chemical, physical and biological (including microbial) processes which are required to cause true reef growth, it is perhaps not surprising that many examples are seen where there is abundant coral growth, but no reef growth. The Arabian region, including the Red Sea, includes many examples of this. Coral communities may flourish on much older limestone, or on volcanic intrusions, without any traces of reef growth, even though the existence of the coral community may be estimated as at least 6,000 years, or since the present sea-level was attained. It is true that the coral communities may be rather less diverse in such cases, but coral cover of the substrate commonly exceeds 50% and is often 100% (Sheppard and Sheppard 1991). The evidence clearly suggests that it is the subsequent sedimentary lithification processes which have failed, not the coral growth itself. The reasons remain unknown.

A final point concerning Red Sea reef sediments is that strong aeolian and alluvial processes, both of which are continuing, results in considerable input of fine terrigenous sediments as well. These contribute additional minerals, which are detectable in the sediments and also in the reef fabric itself. Some studies have not sufficiently differentiated the origins of these. Table 5 shows some typical examples of these from sediments in the northern Red Sea.

Table 5.

Major chemical constituents of reefal sediments from the northern Red Sea. Values in parts per million.

Mineral	Aqaba (1)	Al-Ghardaqa (2)
SiO_2	12.41-45.47	12-33
Al_2O_3	0.96-5.34	6-12
Fe_2O_3	0.27-0.73	0.17-0.6
MnO	0.02	0.01-0.03
CaO	21.7-43.20	16-34.1
MgO	0.97-1.40	3.06-5.26
K_2O	0.42-1.40	0.1-0.3
Na_2O	0.42-1.27	0.1-0.4

(1) Aqaba data from Friedman (1968),
(2) Al-Ghardaqa data from El-Sayed (1984).

6. SUMMARY

The Red Sea contains a particularly wide range of reef types. Although it is not a particularly well studied sea in terms of marine sciences, its geological past is now known sufficiently well to provide a good background to reef investigations. The existence of such a wide variety of reef structures within it is in large measure due to the relatively recent and substantial changes which have taken place to the underlying foundations, particularly with respect to marginal uplift, tectonic spreading, rising underlying salt domes, faulting, introduction of volcanic substrate, and changing sea-level in the Pleistocene.

Several of the types of reefs cannot easily be placed into the classical reef categories, and this has attracted the use of some new names (e.g. "contour" reef, and "ridge" reef") in order to describe the observed features better, while other reefs, such as the huge reef systems which develop on alluvial fans and the southern algal reefs, appear to be unusual in their local importance and size. Placing this variety into categories is unnecessary, however, and probably detracts from understanding the many factors which explain the formation and location of the present reefs; indeed, several clearly grade across "type" boundaries, or could validly occupy two or more categories.

Coral growth is abundant in the north, but much poorer in the south. Reef growth similarly declines markedly in the south, and it is emphasised that the southern Red Sea is now known not to be the "coral sea" that the northern parts are well known to be. Rather the south is more of a sedimentary basin, much richer in mangroves and seagrasses than in corals, and which experiences substantial planktonic enrichment from the Gulf of Aden. In the southern Red Sea, several examples exist where reef growth does not occur even where coral growth does. Present, severe environmental conditions in some parts limit reef growth, and the Red Sea is an excellent place to conduct further research on the development of reefs both on a macro scale (e.g. their development on different, even mobile substrate) and the single reef scale (e.g. diagenetic factors and the coupling of coral growth with reef growth).

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