

Bernhard M. Riegl
Sam J. Purkis
Editors

Coral Reefs of the Gulf

Adaptation to Climatic Extremes

Coral Reefs of the Gulf

Coral Reefs of the World

Volume 3

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 Springer



Editors

Bernhard M. Riegl
National Coral Reef Institute
Nova Southeastern University
Dania Beach, FL
USA

Sam J. Purkis
National Coral Reef Institute
Nova Southeastern University
Dania Beach, FL
USA

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This book is dedicated to our own and the children of the Middle East in the hope that they will still be able to experience coral reef ecosystems

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Contributors

Alaa M. Abdel-Moati Ministry of Environment, Doha, Qatar

Ashraf S. Al-Cibahy Environment Agency-Abu Dhabi, Abu Dhabi, United Arab Emirates

Suaad Al-Harathi Environment Agency-Abu Dhabi, Abu Dhabi, United Arab Emirates

Mohsen Al-Husiani Kuwait Institute for Scientific Research, Salmiyah, Kuwait

F. Al-Jamali University of Qatar, Doha, Qatar

Khalifa Al-Khalifa Public Commission for the Protection of Marine Resources, Environment and Wildlife, Manama, Bahrain

Khalifa Al-Sulaiti Qatar Gas, Ras Laffan Industrial City, Qatar

Faiza Al-Yamani Kuwait Institute for Scientific Research, Salmiyah, Kuwait

James Baldwin Qatar Gas, Ras Laffan Industrial City, Qatar

Rob Baldwin Five Oceans Environmental Services, Muscat, Oman

Aaron Bartholomew American University of Sharjah, Sharjah, United Arab Emirates

Andrew G. Baumann School of Marine and Tropical Biology, ARC Center of Excellence for Coral Reef Studies, James Cook University, Townville, QLD 4811, Australia

Francesca Benzoni University of Milano-Bicocca, Piazza della Scienza, I-20126 Milano, Italy

Institut de Recherche pour le Développement (IRD), Noumea Cedex, New Caledonia, France

James Bishop Kuwait Institute for Scientific Research, Salmiyah, Kuwait

Benno Böer UNESCO, Doha, Qatar

Andrew W. Bruckner Khaled bin Sultan Living Oceans Foundation, Landover, MD, USA

John A. Burt Division of Science and Mathematics, New York University-Abu Dhabi, P.O. Box 129–188, Abu Dhabi, United Arab Emirates

Georgenes H. Cavalcante Coastal Zone and Waterways Management Section, Environment Department, Dubai Municipality, Dubai, United Arab Emirates

Nicholas K. Dulvy Simon Fraser University, Burnaby, British Columbia, Canada

Subba Rao V. Durvasula Dartmouth, Nova Scotia, Canada

Eric Dutrieux Creocan, Montpellier, France

David A. Feary School of the Environment, University of Technology, P.O. Box 123, Broadway, Sydney, NSW 2007, Australia

Greg Foster National Coral Reef Institute, Nova Southeastern University, Dania Beach, FL, USA

Kristi Foster National Coral Reef Institute, Nova Southeastern University, Dania Beach, FL, USA

J. David George Natural History Museum, London, UK

Edwin Grandcourt Environment Agency-Abu Dhabi, Abu Dhabi, United Arab Emirates

David M. John Natural History Museum, London, UK

David A. Jones Cabo La Nao, Alicante, Spain

Ron Loughland AES International Consultants, Manama, Bahrain

David Medio Halcrow Group Ltd., Leeds, UK

M. Nithyanandan Al Khiran Pearl City Project, La'Ala, Kuwait

Graham M. Pilling CEFAS, Lowestoft, Suffolk, UK

Igor Polikarpov Kuwait Institute for Scientific Research, Salmiyah, Kuwait

Andrew R.G. Price University of Warwick, Coventry, UK

Sam J. Purkis National Coral Reef Institute, Nova Southeastern University, Dania Beach, FL, USA

Bernhard M. Riegl National Coral Reef Institute, Nova Southeastern University, Dania Beach, FL, USA

Maria Saburova Institute of Biology of the Southern Seas, National Academy of Science of Ukraine, Sevastopol, Ukraine

Kaveh Samimi-Namin Netherlands Centre for Biodiversity Naturalis, 2300 RA Leiden, The Netherlands

Charles Sheppard University of Warwick, Coventry, UK

Oliver Taylor Five Oceans Environmental Services, Muscat, Oman

Len van Ofwegen Netherlands Centre for Biodiversity Naturalis, 2300 RA Leiden, The Netherlands

Simon Wilson Five Oceans Environmental Services, Muscat, Oman

Khadija Zainal The University of Bahrain, Sakhir, Bahrain

Coral Reefs of the Gulf: Adaptation to Climatic Extremes in the World's Hottest Sea

1

Bernhard M. Riegl and Sam J. Purkis

1.1 Introduction

This book treats coral reefs in the water body enclosed between Iran and the Arabian peninsula that in this book we refer to as “the Gulf”. The area is variably also known as the Persian or Arabian Gulf, or as the ROPME Inner Sea Area. Much national pride is attached to the usage of either term and, in order to avoid confusion (for example Arabian Gulf with Arabian Sea) or infringement on national sentiments, we have resorted to use the more general terminology of “the Gulf”. This term has become increasingly common in the media, scientific literature and general use to sufficiently clearly indicate the geographic area we refer to. The deletion of the various adjectives is not meant to ignore their cultural or national significance. But given that the dynamics of coral reefs, indeed of all marine organisms, is transnational, deletion of the adjective assists us in increasing linguistic clarity and coherence across the pages of this book.

As far as coral reefs are concerned, the Gulf is a very special area. It harbors some of the northernmost coral reefs in the western Indian Ocean and is in summer the world's hottest sea while in winter among the coldest with abundant coral growth. This is of special importance in a world subjected to climate change – the Gulf is characterized today by a thermal regime comparable to that predicted for the tropical ocean in 2090–2099 (IPCC 2007). Dynamics of Gulf coral reef organisms have adapted over the last 6ky to this climatic regime and many important lessons for the world's oceans in general can be learned. This book is organized into three logical sections that collect studies on geological and biological dynamics, then systematics and taxonomy, and finally the management and conservation of this unique sea (Fig. 1.1).

Chapters 2 (Riegl and Purkis) and 3 (Purkis and Riegl) provide a background of the environmental and geomorphological

backdrop driving reef development in general, while chapter 4 (Foster et al.) provides monitoring data with specific respect to reefs in the SE Gulf. Chapter 5 (Riegl and Purkis) uses such data as backdrop to explore, using observation and mathematical modeling, the ecological and framebuilding dynamics of coral communities. Chapters 6 and 7 (Riegl et al.) treat health issues on coral reefs, such as bleaching and diseases, in great detail providing a quantification of bleaching thresholds and all known diseases and afflictions of corals in the Gulf. Chapter 8 (Grandcourt) treats fisheries and fish population dynamics issues, bridging the book's sections of biological dynamics and management. Chapter 9 (Feary et al.) outlines the value of Gulf coral reefs as a laboratory in which to learn about climate change and shows details about coral reproduction. Chapter 10 (Burt et al.) acknowledges the fact that the spectacular economic development in the Gulf region has created miles of artificial reef habitat and explores the dynamics, and conservation value, of man-made habitats. The following section reviews the systematics and taxonomy of some major animal and plant groups found on coral reefs. Chapter 11 (Riegl et al.) reviews the hard, scleractinian, coral fauna, while chapter 12 (Samimi-Namin and van Ofwegen) reviews the soft, alcyonacean coral fauna. In Chapter 13 (George), a spectacularly illustrated overview of all major invertebrate groups and in chapter 14 (John) of all major macroalgae groups found on Gulf reefs is given. The final section concerns itself with management and conservation issues. Chapter 15 (Al-Cibahy et al.) describes protection of reefs and marine resources in the Gulf States, while chapter 16 (Sheppard et al.) provides a detailed overview of the many threats and woes besieging the reefs of this interesting region.

Although the research history of the Gulf may be a bit shorter than that of some better publicized coral reef areas, it is wide and varied and a wealth of information exists. Most early research in the region was motivated by exploration for hydrocarbons and metallic ores. Physical geographical research (Lees 1948; Lees and Falcon 1952) was followed by sedimentology (Emery 1956). The Imperial College engaged in important research efforts in the UAE (Evans and Shearman

B.M. Riegl (✉) • S.J. Purkis
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu; purkis@nova.edu

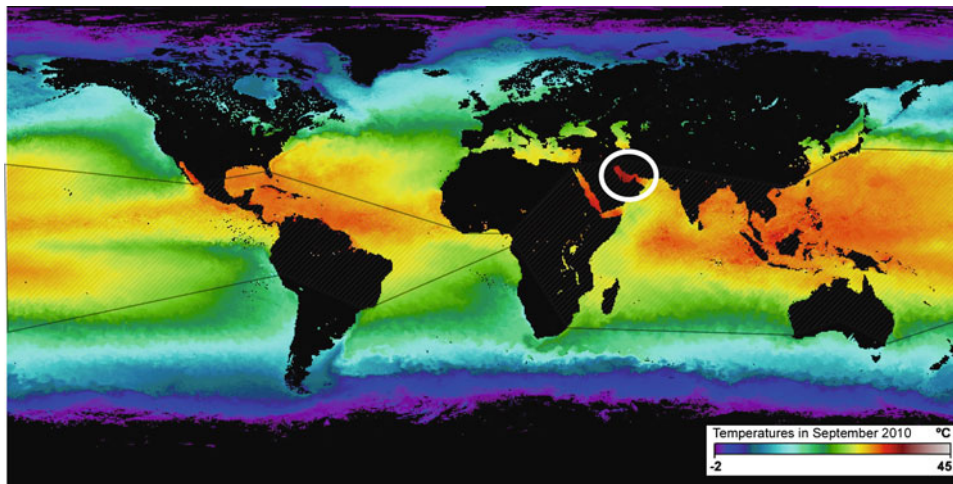


Fig. 1.1 The study area treated in this book is the hottest ocean-basin worldwide during summer and certainly the hottest with abundant coral growth (most of the world's shallow coral reefs occur within the black lines bracketing tropical and subtropical seas). Shown is a sea-surface temperature mosaic of monthly averaged MODIS data from September 2010 (Data from neo.sci.gsfc.nasa.gov). Although 2010 was one of the

hottest years in record, the Gulf routinely exceeds temperatures of all other reef areas (Chap. 2). In winter, the Gulf is colder than most other ocean basins (Chap. 2). Summer temperatures in the Gulf today equal those predicted for the tropical ocean around 2099 (IPCC 2007). Thus, the Gulf is a good laboratory for climate change studies

1964; Evans 1966, 1970; Evans et al. 1964, 1969; Kinsman 1964; Murray 1965a; Shearman 1963) as well as in the northern Gulf and the Gulf of Oman (published in the “Meteor Forschungsergebnisse” 1969–1972). Shell Research investigated Qatar in the 1950s and 1960 (Houbolt 1957; Wells 1962; Illing et al. 1965; Taylor and Illing 1969). Purser (1973) combined these results combined with research by the Swiss Institute of Technology Zürich (Hsü and Schneider 1973), the Central Geological Survey Prague and the University of Baghdad (Kukal and Saadallah 1973) into the first comprehensive volume of Gulf sedimentology that also contained some of the first organized information about coral reefs in the region. The book remains a classic to this day, as can be seen from its abundant citation in many chapters of the present volume. Recent overviews of coastal carbonates that also mention coral reefs were written by Alsharhan and Kendall (2003), and Gischler and Lomando (2005).

The Gulf's biology has been investigated since the late eighteenth hundreds. Mollusks received early attention (Issel 1865; Smith 1872; von Martens 1874; Fischer 1891). F.W. Townsend collected mollusks while cleaning cables for the Indo-European Telegraph Department on the steamer “Patrick Stewart”, which were then scientifically treated by J.C. Melville (1897, 1898, 1899, 1904, 1917, 1928 and many others). H.E.J. Biggs (1973) collected from 1911–1935. The 1950 Yale Peabody Museum Harvard Expedition to the Near East yielded Haas (1952). The mollusk fauna and history of malacological research is exhaustively reviewed in Bosch et al. (1995). Oil exploration greatly accelerated the pace of biological research. Foraminifera, a most important group for carbonate sedimentologists, were studied by J.W. Murray (1965a, b, 1966a, b, c, 1970a, b), the German Meteor expedition led by E. Seibold (Lutze et al. 1971)

and others (Basson and Murray 1995; Cherif et al. 1997). Largely funded by oil companies, detailed overview work on the biological component of the sedimentary system was published (Basson et al. 1977). Early work on corals of the Gulf was by Burchard (1979); Downing (1985); Coles (1988); and Sheppard (1988). Sheppard produced several exhaustive reviews of the area's fauna and ecology (Sheppard and Sheppard 1991; Sheppard et al. 1992). Saudi Arabian corals received detailed treatment by Fadlallah et al. (1992, 1995a, b). Many other studies followed (George and John 1999, 2000a, b; Riegl 1999, 2002, 2003; Sheppard and Loughland 2002; Purkis and Riegl 2005; Purkis et al. 2005; Burt et al. 2008; Riegl and Purkis 2009; Sheppard 1993; Sheppard et al. 2010; Sale et al. 2010). New hard coral species were described from the Gulf by Hodgson and Carpenter 1995, Wallace 1999, Veron 2000, Benzoni 2006 and Claereboudt 2006, while the soft corals received a detailed review by Samimi-Namin and van Ofwegen (2009). Early phycological work in the Gulf goes back to Endlicher and Diesing (1845); Borgensen (1939); and Newton (1955a, b). The most exhaustive recent overview was provided by De Clerck and Coppejans (1996) and John (2005).

The 1991 Gulf War, oil spill, and ensuing ecological problems led to several international expeditions (ROPME 1993; Abuzinada and Krupp 1994; Downing and Roberts 1993; Krupp et al. 1996). Since then, the amount of sedimentological and biological research in the area has increased with the influx of interest and money centered on oil and recently real-estate and industrial development, with the result of attracting an increasingly diverse and active research community. Unfortunately, more science is being done than published since many research reports remain confidential and are never made publicly available. One of the reasons for us

producing this book was to provide an easily available, generally valid, baseline that can assist in furthering applied and basic research on coral reefs in the wider Gulf area.

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Bernhard M. Riegl and Sam J. Purkis

2.1 Introduction

The Gulf is a peripheral basin of the Indian Ocean, at roughly 23°50′–29°52′ degrees northern latitude. It harbors extensive coral growth in one of the highest latitude locations in the world (Table 2.1). Due to its high-latitude position, its shallow nature, and its position within the great desert belt, the Gulf and its corals are exposed to extremes in temperature, salinity and other physical factors (Kinsman 1964a, b; Sheppard et al. 1992). But despite a seemingly hostile climate, corals endure and have been shown to exhibit remarkable resilience and vitality even if faced by some of the most extreme environmental conditions corals have to endure anywhere. This chapter will outline the most important physical constraints on reef building.

But it is not only corals that make the Gulf interesting. It is a famous study system for carbonate geology in general and is frequently cited as a classic example of a mixed carbonate-siliciclastic ramp system in an arid climate. This notion of a ramp is supported by the recognition that the Gulf area has a dominant shallow water carbonate/evaporite basin fill from the Permian to today despite a complex tectonic history (Alsharhan and Kendall 2003). The current depositional setting is that of a proximal foreland ramp (Burchette and Wright 1992; Evans 1995; Kirkham 1998).

We therefore have the opportunity to explore reef building, and carbonate sedimentology in general, in a typical ramp setting in an epicontinental sea. This is important from the modern point of view, since it is a quite unique environment. For the geologist and paleontologist, however, the interest lies in the analogies that can be drawn with other such systems that existed in earth history, such as the Paratethys in Europe (Riegl and Piller 2000).

B.M. Riegl (✉) • S.J. Purkis
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu; purkis@nova.edu

2.2 Sedimentary and Tectonic Environment

The Gulf is a marginal, epicontinental sea of approximately 1,000 km length, 200–300 km width with an area of 226,000 km² (Purser and Seibold 1973), connected to the Indian Ocean via the 60-km-wide Straits of Hormuz. An unstable Tertiary fold belt system lines the Iranian side, opposed to the stable Arabian foreland on the Arabian side (Purser and Seibold 1973). The Gulf is a distal foreland basin that, throughout Earth History, has been periodically flooded via the Straits of Hormuz (Figs. 2.1 and 2.2).

The Gulf basin is asymmetrical and has a gently inclined floor with a slope of 175 cm/km on the Iranian side and 35 cm/km on the Arabian side (Purser and Seibold 1973). Because the Gulf is surrounded by land and situated in an arid subtropical climate, no buffering systems like riverine input or the rapid turn-over of oceanic waters exist for temperature and salinity. Thus temperature variability is high (Kinsman 1964b) as is evaporation.

Important structural elements of the Gulf region include the Arabian platform, the Zagros Mountains and the Musandam Peninsula (Fig. 2.2). The Arabian platform underlies the Gulf and the Arabian Peninsula (the Gulf being a flooded distal portion of the platform) and exhibits anticlines formed in response to uplift of the Oman Mountains and possibly salt diapirism (Ross et al. 1986). The Zagros Mountains border the northern Gulf coast and consist of folded Paleozoic to Cenozoic shelf carbonates (Ross et al. 1986). This gives rise to the markedly different morphology at the northern, Iranian, coast, which is steep in contrast to the southern, Arabian, coast with very gentle gradients. The Musandam Peninsula consists largely of Mesozoic carbonates and juts into the Gulf at its entrance. It is presently subsiding while the Oman Mountains were uplifted to a rate of 60 m in the last 10,000 years (Ross et al. 1986).

The tectonics of the coastline surrounding the Gulf and the antecedent topography of the basin exert control on the distribution of facies belts. The Iranian coastline consists of steeply dipping anticlines trending NW-SE that formed

Table 2.1 The position of reefs in the Gulf in relation to other high latitude settings. “Reef” refers to documented reef frameworks. Since no cores or quantitative descriptions of any frameworks in Kuwait exist, it is also possible that what is described as reef is just corals following morphology

Locality	Latitude	Longitude	Temp. (°C)	Species	Reef	Citation
Kuwait-Kubbar Island	29°04' N	48°29' E	13–34	29	?	Benzoni et al. (2006)
Eilat-Gulf of Aqaba	29°30' N	34°55'	20–27	~100	Yes	Loya (2004)
Gulf of Suez	29°32' N	32°24'	14–34	35	Yes	Moustafa et al. (2008)
Japan, Shirahama	34°53' N	139°56' E	15–28	22	No	Nojima in Tsuchiya et al. (2004)
Lord Howe Island	31°32' S	159°04' E	17–25	65	Yes	Veron (1995)
Rottneest Island	32°00' S	115°32' E	19–23	18	No	Veron (1995) and Playford (2004)
Houtman Abrolhos	28°30'–29°0' S	113°05' E	20–24	201	Yes	Veron (1995) and Collins (2011)

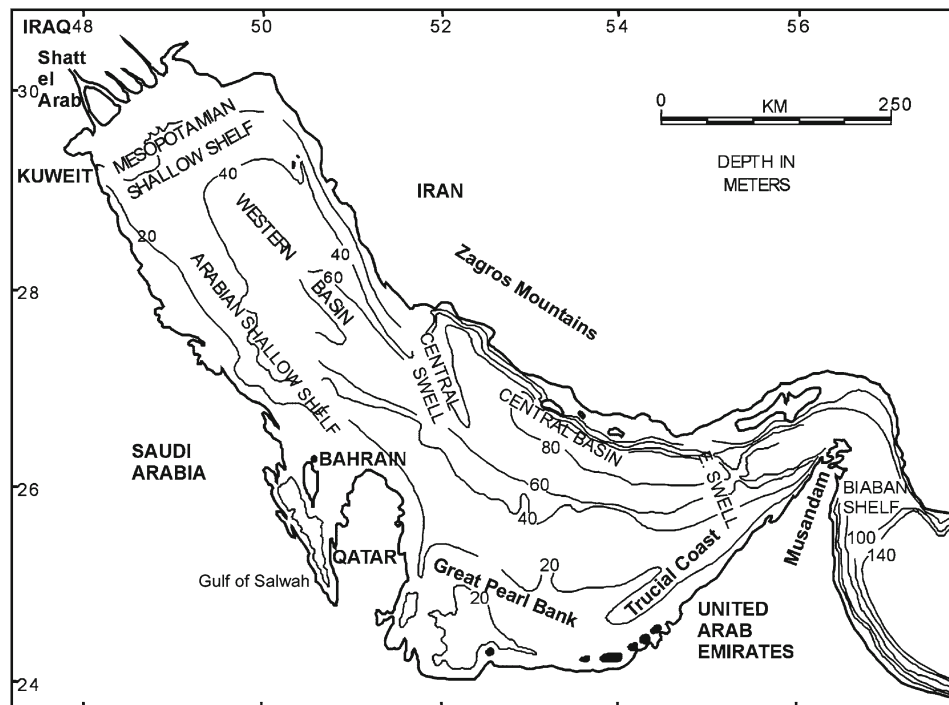


Fig. 2.1 Overview and basin subdivisions of the Gulf (Purser and Seibold 1973). The Central Swell divides the Western Basin from the Central Basin (Permission by Springer)

during the Plio-Pleistocene Zagros Orogeny (Kassler 1973). The anticlines' dips decrease from 50° on the mainland to 10–20° near the coast (Kassler 1973). As a result of mountain building, the Iranian shelf is narrow and is bound by a discontinuous island chain on its seaward side (Ross et al. 1986). Rivers import mud and fine sand, and the resulting sediment off the Iranian coast is dominated by marl. Grain size and carbonate content increases away from this coast (Seibold et al. 1973).

The Arabian coast consists of N-S to NE-SW trending, gently dipping anticlines (Kassler 1973) and the flooded portion of the Arabian Shield. The most recent uplift event of the Oman Mountains began in the late Tertiary and still continues (Kassler 1973). The Arabian marine shelf is wider and gentler than the Iranian shelf with flat-topped banks and

shoals produced largely by salt diapirism and erosional relicts of the Quaternary (Kassler 1973). It is characterized by low sandy islands, beaches with shallow channels, and coastal salt flats in which evaporites are precipitated, locally known as sabkhas (Ross et al. 1986).

The local sedimentation regime, especially if heavily terrigenously influenced, is a major issue for reef building. The Gulf can be separated into two clearly distinct regions. The Iranian side receives terrigenous sediments from the Zagros Mountains of Iran and the Tigris-Euphrates delta of Iraq (Enos 1983) while its Arabian side is gently sloping and fits the model of a typical carbonate ramp setting. It receives virtually no riverine input at all. On the Arabian side, the coastal area is formed by wide sabkhas (tidal flats composed mainly of fine, windblown material and *in situ* evaporites that

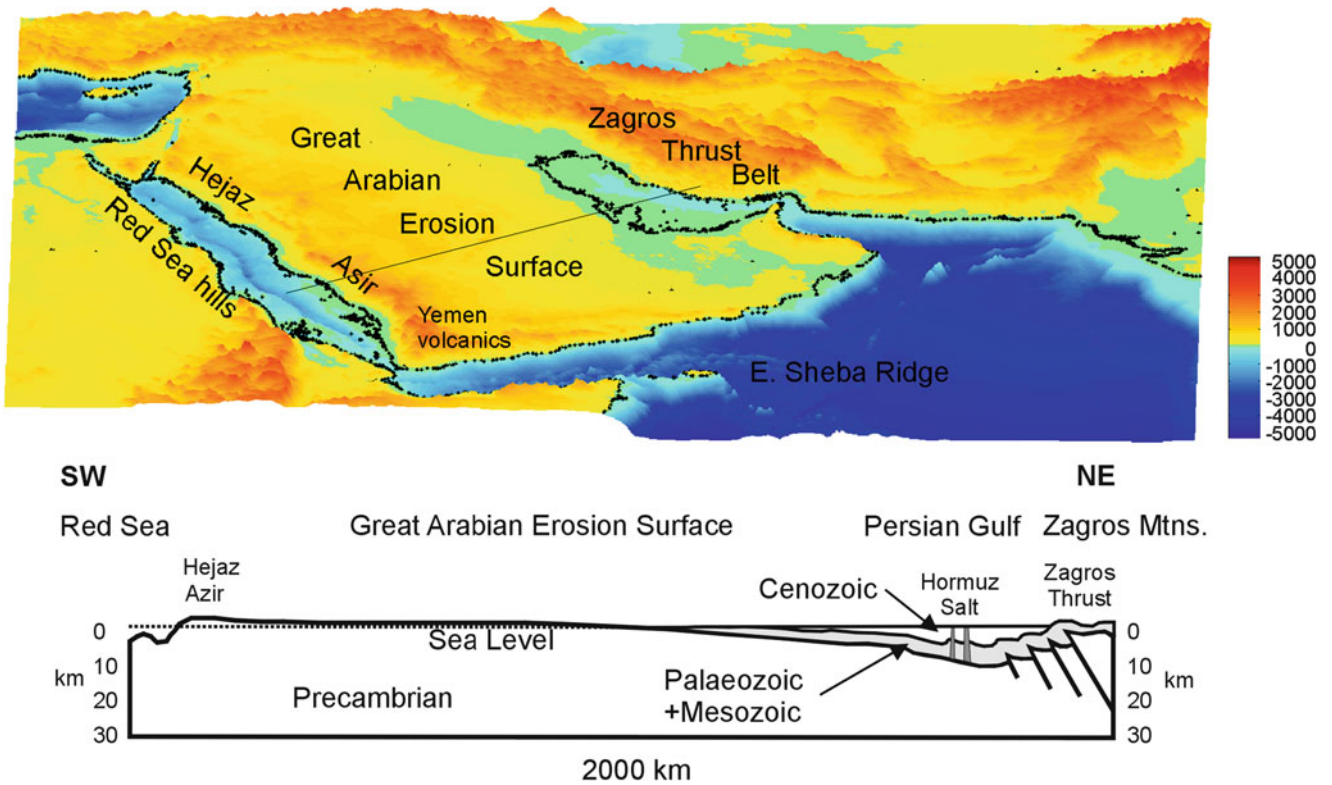


Fig. 2.2 Overview and schematic NE-SW section through the Arabian plate. The Gulf represents a flooded foreland basin (elevation data Etopo2, courtesy NOAA NGDC; section from Walkden and Williams 1998) (Permission by Geological Society of London)

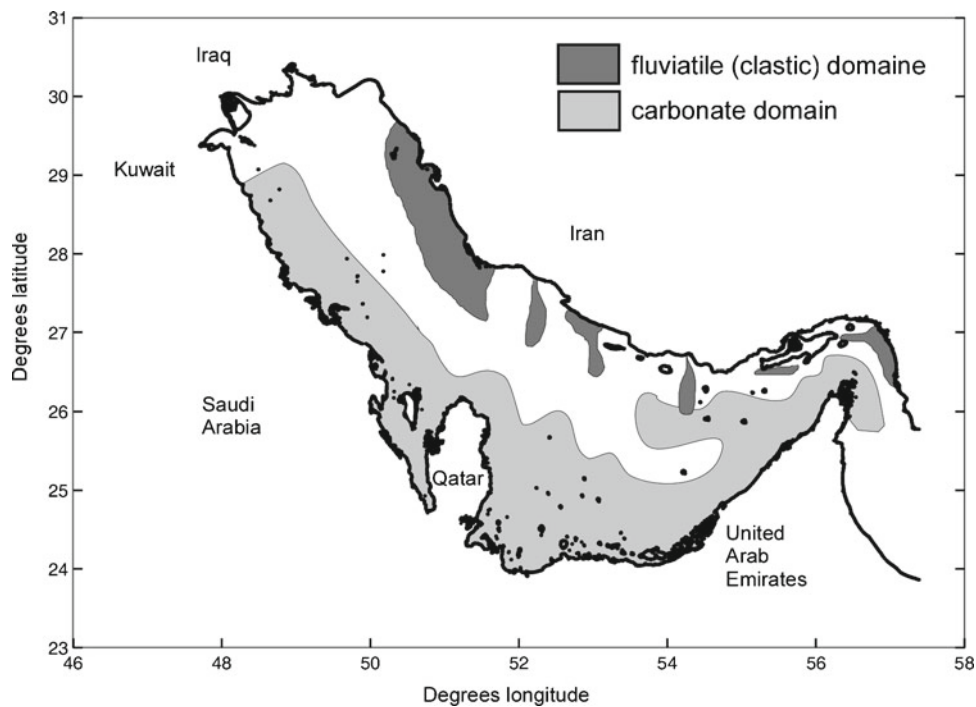


Fig. 2.3 Major sedimentary domains of the Gulf. Northern domain characterized by high fluvialite input, Southern by carbonate sedimentation. In areas with strong fluvialite sediment input, coral reefs are absent (combined from Diester-Haas 1973; Uchupi et al. 1999) (Permission by Springer)

prograde into the shallow coastal sea), tidal lagoons and flats, channels, sand bars, and coral buildups (Fig. 2.3; Diester-Haas 1973; Uchupi et al. 1996, 1999).

2.3 Bathymetric Environment

The southern Gulf is marked by numerous bathymetric highs that range from tens of meters to kilometers in diameter and occur at variable depths from around 20 m to depths shallow enough to allow reef growth or exposure at low tide (Purser 1973b). Bathymetric highs can be categorized as basin central, intermediate, or coastal (Purser 1973b). Many of these topographic irregularities are an expression of salt tectonics by the Hormuz salt, and are formed on so-called salt diapirs (Fig. 2.2).

Sedimentological trends on the offshore bathymetric highs include: (1) foraminiferal sands on more deeply submerged highs towards the basin axis and coral-algal reefs on the less deeply submerged highs towards the Arabian shoreline and (2) increased sand size with increasing water energy near the Arabian shoreline (Wagner and van der Togt 1973; Purser 1973b) and (3) reef building, in particular on the upwind fringes of such highs. The surfaces of the shallower offshore highs were also repeatedly exposed during sea-level lowstands which has led to the development of characteristic karstic features that later were overprinted by reef frameworks (Purkis et al. 2010; Chap. 3).

Islands in the Gulf are of variable origin. In the extreme northern Gulf, near the delta of the Shatt el Arab, they are depositional and consist largely of mud derived from the river. Also mainly depositional are the barrier islands of the Abu Dhabi nearshore region. These consist of an older core (usually of Pleistocene or older origin) and an accretionary tail of Holocene sands that accumulates in their lee. These islands were fronted by reefs (or at least well-developed coral communities) until recently (some still are; in others the reefs were removed by dredge-and-fill projects) and have well-developed oolitic bars in the tidal deltas between adjacent islands (Purser and Evans 1973). The offshore islands in the southern Gulf, and most in the northern Gulf, are of structural origin. Bahrain is an anticline and the island chain off Iran is part of the Zagros fold belt (Ross et al. 1986). Most of the islands in the SE Gulf are entirely made up by, or at least include some salt diapirs. Salt diapirs cause continuous rise, and have created terraces of raised reef and shoreline deposits, for example at Kish, Qeshm, Larak and Hormoz (Pirazzoli et al. 2004; Bruthans et al. 2006).

Around salt domes “exotic” material, pushed to the surface by the salt’s action, can be reworked and incorporated into the sediment. Thus, Paleozoic dolomite, volcanic rocks and heavy minerals such as magnetite can be locally found (Purser 1973b). For reef building, bathymetric highs



Fig. 2.4 Arzanah (UAE) is a typical salt-dome island. In the core of the uplift (inside the *white circle*), “exotic”, i.e. much older than the surrounding sedimentary sequences, underground material is pushed to the surface. A well developed reef fringe surrounds much of the island (Courtesy Google Earth)

are important in providing shallow habitat for the initial-ization of coral growth. Virtually all of these shallow areas either have, or have had until recently, more or less dense coral cover and on many, active reef-building is observed (Chap. 5) (Fig. 2.4).

On the northern, Iranian, side of the Gulf, several islands, or parts thereof, are being uplifted as a result of salt tectonics and with them, reef terraces mostly of Pleistocene age. Such fossil reef terraces have been described from Kish and Qeshm by Pirazzoli et al. (2004), Hormoz and Qeshm by Bruthans et al. (2006), and also occur at Larak and Hengam. In striking contrast to late Holocene reefs of today, where very little apparent framebuilding is observed in most regions of the Gulf, some of these Pleistocene terraces expose thick coral framestones, many of them dominated by *Acropora* (Samimi-Namin, personal communication; Fig. 2.5).

2.4 Marine and Atmospheric Environment

Reef building in the Gulf faces severe physical constraints and despite a rich coral fauna and widespread coral growth, frameworks and reefs in the traditional sense (as observed in the Indo-Pacific) are relatively scant. The reason is in the



Fig. 2.5 Aspect of a raised Pleistocene reef framework terrace on Kish and Larak Islands, Iran (Images by K. Samimi-Namin). The two images from Kish on the *left* show a massive coral facies, the image on the *right*

from Larak shows *Acropora clathrata* or *downingi* tables, comparable to today (Preliminary dating suggests MIS 5)

physical configuration of the Gulf, a high-latitude, semi-enclosed basin situated within the great desert belt. The major physical constraints to carbonate sedimentology in general and reef-building in particular are the semi-enclosed, shallow nature and the arid setting with resulting hypersalinity, strong temperature variability, and the complicated circulation (John 1992a; Sheppard 1993). However, much of the seafloor is located within the photic zone, allowing for an expansive photozoan tropical carbonate factory (Schlager 2005) – which includes reef builders. Restriction of oceanic circulation due to the narrow Straits of Hormuz results in a relatively low rate of water exchange with an estimated 90% flushing time of 5.5 years (Hughes and Hunter 1979).

The Gulf is situated in a strictly arid climatic zone (Grasshoff 1976) characterized by low rainfall (Emery 1956) and high evaporation rates (estimates vary from 144 to 5,000 cm/year, Seibold 1973; Johns et al. 2003). Not surprisingly, it loses more water by evaporation than it gains by land run-off and consequently exhibits a Mediterranean-style, reverse-flow, estuarine-type circulation (Reynolds 1993). The Gulf region is mainly subjected to extra-tropical weather systems that are strongly influenced by orography (Murty and El-Sabh 1984). The Straits of Hormuz form a boundary between the generally east to west travelling tropical weather systems south of the Gulf and the west to east travelling extra-tropical weather systems within the Gulf basin (Murty and El-Sabh 1984). The arid climate, in the context of sediment transport, translates to low stream discharge with

consequently slow deposition of clastic sediments (Emery 1956). Additionally, because rainfall is scarce, few perennial streams other than the Shatt el Arab, ever reach the Gulf. Most of the approximately 4–24 cm/year of rainfall occur in just a few days during the winter months resulting in markedly pulsed delivery of clastic sediment. Since this is deleterious to reef building, reefs are largely absent close to major drainage lines, particularly on the Iranian coast.

The Gulf marine environment has been differentiated with respect to vitality, diversity, abundance and sediment-production potential of calcareous biota into (Hughes Clarke and Keij 1973):

- The **normal marine environment** of salinities up to ~50‰ that is roughly comparable to the normal marine environment of the Indo-Pacific, but poorer in species. It is here that reefs are found. Upon entering areas with restricted flow and higher salinities (such as the Gulf of Salwah) important fauna is lost (e.g. almost all corals, the perforate foraminifera *Operculina*, *Heterostegina*, *Amphistegina*; the gastropods *Strombus*, *Conus*, *Xenophora*, all pectinids and all echinoids except *Clypeaster*).
- The **restricted environment** of salinities between 50‰ and 70‰ is found in many coastal areas and dominated by imperforate foraminifera and gastropods, in particular of the genus *Cerithium*. Corals are usually absent or very rare in this environment, although faviids sometimes do occur.
- The **highly restricted environment** of salinities exceeding 70‰ is found only in some isolated lagoons, such as Khor

Table 2.2 Summary of physical parameters

Parameter	Datum	Source
Waves	4–5 m (storm)	Murty and El-Sabh (1984)
	6 m (storm)	Shinn (1976)
	Wave base 20 m	Purser and Seibold (1973)
Wind	Speed: 5–12 m/s	John et al. (1990)
	Dominant direction: N-WNW	Murty and El-Sabh (1984)
	Max. sustained speed: 40–50 km/h	Shinn (1976)
	65 km/h	John et al. (1990)
Tides	Max. gust speed: 100 km/h	
	1–3 m	Lehr (1984)
	2–4 m	Jones (1986) and Sheppard (1993)
Currents	0.5 m (Gulf of Salwah)	Sheppard (1993)
	Tidal: 50+ cm/s 0–4 m from bottom	Seibold (1973)
	100–200 cm/s through restrictions and past islands	Sheppard (1993)
	Residual: 20 cm/s bottom current exiting strait; else 10–40 cm/s	Koske (1972) and Grasshoff (1976)
Typical water temperature		Johns et al. (2003) and Thoppil and Hogan (2010b)
	20–32°C (offshore)	Hughes Clarke and Keij (1973)
	15.9–35.5°C (W Gulf)	John et al. (1990)
Light penetration	15–40°C (lagoons)	Purser and Seibold (1973)
	20 m (shallow-deep water transition depth based on biota)	Hughes Clarke and Keij (1973)
	30+ m (Gulf axis)	Purser and Seibold (1973)
Storms	Several Shamals per year	Murty and El-Sabh (1984) and Thoppil and Hogan (2010a)
Rainfall	3–8 cm	Reynolds (1993)
Evaporation	140–500 cm	Reynolds (1993)

al Odaid in Qatar and other lagoonal areas. These areas are largely devoid of fauna, except cyprideid ostracods.

In the following we shall provide a brief discussion of the most important physical factors that influence reef building in the Gulf (Table 2.2).

2.4.1 Wind

Atmospheric circulation patterns are strongly influenced by the Indian Ocean monsoon. The Gulf basin is enclosed by the Arabian landmass with its northern barrier formed by the Zagros Mountains and the Anatolian Plateau which exert strong influence on local weather patterns. The dominant wind direction is generally from NW towards SE (Figs. 2.6 and 2.7).

Among the most important weather patterns is the Shamal, meaning “north” in Arabic and referring to NW winds that occur most dramatically during winter. Alsharhan and Kendall (2003) consider the Shamals as equally important sedimentological drivers as the Caribbean hurricanes and they certainly have a dramatic effect on Gulf reef building (Shinn 1973; Fadlallah et al. 1994, 1995). Shamals can be

dramatic events that tend to set in with great abruptness and force (Murty and El-Sabh 1984; Thoppil and Hogan 2010a), often with wind speeds of 40–50 km/h and gusts up to 100 km/h (Membery 1983; John et al. 1990; Fig. 2.7). Both summer and winter Shamals are known, those in summer being less powerful. The Shamal is a low-level wind (the air masses close to the ground flow faster than those higher up, Fig. 2.8) and is generally speaking the result of an interaction between barometric lows and highs over Arabia and the Gulf region as well as Iran, Pakistan and Anatolia (Fig. 2.9). The dominant NW to SE airflow of the region is attributed to orography. Sharply rising mountains lie to E and N while gently rising mountains lie to W and SW effectively funneling the low-level airflow.

Low-level channeling of air can also affect southerly to southeasterly winds and create what is known as “Kaus” in Arabic and “Shakki” in Farsi (Fig. 2.9). These winds are strongest on the eastern side of the Gulf where the Zagros mountains in western Iran intensify the flow. The Kaus can precede the Shamal and increase in intensity as the Shamal-bearing cold fronts approach. These Kaus-events, like Shamals, have the potential to generate galeforce winds (62–74 km/h) (Murty and El-Sabh 1984).

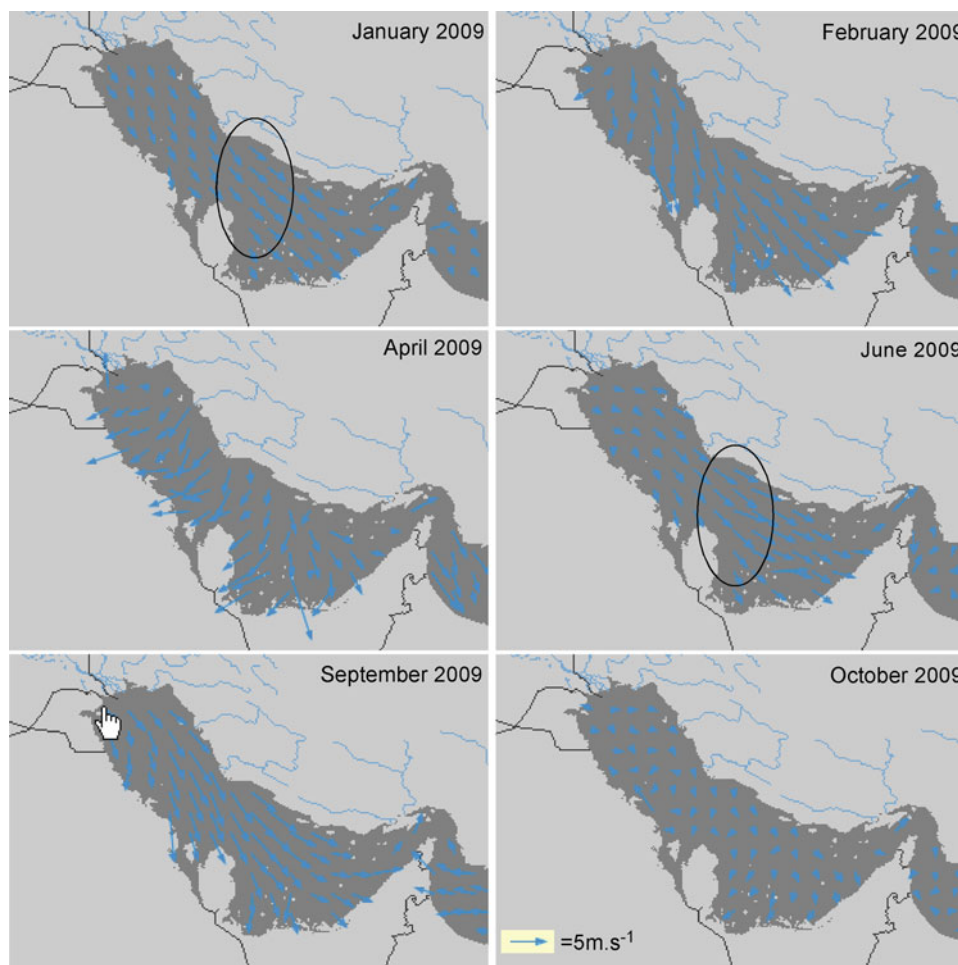


Fig. 2.6 Monthly composite Quikscat wind vectors for 2009. It can be seen that throughout the year, dominant airflow is from NW-SE, funnelled by the regions topography. The winter months are generally windier than the summer and fall (October 2009 being an example of a particularly calm month). The difference in average wind strength between January 2009 and February 2009 shows the strong contribution of the winter Shamal. The wind direction in April 2009 is

characteristic of the strong seabreezes caused by the springtime warming of the Arabian desert. June and September 2009 show the contributions of summer Shamals. In January and June 2009, wind funnelling between Ras Rakan (N tip of Qatar) and Lavan Island in Iran is clearly visible as a strengthening (lengthening) of averaged wind-vectors in this area (inside the *black oval*) (Data courtesy NOAA, <http://coast-watch.pfeg.noaa.gov/erddap>)

The Shamal has two characteristic durations, short (24–36 h) or long (3–5 days), that are determined by the interaction between upper and lower airflows. Longer Shamals are associated with a large pressure gradient between the Gulf of Oman Low and the Saudi Arabian High making the Shamal strongest in S and SE ranging from 30 to 40 knots ($\sim 15\text{--}20$ m/s) and peaking at over 50 knots (~ 25 m/s). Typical speed is about $\sim 2.5\text{--}7.5$ m/s, which is greater than the average wind speed in the northern Gulf, but can reach 16 m/s (Thoppil and Hogan 2010a). Upon the Shamal's onset, the wind direction at a given locality depends on coastal orography. In the northern part of the Gulf the wind blows from between N and WNW. Winds in the middle Gulf blow from between WNW to NW. On the SE coast, the Shamal blows from the W. Around the Straits of Hormuz it flows from the SW (Table 2.3). Not surprisingly, Shamals are among the most

important wave-generating winds that also modify current-strength and even flow patterns.

The dry Shamal picks up dust and sand from the unprotected surfaces of the desert regions and aeolian transport can create dust storms that account for an appreciable proportion of the delivery of siliciclastic material to the Gulf (Emery 1956). This dust-input is not sufficient to have any appreciable effect on reef building. But airborne dust can become so thick that visibilities of less than 55 m have been reported (Table 2.4). In the northern Gulf, dust fall-out from southern Iraq amounted to 6.9 g/m²/year (ROPME 1987) while elsewhere in Arabia, dust precipitation values of up to 22 g/m²/year have been recorded (Behairy et al. 1985).

Shamals have strong effects on the thermal balance of Gulf waters as cooling agents. Latent heat flux can be increased up to $>1,000$ W.m⁻², resulting in cooling of surface

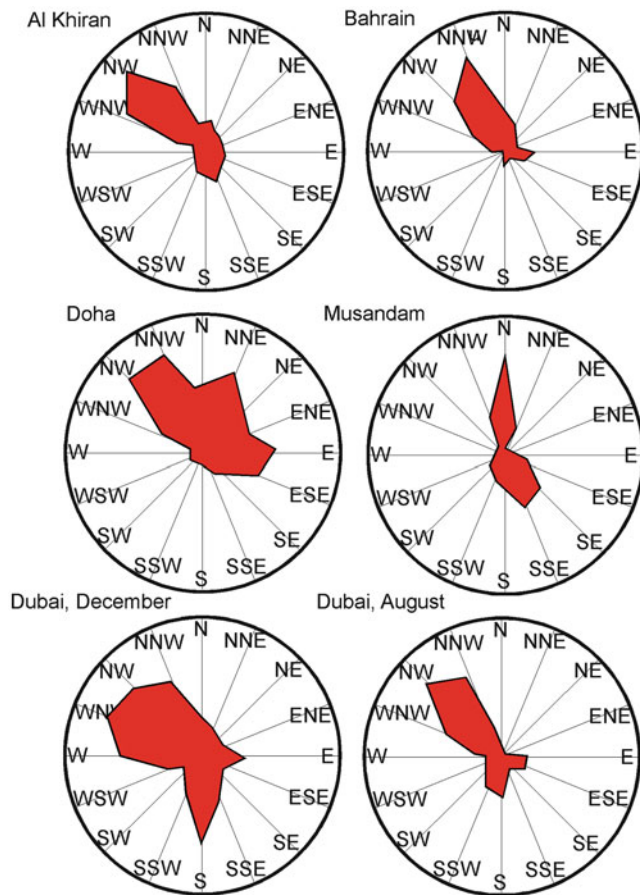


Fig. 2.7 Annual windroses for several sites in the Gulf. Winds in the Musandam no longer conform to the typical Gulf pattern

waters by up to 10°C, mostly in the Gulf's northern reaches and the more shallow areas in the S and SE (Thoppil and Hogan 2010a; Fig. 2.10). Much of the net heat loss (~38%, Thoppil and Hogan 2010a) is due to air-sea humidity differences. In 1964 in Qatar, air temperature dropped to 0.5°C and surface water to 4°C, while 80 km offshore at a depth of 17 m, the water temperature dropped to 14.1°C (Shinn 1976). Air temperatures approached the freezing point in 1982 off Kuwait, driving sea surface temperatures to below 7°C (Downing 1985). Sheppard (1993) and Sheppard et al. (1992) report fish kills that follow such cold weather episodes almost annually off the Saudi Arabian coast.

Additionally, the Shamals cause an erosion of the thermocline, which is usually strongly developed in the Gulf's deeper areas (Azarmsa 2008; Ezam et al. 2010; Thoppil and Hogan 2010a). Shamals also induce convective vertical mixing, which erodes and deepens the mixed layer by up to 30 m. The strong wind's action on surface waters reduces sealevels in the Gulf's northern reaches while increasing them in the south in the form of a storm surge. Storm surges create ~25–40 cm sealevel differences during a 4-day Shamal (Thoppil and Hogan 2010a). Extremes of 2–3 m positive surge in the Gulf of Salwah as well as the shallow southern Gulf and 1 m negative surge have been reported from the northern Gulf (Murty and El-Sabh 1984; El-Sabh and Murty 1989, Fig. 2.11). Negative storm surges combined with cold air temperatures have killed corals in Saudi Arabia due to exposure (Fadlallah et al. 1994, 1995).

Shamals also increase the speed of the Iranian Coastal Current from about 10 cm/s to 25–30 cm/s (Thoppil and

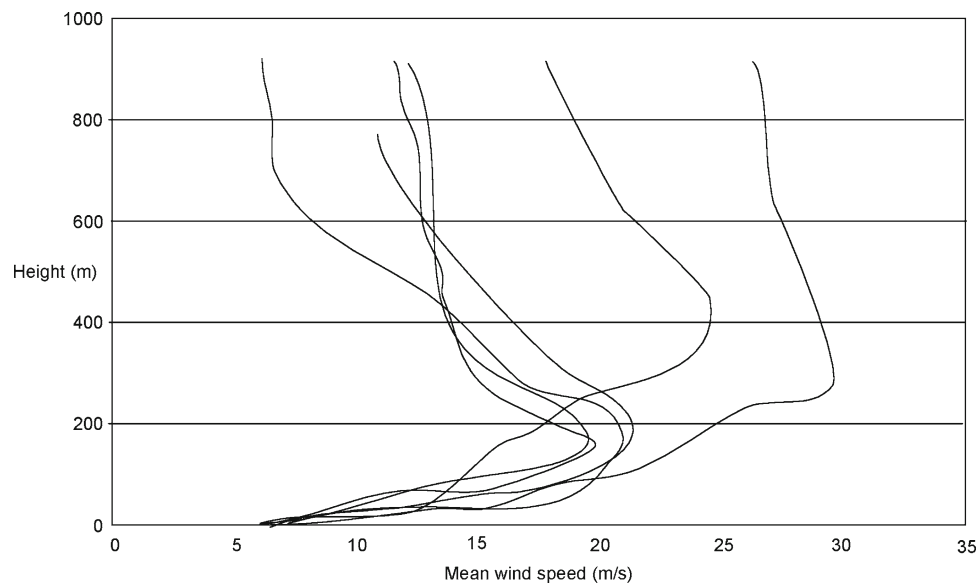


Fig. 2.8 Shamal and Kaus winds are low-level winds, and thus strongly influenced by topography. Graph shows wind profiles of several Shamal events that clearly show maximum flow at low elevations (From Membery (1983))

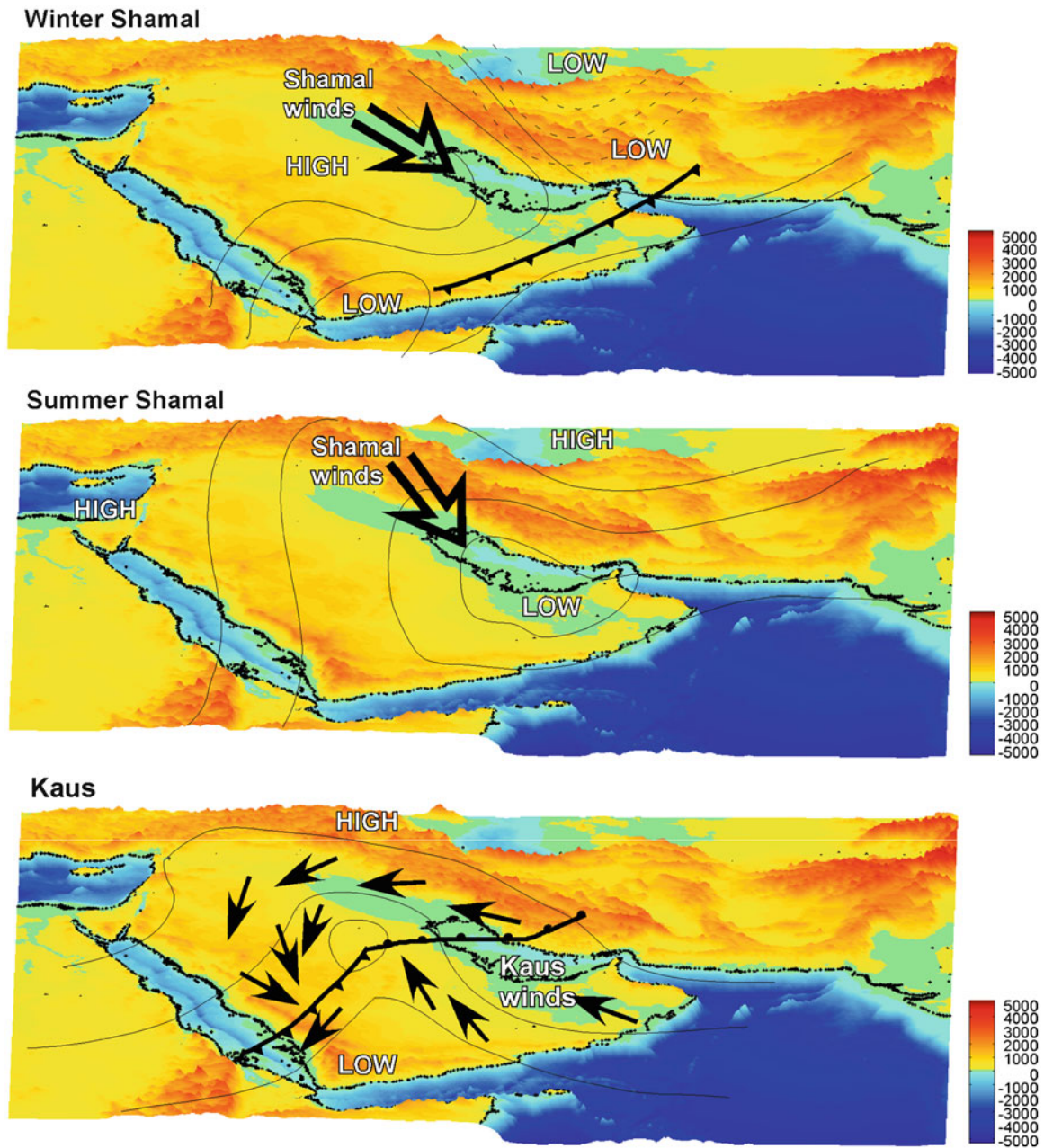


Fig. 2.9 Winter Shamals tend to follow cold fronts emanating from the Anatolian/Iranian highlands and move across a low over Arabia and Pakistan. Summer Shamals are a direct reaction to the summer heat buildup over Arabia and the southern Gulf region. Air

flows in from the NW to fill this low. The Kaus winds are the result of cyclonic-type disturbances over Arabia and are strongly funneled by the Zagros mountains. In the Gulf region, they flow from the S

Hogan 2010a) and cause the formation of eddies at about 52°E, creating currents directly from the Iranian coast towards the SE. Such eddies may be important for the transport of larvae, significantly shortening the time required for planctonic organisms and larvae to travel from Iran to the SE Gulf while also avoiding the colder northern Gulf.

Typical and ubiquitous winds are strong local seabreeze-landbreeze systems (Table 2.4). The effects of local winds

are probably more important to the marine biota, especially in terms of exerting stress, than the broad scale wind systems (Sheppard 1993), which is shown by a clear seaward-landward gradient of reefal buildups around offshore highs and islands. During summer afternoons along the coastlines, the sea breeze, caused by convection associated with heating of the nearby land, can reach tens of m/s and form dust storms. These breezes cause mixing of the water layers, removing

Table 2.3 Wind speed and directions of western Gulf stations (John et al. 1990)

Month	Speed and direction		
	<i>Dhahran</i>	<i>Ras Tanura</i>	<i>Safantyah</i>
January	19 NW	17 NW	15 NW
February	21 NNW	17 N	15 N
March	21 N	18 N	17 N
April	21 N	17 N	15 N
May	22 N	17 NNW	15 NNW
June	24 NNW	18 NNW	15 NNW
July	19 N	15 N	12 N
August	19 NNW	15 NNW	13 NNW
September	19 N	13 NNW	10 NNW
October	16 N	13 NNW	13 WNW
November	19 NW	15 WNW	15 WNW
December	19 NW	17 WNW	17 WNW
# Year	24	6	6

Table 2.4 Frequency of dust storms as a proxy for strong landbreezes in 1967 and average for 1943–1967 in central (Baghdad) and southern (Basrah) Iraq (Kukul and Saadallah 1973)

	Baghdad 1967	Baghdad average	Basrah 1967	Basrah average
January	1	1.1	0	0.3
February	1	2.1	0	0.6
March	1	2.5	2	1.0
April	4	2.3	4	1.3
May	3	2.3	3	1.4
June	1	2.2	0	2.9
July	1	3.6	4	3.1
August	0	1.6	3	1.7
September	0	0.6	1	1.2
October	3	1.3	1	0.8
November	1	1.1	0	0.3
December	2	0.8	1	0.1
Total	17	21.5	19	14.7

stratification and thermal stress, which is important for the avoidance of bleaching and the persistence of corals (Chaps. 5 and 6). At night, the breezes reverse and can have a powerful desiccating effect on intertidal biota and coastal vegetation (Sheppard 1993). Dew caused by the seabreeze-landbreeze systems encourages the development of vegetation on the nearshore dune systems protecting sediment from the wind (Kendall et al. 2003) and leading to the formation of phytodunes (nebkhas). Kirkham (1998) and Alsharhan and Kendall (2003) suggest a constant dominant wind direction throughout the Holocene and Quaternary. Even throughout the Pleistocene, wind-direction was generally comparable though during the glaciials, winds were stronger than during the interglaciials (Glennie 1996) (Table 2.5).

2.4.2 Waves

Waves and surface currents are the most important mechanisms of sediment transport in the Gulf (Purser and Seibold 1973) and of key importance to reef building processes. Since the strongest winds are the NW Shamals, waves and surface currents are, for much of the year, also mainly oriented towards the SE. This makes the SE Gulf the most exposed environment and the NW Gulf, near the Shatt el Arab, the most sheltered (Figs. 2.6 and 2.12). The sediments on the Arabian (southern) side of the Gulf are clearly more of the “exposed” type (i.e. bioclastic and oolitic) and can occur to depths of about 20 m in its SE portion. Waves and surface currents produced by Shamals can cause strong water column mixing to a depth of about 30 m (Sarnthein 1970; Thoppil and Hogan 2010a).

Shallow depth and strong stratification produce wave amplitudes that are larger than would be expected under similar conditions in deeper water (Perrone 1981). After 12 h, gale force winds can generate wave amplitudes of 4–6 m (Murty and El-Sabh 1984; Shinn 1976). During Shamals, the entire Gulf experiences gale force winds, with the strongest winds and largest swells in the S portion (Murty and El-Sabh 1984) and lows in the N due to fetch limitations. The highest wave amplitudes occur near the NE coast of the Qatar Peninsula (Ras Rakan), Lavan Island in Iran and the Abu Dhabi, Umm al Qawein and Al Hamra regions (Purser and Evans 1973; Murty and El-Sabh 1984). Between Qatar and Lavan this is due to wind-funnelling (winds exceeding ~10 m/s occur ~10% of the year, which is twice the Gulf average, Perrone 1981), in the UAE to the coastline being almost perpendicular to the dominant swell direction (Fig. 2.13).

2.4.3 Tides

Gulf tides are complex and regionally variable. They range from diurnal to semi-diurnal to mixed. Tidal ranges are relatively large, exceeding 1 m everywhere and at the Shatt el Arab surpassing 3 m (Lehr 1984). Off Kuwait, spring tidal ranges are 2 m in the S and up to 4 m in the N (Jones 1986; Sheppard 1993). The diurnal tide enters the Gulf through the Strait of Hormuz and progresses along the coast of Iran in a NW direction, then turning to the SE hugging the Saudi Arabian coast. It proceeds back toward the Straits in a Kelvin wave fashion with a central nodal point, the tidal range increasing progressively from the node to the coast (Defant 1961; Lehr 1984; John 1992b). The diurnal component of the tides has dimensions close to resonance (Hughes and Hunter 1979), with a natural period of 22.6 h (Defant 1961). The diurnal tidal constituents have a single amphidromic point in the centre of the Gulf near Bahrain (Kaempf and Sadrinasab 2006). There are also semi-diurnal components, which propagate

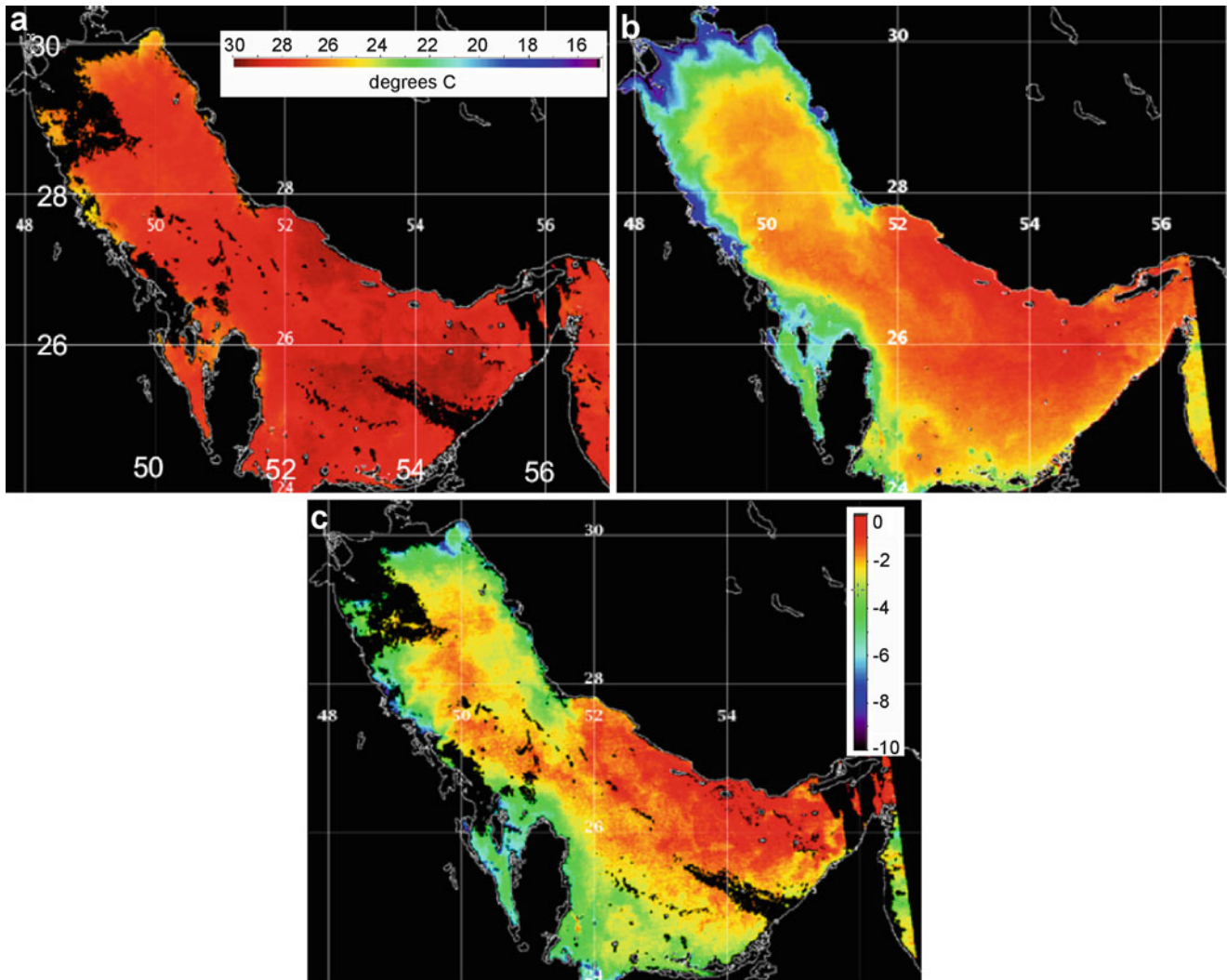


Fig. 2.10 SST cooling forced by a strong Shamal in 2004. (a) SST on 17 November 2004, (b) SST on 29 November 2004, (c) SST difference (From Thoppil and Hogan (2010a) by permission of Elsevier)

counter-clockwise around two amphidromic points within the Gulf (Figs. 2.14 and 2.15), one in the northwest and the other in the southwest (Lehr 1984).

Off Kuwait and Bahrain, the generally irregular diurnal nature of the tides ameliorates the extreme temperature conditions for shallow and intertidal biota to some degree (Sheppard 1993). High tide covers the shallows in daytime during the summer and exposes them at night, while in winter, when night air temperatures are low, the high tide occurs at night providing protection. This advantage does not occur throughout the entire Gulf, however, and in parts of Qatar, Saudi Arabia, and the UAE the intertidal areas are often exposed during the day in summer (Sheppard 1993).

In Bahrain, a complex of coral buildups and sand shoals (Fasht Al-Adhm) stretches across the northern portion of the Gulf of Salwah. It is believed that these structures are partially responsible for restricting water exchange and significantly

reducing the tidal range from 1.2 m just north of Bahrain to 0.5 m in the south of the Gulf of Salwah (Sheppard 1993). The significance of this restriction is profound when viewed in light of the fact that the Gulf of Salwah produces a portion of the dense saline bottom water that drives overall circulation in the Arabian Gulf (John et al. 1990, 1991). In this case the coral buildups and associated sedimentary bodies around the Fasht Al-Adhm control not only the local tidal range, but also influence the overall circulation within the entire Gulf.

2.4.4 Currents

The current regime is a complex and variable combination of tidal, wind- and density-driven components (Figs. 2.16 and 2.17). The kinetic energy of the water velocity associated with the three current-driving mechanisms can be partitioned

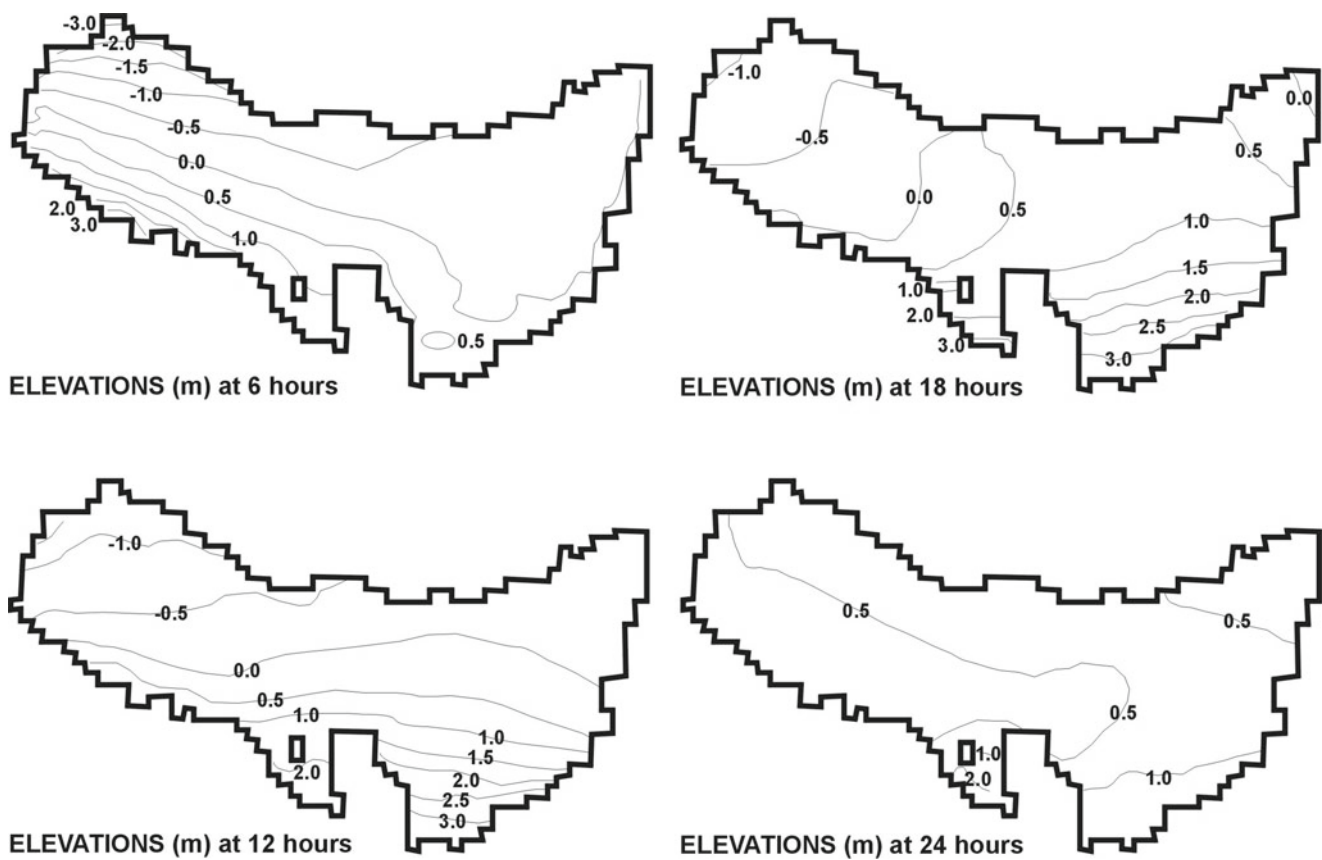


Fig. 2.11 Distribution of positive and negative storm surge heights (Murty and El-Sabh 1984) for the peak hours of a long duration winter Shamal (Permission by UNESCO)

Table 2.5 Location and sedimentary parameters of the delta region of the Hilleh River in Iran (Melguen 1973). These sedimentation rates far outpace reef growth rates, which is consequently suppressed along the shoreline (Permission by Springer)

15 km	8 m	<50 cm/s	4–5 m/ka
15–17 km	8–15 m	<50 cm/s	2–4 m/ka
19 km	25 m	<50 cm/s	1.5–2 m/ka
19 km	25 m	<50 cm/s	1 m/ka
18 km	21 m	<50 cm/s	0.8 m/ka
80–120 km	21–46 m	<50 cm/s	0.8–1 m/ka
18 km	21 m	<50 cm/s	<0.8 m/ka

among tidal, wind, and density at approximately 100, 10, and 1, respectively (Reynolds 1993). Tidal currents are complex and run mainly parallel to the Gulf's long axis, with velocities in excess of 50 cm/s at 0–4 m from the bottom (Seibold 1973). Tidal streams commonly exceed 1–2 m/s past islands and through constrictions (John 1992b; Sheppard 1993). Local tidal types not always match local tidal current regimes, so a diurnal tide may result in a semi-diurnal current regime and flow reversals may be directionally bimodal or rotary. Additionally, wind-driven currents are produced by local phenomena like land-sea breeze regimes, but are influenced on a Gulf-wide scale by the Shamal.

Density driven currents result primarily from the high evaporation rate. Wind and density-driven currents are collectively called the residual current (Fig. 2.17). The general flow regime can be characterized as: a surface flow of Arabian Sea water entering the Gulf through the Strait of Hormuz, then flowing NW along the Iranian coast as Iranian Coastal Current, the strongest current in the Gulf with a magnitude >40 cm/s in July, accompanied by a weaker counter-flow (~5 cm/s) at depth (Thoppil and Hogan 2010b). During March–April, a quasi-permanent cyclonic circulation develops in the central Gulf (52–55°E) due to Ekman drift driven by prevailing NW winds and buoyancy differences. In July and August, the cyclonic circulation dissociates into 3–4 cyclonic eddies and often an additional anticyclonic eddy (Fig. 2.18), which are the Iranian Coastal Eddies (ICE, Thoppil and Hogan 2010b). These eddies have diameters of ~115–130 km, extend over most of the water column and remain stationary. Around November, the eddies then dissipate. When reaching near the Shatt el Arab water cools in winter and sinks. Also in the Gulf of Salwah and other portions of the SE Gulf, water becomes dense enough to sink due to evaporation. After sinking, it flow NE toward the Strait of Hormuz where it exits as a bottom current with a velocity of about 10 cm/s (Koske 1972; Grasshoff 1976; Ezam et al. 2010).

Fig. 2.12 Wave amplitudes in meters in the Gulf for January, April, July and October (Modified from Murty and El-Sabh (1984). Permission by UNESCO)

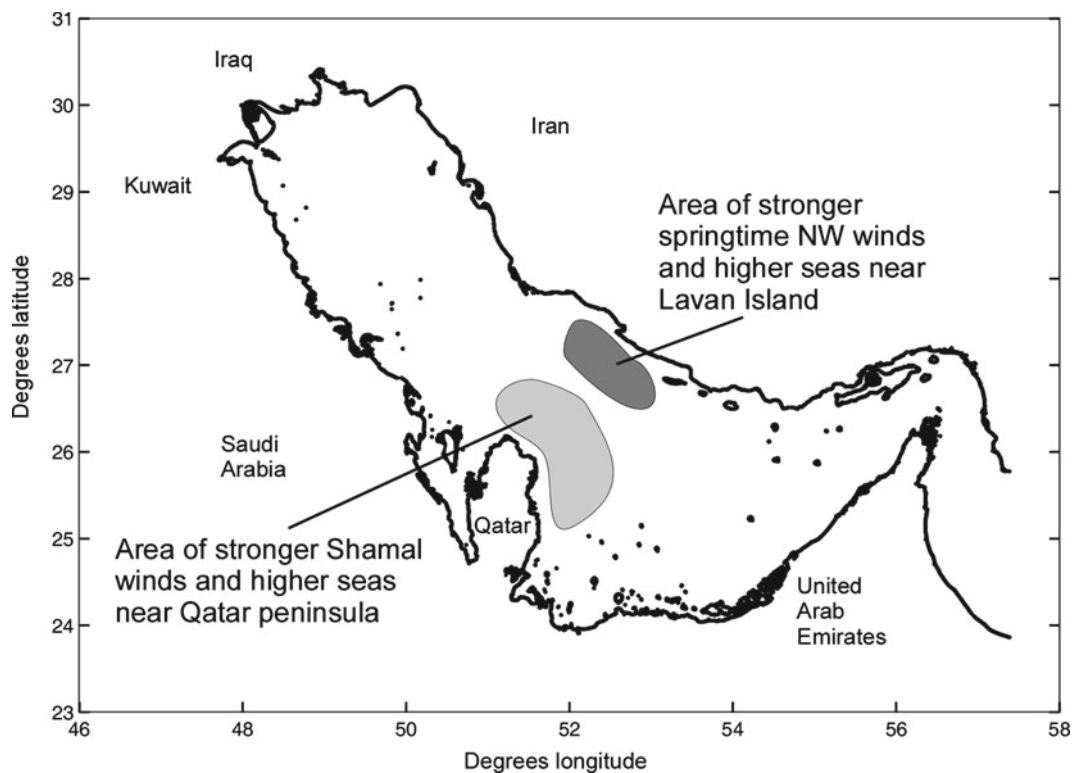
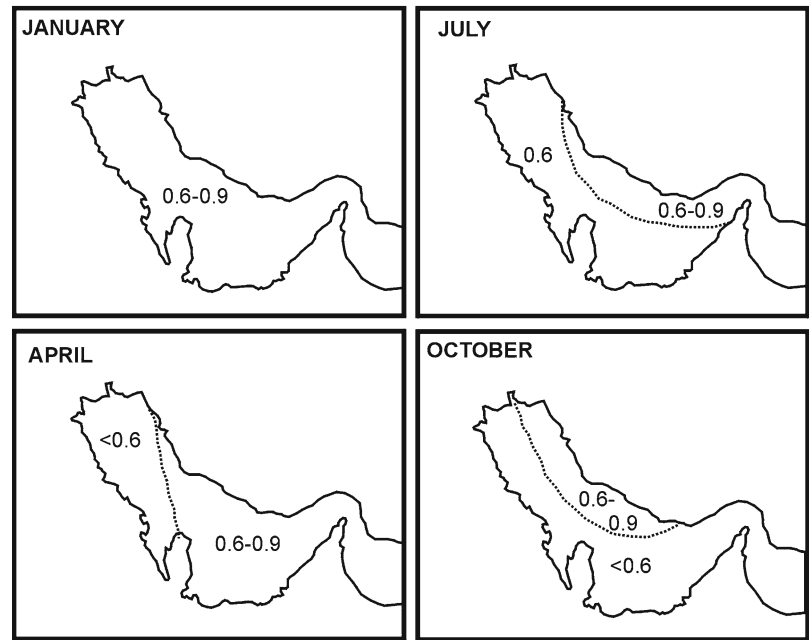


Fig. 2.13 Areas of wind-funneling in the central Gulf, where the frequency of gale-force winds is double that from the Gulf average, as is the occurrence of high waves

An upwelling cell exist along the northern Iranian coast (49–51°E; Sadrinab 2009; Thoppil and Hogan 2010b) which is forced by coast-parallel winds of speeds >9 m/s blowing for at least 4 days (Sadrinab 2009). This coincides with absence of coral reefs along the Iranian mainland coast (Figs. 2.17 and 2.25).

Fresh water runoff has a significant impact on the residual currents in the northern Gulf (Galt et al. 1983), where it and terrigenous material is introduced by intermittently flowing rivers from the Zagros Mountains. River input is deflected to the right by the Coriolis force and forms an ~20 km wide plume continuing along the Iraqi coast towards Kuwait

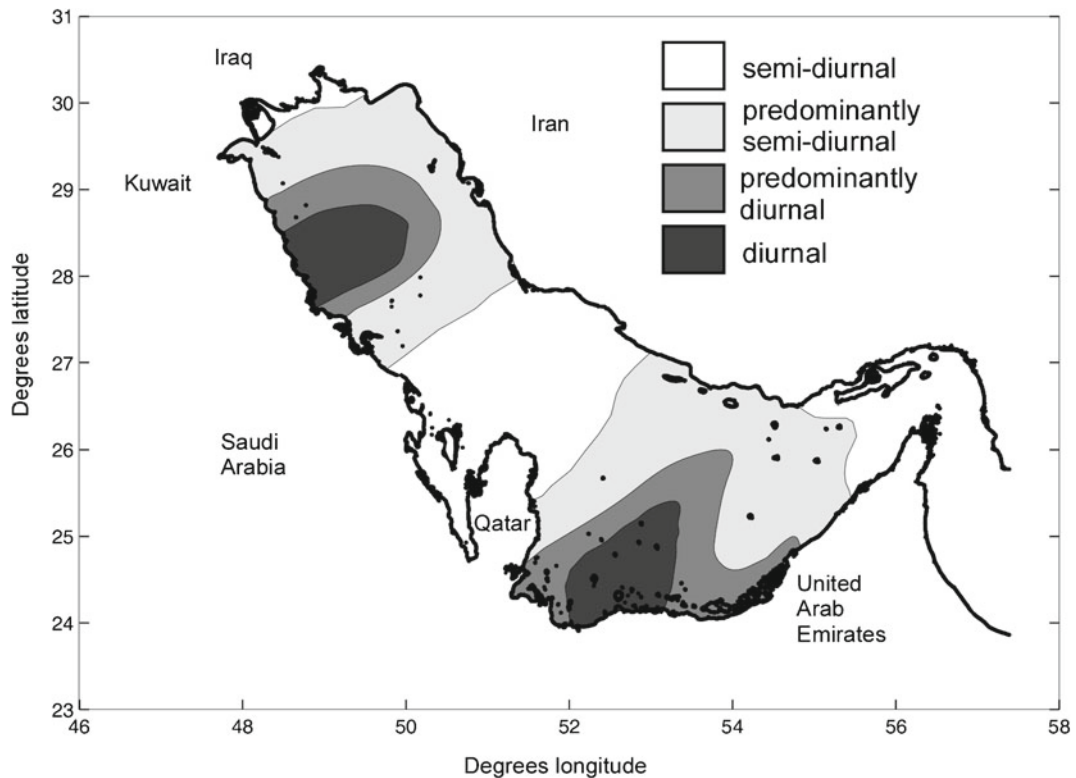


Fig. 2.14 Tidal classification in the Gulf (Jones 1986)

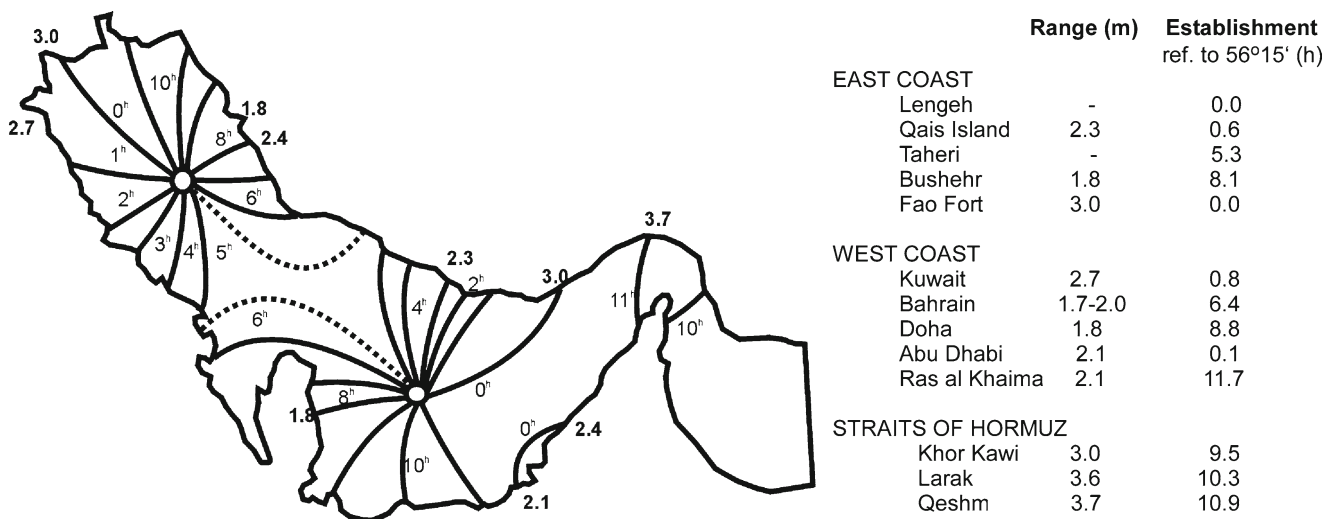


Fig. 2.15 Tidal ranges and amphidromic points of the semi-diurnal tidal constituents in the Gulf (Defant 1961; Reynolds 1993)

(Matthews et al. 1979; Hunter 1983a, b) (Fig. 2.16). The fluviially derived sediment has built up a young Holocene blanket deposit in the West Basin extending up to 30 km into the Gulf. The supply rate of fluvial source material is enough to allow sedimentation rates on the order of several m/ka, which renders the several cm/ka supply rate of the

wind-transported fraction insignificant in comparison (Seibold 1973) and explains the absence of reefs near major rivers along the Iranian coast.

The tidal currents, in concert with wind-driven currents and waves, then transport the fluviatile material parallel to the coast towards the SE (Seibold 1973), which is opposite to

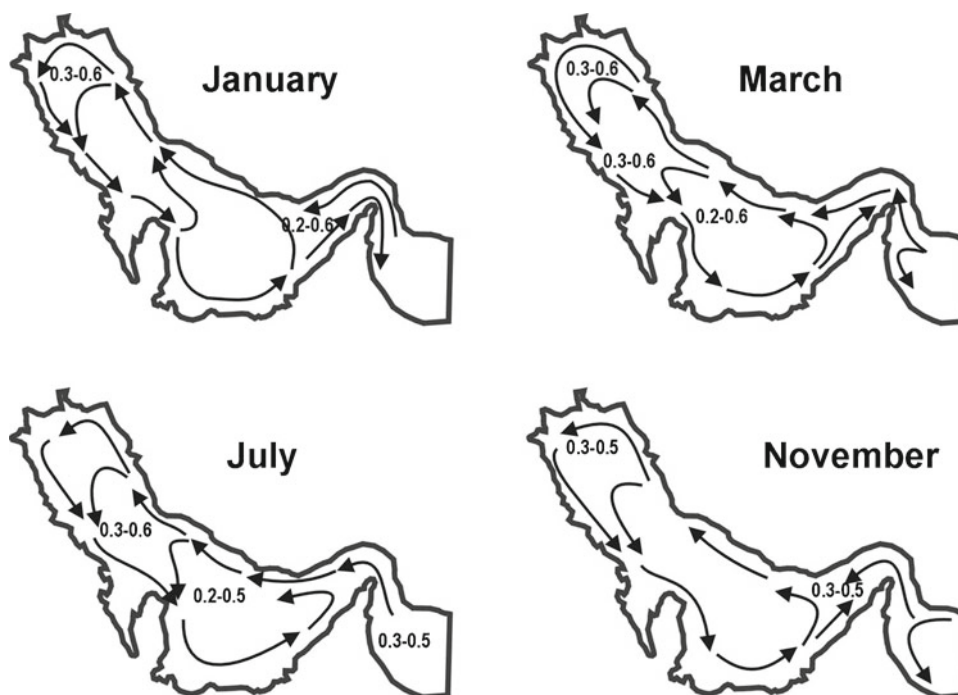


Fig. 2.16 General surface currents, average speed in knots (From U.S. Navy Hydrographic Office 1960)

the reported counter-clockwise flow of the residual current (Figs. 2.16 and 2.17). This dominant transport direction also helps explain why the Central Swell has prograded into the Gulf and built up to a height reaching 10–40 m. Further to the SE, longshore transport is interrupted by islands and steeper bottom slopes. Here, the fluvial material is carried directly into the deeper water of the Central Basin (Seibold 1973).

2.4.5 Water Temperature

The seasonal range of sea surface temperatures underlines the variability of the basic hydrographic parameters (Grasshoff 1976). Highs can exceed 36°C in summer and fall below 15°C in winter (John et al. 1990, Table 2.6, Fig. 2.17). Temperature data with direct relation to reefs are shown in Chaps. 4 and 6. Temperature has since long been identified as a key component in the control of reef building (Kinsman 1964b; Downing 1985; Sheppard 1993; Riegl 1999) as well as in the composition of other fauna and flora (Schils and Wilson 2006).

From a sedimentological perspective, the high summer temperatures are favorable for biogenic (Emery 1956; Seibold 1973) as well as chemogenic (Emery 1956) carbonate production, resulting in prolific hardground generation, important for the initiation of coral growth. Ooids form near the Strait of Hormuz, where they account for over 80% by weight of the calcium carbonate in the sand size fractions.

Together with salinity, water temperature is the most powerful determinant of Gulf reef building. Over 20°C fluctuations

between summer and winter are reported (Kinsman 1964a, b; Coles 1988; Coles and Fadlallah 1991; Sheppard et al. 1992; Fig. 2.18). Consequently, species-specific tolerances to low or high temperature (Coles and Fadlallah 1991; Sheppard et al. 1992) and to salinity are deciding factors for assemblage structure and richness of the fauna and flora. Fadlallah et al. (1995) report that extreme low water temperatures are among the major control for coral die-off and an obstacle to expansion of certain species in the Gulf. They provide evidence for repeated cold-related coral kills in the winters of 1983, 1985, 1989 and 1992. Mass-coral bleaching and significant mortality occurred due to high-temperatures in 1996, 1998, 2002 and 2010 (Chaps. 5 and 6). There is agreement that temperature is a key factor affecting coral distribution, community structure and reef-building processes.

Sheppard et al. (1992) give an overview of species-specific reactions to temperature fluctuations (Table 2.7).

2.4.6 Salinity

Marked horizontal and vertical salinity gradients exist (Brewer and Dyrssen 1985) (Fig. 2.19). Inflowing surface waters from the Arabian Sea are at a salinity of about 36.5‰ and increase rapidly to about 40‰ roughly along the E-W axis. Salinity characteristics change seasonally with less Indian Ocean water entering the Gulf in winter and the boundary of higher saline Gulf waters and less saline inflowing Indian Ocean water migrating east from a line ~50°E to ~52°E.

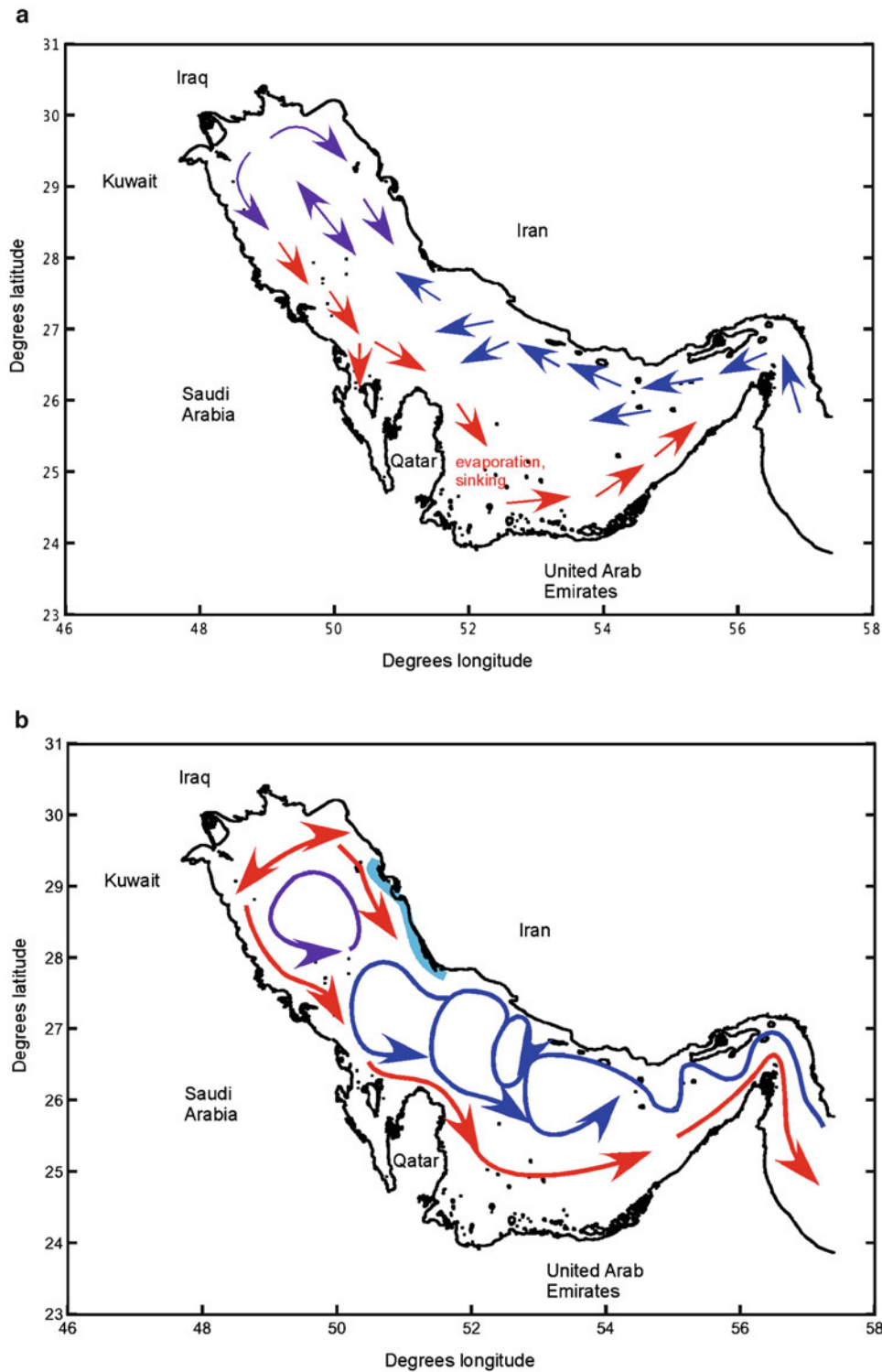


Fig. 2.17 Schematic of surface currents and circulation processes in the Gulf. (a) General pattern (Reynolds 1993; Lardner 1993), (b) circulation when the Iranian Coastal Eddies are fully developed (Thoppil and Hogan

2010b) (Permission by American Meteorological Society). *Blue arrows*=inflowing low-salinity water, *red arrows*=outflow of high-salinity water, *purple*=transition zone, *light blue* along the coast=upwelling

Maximum inflow from the Indian Ocean is in May-June (Johns et al. 2003). The Shatt el Arab, the only continuous freshwater source causes salinities to decrease in the extreme

N to about 36‰ in summer (Fig. 2.20). Highest salinities, up to and in some places in excess of 43‰, are found on the shallow Arabian side (Azam et al. 2006; Kaempfer and

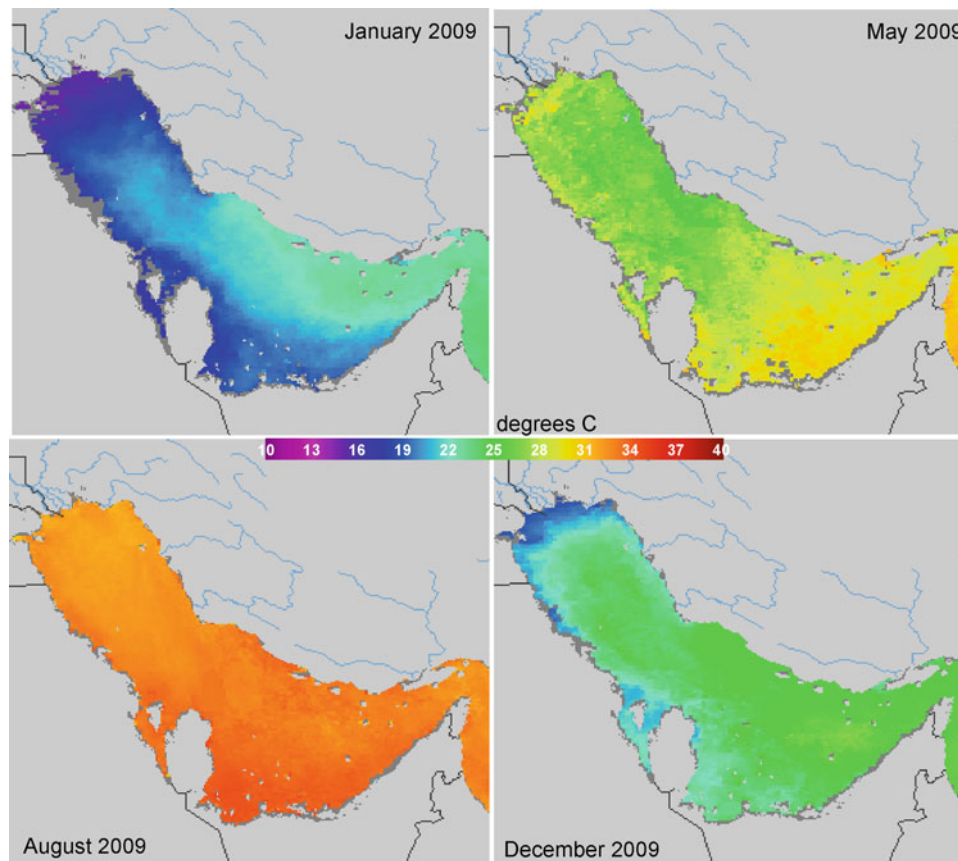


Fig. 2.18 Averaged monthly Pathfinder SST in 2009. Maximum water temperature differences between monthly averages were 21°C in the northern Gulf, and ~17°C in the SE Gulf (Data courtesy NOAA (<http://coastwatch.pfeg.noaa.gov/erddap/>))

Table 2.6 Temperature extremes and ranges of Arabian reef areas (Sheppard 1993)

Location	Latitude	Min (°C)	Max (°C)	Range
Saudi Gulf	27°N	11.4	36.2	24.8
Qatar Gulf	24°N	14.1	36.0	21.9
Abu Dhabi Gulf	25°N	16.0	36.0	20.0
Kuwait Gulf	29°N	13.2	31.5	18.3
Suez Red Sea	29.5°N	17.5	30.0	12.5
Aqaba Red Sea	29°N	20.0	28.0	8.0

Sadrinasab 2006) dividing the Gulf in a northern less saline, and southern more saline realm. Dense waters are created in the northern Gulf in winter, which together with the highly saline waters from the Arabian side forms the deep water on the Iranian side, with salinities above 40‰, that eventually leave the Gulf as a deep outflow with ~20 m/s velocity (Brewer and Dyrssen 1985; Reynolds 1993; Swift and Bower 2003; Johns et al. 2003; Kaempfer and Sadrinasab 2006). The Gulf is most saline and water is densest in winter which is the period of the region's maximum rainfall. Much of that precipitation is bound in snow and what fresh water enters the Gulf is diverted into currents flowing S along the Iranian and Arabian coast (Swift and Bower 2003) allowing a center of

Table 2.7 Coral and brown algae species surviving high temperature ranges in the Gulf. Sheppard et al. (1992). Values are in degrees Celsius

Temperature fluctuation	8–15	15–20	20–28	30
<i>Acropora</i> sp.	X			
<i>Stylophora pistillata</i>	X	X		
<i>Porites nodifera</i>	X	X		
<i>Cyphastrea microphthalma</i>	X	X	X	
<i>Siderastrea savigniana</i>	X	X	X	
<i>Porites harrisoni</i>	X	X	X	
<i>Platygyra daedalea</i>	X	X	X	
<i>Porites lutea</i>	X	X	X	
<i>Psammocora contigua</i>	X	X	X	
<i>Pavona varians</i>	X	X	X	
<i>Coscinarea monile</i>	X	X	X	
<i>Leptastrea purpurea</i>	X	X	X	
<i>Favia pallida</i>	X	X	X	
<i>Favia speciosa</i>	X	X	X	
<i>Favia fava</i>	X	X	X	
<i>Favites pentagona</i>	X	X	X	
<i>Turbinaria</i> sp.	X	X	X	
<i>Sargassopsis</i> brown algae	X	X	X	X

dense water to develop in the northern Gulf off Kuwait (Fig. 2.20). Dense water is also produced on the banks and in

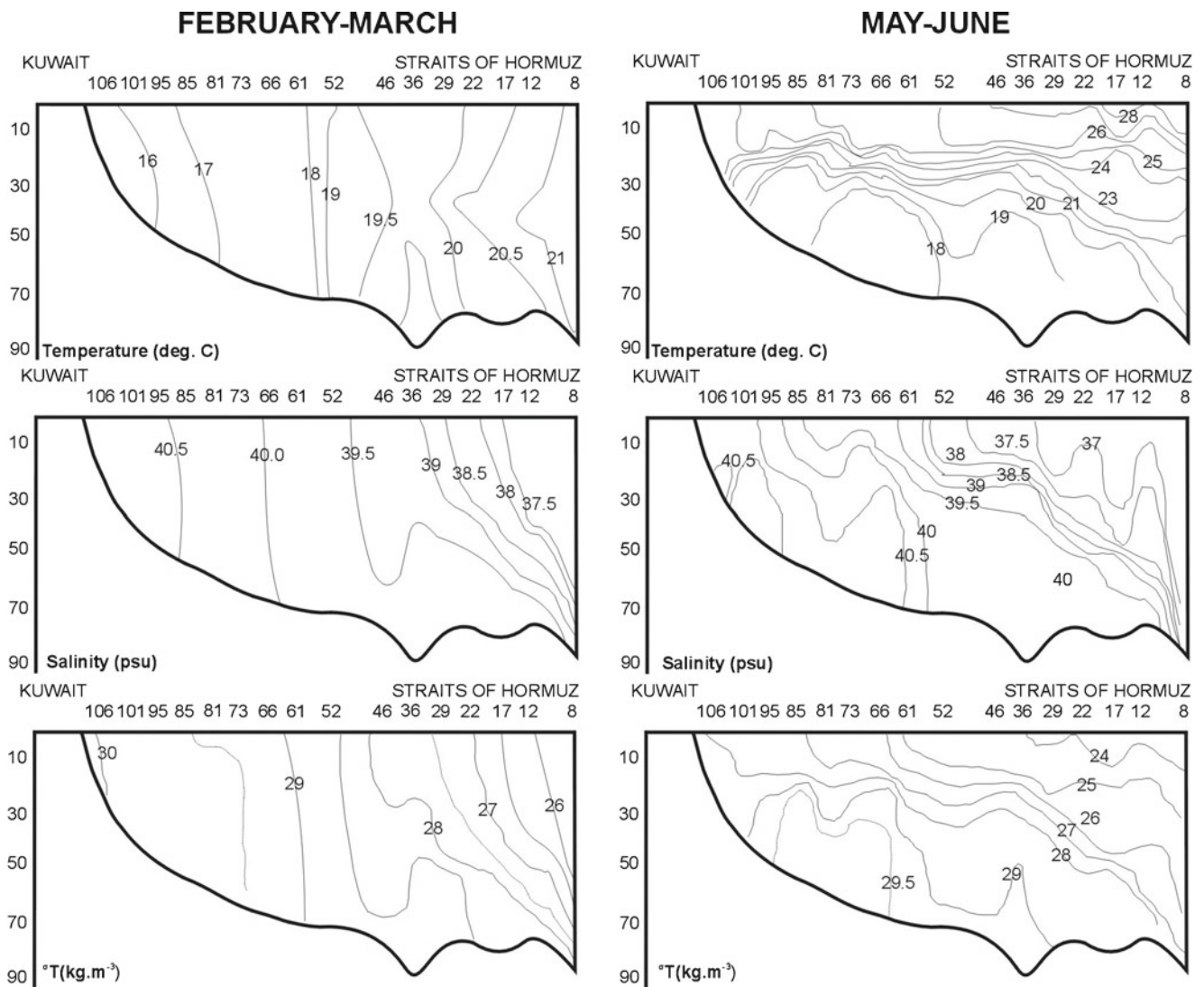


Fig. 2.19 Temperature, salinity and density depth profile of Gulf axis in summer and winter (Reynolds 1993) (Permission by Elsevier)

the shallow lagoons of the SE Gulf. As a result of the sinking of dense water, the surface incurs heat loss, strengthening the seasonal cooling trend in winter. Salinity gradients are steep with regards to coral reef development, and seasonal variability adds to the stress.

After temperature, salinity is the second most important determinant of the distribution of coral species and the consequent assemblage of communities and reef-building potential. Sheppard et al. (1992) give an overview of coral species-specific reactions to salinity fluctuations (Table 2.8).

2.4.7 Rivers

Wherever reefbuilding in the Middle East occurs, it tends to avoid river mouths since rivers tend to carry large amounts of sediment in the rare instances when they do flow (Table 2.9). Riverine input into the Gulf is overall small and has little

influence on salinity. The rivers comprising the Shatt el Arab, the Tigris, Euphrates, and Karun are the Gulf's only year round source of fresh water. They are also the major source of fluvial sediments (Fig. 2.21), have constructed a large delta and maintain nearby a naturally turbid and soft-bottomed region devoid of reefs. Seasonal turbidity near the delta and along part of the Iranian coast is the reason that coral reefs are absent and oyster beds are rare while being abundant in the SE Gulf (Emery 1956). The Coriolis effect deflects the Shatt el Arab river plume towards Kuwait and suppresses reef growth there. Reefs along the Kuwait mainland are only found at Ras as Zaur in southern Kuwait, and on the southern offshore islands (Kubbar, Qaro and Umm Al-Maradim; Gischler and Lomando 2005). Other important rivers are the Hilleh and Mand in Iran, which also suppress, together with temporary upwelling along this stretch of coastline (Sadrasab 2009), reef building on the northern Iranian mainland coast.

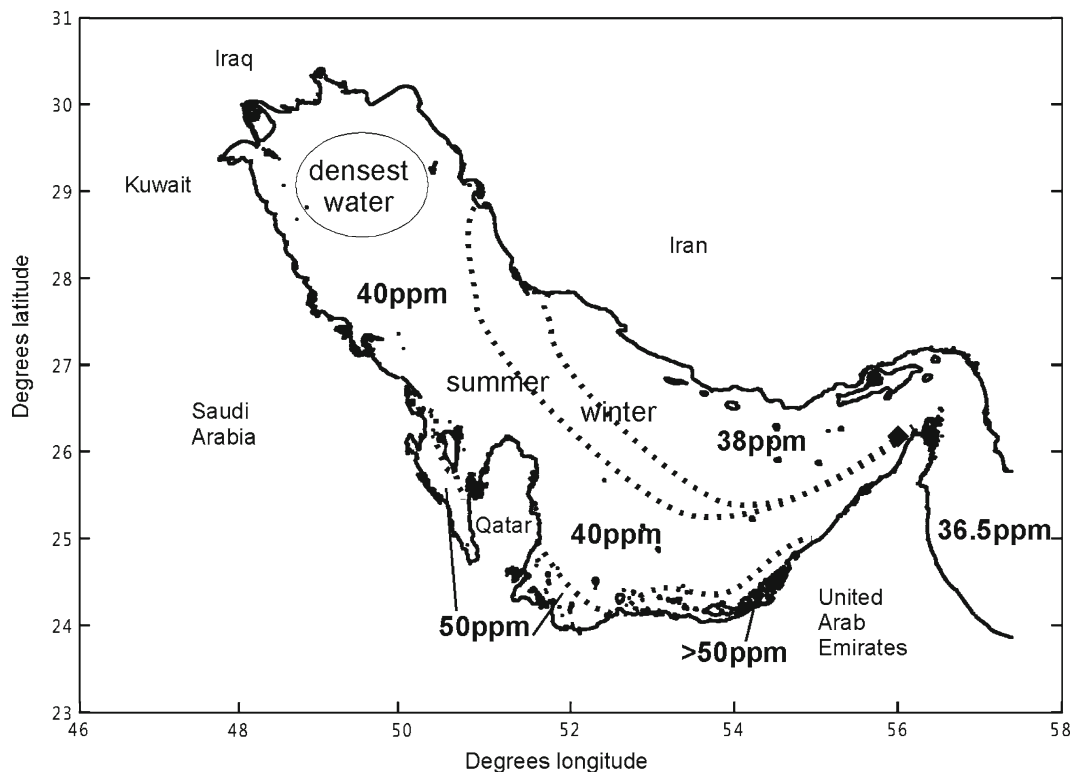


Fig. 2.20 Major salinity trend in the Gulf. The *dotted line* is the interface of the lower salinity Indian Ocean inflow and the more saline Gulf waters. It moves seasonally. Salinities are approximate

Table 2.8 Coral and brown algae species surviving high salinity in the Gulf. Sheppard et al. (1992)

Salinity (ppt)	46 ppt	48 ppt	50 ppt	>50 ppt
<i>Cyphastrea serailia</i>	X			
<i>Porites harrisoni</i>	X	?		
<i>Platygyra daedalea</i>	X	X		
<i>Favia pallida</i>	X	X		
<i>Favites chinensis</i>	X	X		
<i>Leptastrea purpurea</i>	X	X		
<i>Porites nodifera</i>	X	X	X	
<i>Cyphastrea microphthalmia</i>	X	X	X	
<i>Siderastrea savignyana</i>	X	X	X	
<i>Sargassum</i> brown algae	X	X	X	X

2.4.8 Light Penetration

In the shallow Gulf, suspended sediment can lead to considerable reduction of light penetration (Hughes Clarke and Keij 1973). Based on the relative abundance of light-dependent benthic organisms as an indicator of light penetration, the boundary between the well-lit zone and deeper water is at 20 m (Hughes Clarke and Keij 1973). This division is based on the presence of blue-green algae, calcareous and other algae, hermatypic corals and large perforate and imperforate foraminifera. The euphotic zone extends to

30 m or more in the less turbid, axial parts (Purser and Seibold 1973).

2.4.9 Oxygen and Nutrients

Nutrient-rich waters enter through the Straits of Hormuz and Coriolis deflection then concentrates them on the Iranian side (Johns et al. 2003). Thus, the highest nutrient concentrations are found in shallow waters of the northern Gulf. These waters originate in the north-eastern Arabian Sea, which has a strong vertical oxygen gradient with a maximum at about 50 m depth (Brewer and Dyrssen 1985; Reynolds 1993). Oxygen consumption and nutrient buildup within the Gulf are not high due to the short residence time and the deep outflow (Brewer and Dyrssen 1985). Silicate values are low, but rarely zero. The highest values (~6 moles/kg) were measured in the outflow of the Shatt el Arab (Brewer and Dyrssen 1985). Thus the Gulf is an oligotrophic sea.

2.5 The Carbonate System and Coral Reefs

Carbonate chemistry in the Gulf is advantageous for reef building and it is in general an area of active carbonate deposition. In most areas the CaCO_3 fraction of the sediments is >50%, except near the Iranian coast (Hartmann et al. 1971).

Table 2.9 Location and sedimentary parameters of the delta region of the Hilleh River in Iran (Melguen 1973). These sedimentation rates far outpace reef growth rates, which is consequently suppressed along the shoreline (Permission by Springer)

Distance from the estuary or the coast (km)	Water depth (m)	Current velocity (cm/s)	Sedimentation rate (approx.) (m/ka)
15	8	<50	4–5
15–17	8–15	<50	2–4
19	25	<50	1.5–2
19	25	<50	1
18	21	<50	0.8
80–120	21–46	<50	0.8–1
18	21	<50	<0.8

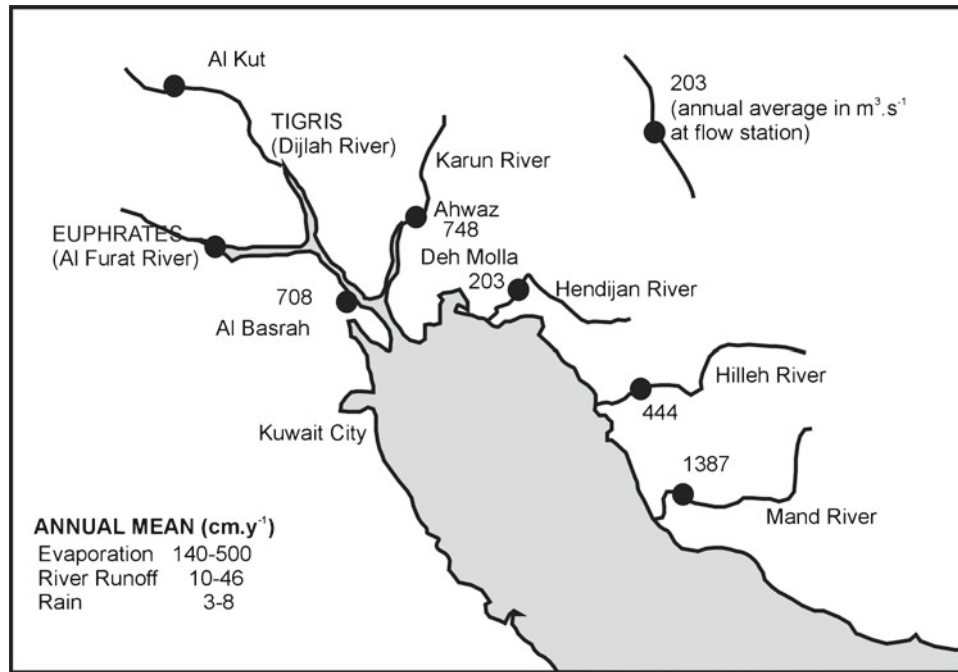


Fig. 2.21 River systems and fresh water import (Reynolds 1993). The river formed by the confluence of the Tigris and the Karun River is called Shatt el Arab, which is the major fresh water input into the Gulf.

The area between the Hilleh and the Mand is also subject to temporary coastal upwelling (Permission by Elsevier)

This active carbonate depositional regime is also expressed in solution chemistry with clear alkalinity losses of waters after entering the Gulf (Brewer and Dyrssen 1985). The greatest carbonate losses occur in the shallow areas off the coast of the UAE, which correspondingly is an area with very high biogenic carbonate sedimentation, submarine lithification and formation of whittings (precipitation of carbonate in the water column). Low alkalinity with high salinity is also found in the saline Gulf bottom waters. Part of these depleted, highly saline waters derive from the area of alkalinity depletion off the coast of the UAE (Brewer and Dyrssen 1985; Swift and Bower 2003). Thus, cementation certainly does not appear to be an issue for Gulf coral reefs. A greater issue are the temperature and salinity extremes

that in many areas do not allow corals to form extensive frameworks of enough coral density that could be cemented into solid reefs (Riegl 1999; Purkis and Riegl 2005).

Wide areas of the Gulf, in particular on the Arabian homocline, are characterized by marine hardgrounds consisting of recently lithified sand (Figs. 2.22 and 2.23). This is of prime importance for reef building and coral growth in general, which often takes place on such hardgrounds (Riegl 1999; Purkis and Riegl 2005). Shinn (1969) provided evidence by using pottery and other artifacts in the lithified sediment that the lithification process is syndimentary, taking place over just a few decades in depths to 30 m. Hardgrounds are cemented by acicular and fibrous aragonite and often also contain micritic cement of high-magnesium calcite

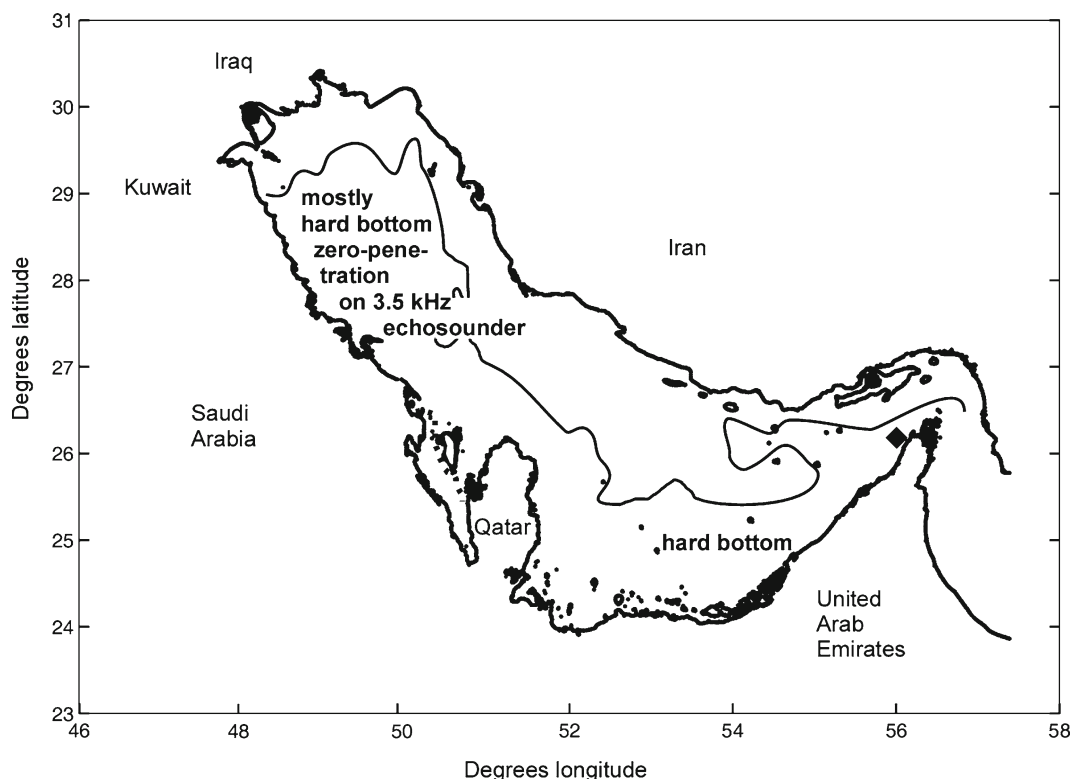


Fig. 2.22 The distribution of hard bottom in the Gulf (Uchupi et al. 1996). The southern Gulf is mostly hardground (Permission by Elsevier)

(Shinn 1969). The principal physical factors involved in this rapid lithification process are relatively low rates of sedimentation, sediment stability and a high initial permeability of the sediment.

Areas of rapid sediment accumulation, such as the leeward flanks of offshore highs and the nearshore belt of spits, bars, and tidal flats have only slight submarine cementation (Shinn 1969). However, where present, the lithification process leads to the expansion of the sediment layers and thus the generation of “submarine anticlines” and overthrust tepees. These areas are important nucleation points for coral reefs (Fig. 2.24).

2.5.1 Corals in the Gulf

Corals will be treated in much detail throughout this book (Chap. 11 for a systematic treatment of hard corals, Chap. 12 for soft corals), as will be reef-building (Chap. 3), so we here only present a brief outline. Records of coral growth in the Gulf are widely spread throughout the literature and few compilations regarding their specific occurrence in the entire region have been attempted except for Sheppard and Wells (1988) and Spalding et al. (2001) who give overview

descriptions and rough site maps. Detailed records and maps can be found in Purser (1973a) for the southeastern Gulf (Abu Dhabi and Qatar). Shinn (1976) provides a rough sketch of the distribution of *Acropora* communities in the southern Gulf. Downing (1985, 1988) describes coral community dynamics and distribution of reefs in Kuwait. Krupp et al. (1996) provide maps for the Jubail area and some of the offshore islands. Sheppard and Salm (1988) provide an overview for Musandam but sites are not specified, Sheppard and Sheppard (1991) provide descriptions of reefal areas mainly from Bahrain. Fadlallah et al. (1994) list sites in Qatar, Bahrain, Saudi Arabia and Kuwait and Fadlallah et al. (1995) give details about the Tarut Bay reef. Shokri et al. (2000) list sites with coral growth and attempt a classification of type for Iran. George and John (1999), and John and George (2000, 2003) describe coral growth from Abu Dhabi, Riegl (1999, 2001, 2002) and Riegl et al. (2001) and Purkis and Riegl (2005) and Purkis et al. (2005) provide detailed maps and sketches of the reefs in Dubai Lomando et al. (2003) map and discuss coral areas in Kuwait. Corals grow virtually throughout the entire Gulf (Fig. 2.25), with best development on offshore shoals but important fringing systems along the mainland shoreline (in particular UAE, Qatar, Saudi Arabia). Relatively few records exist of coral

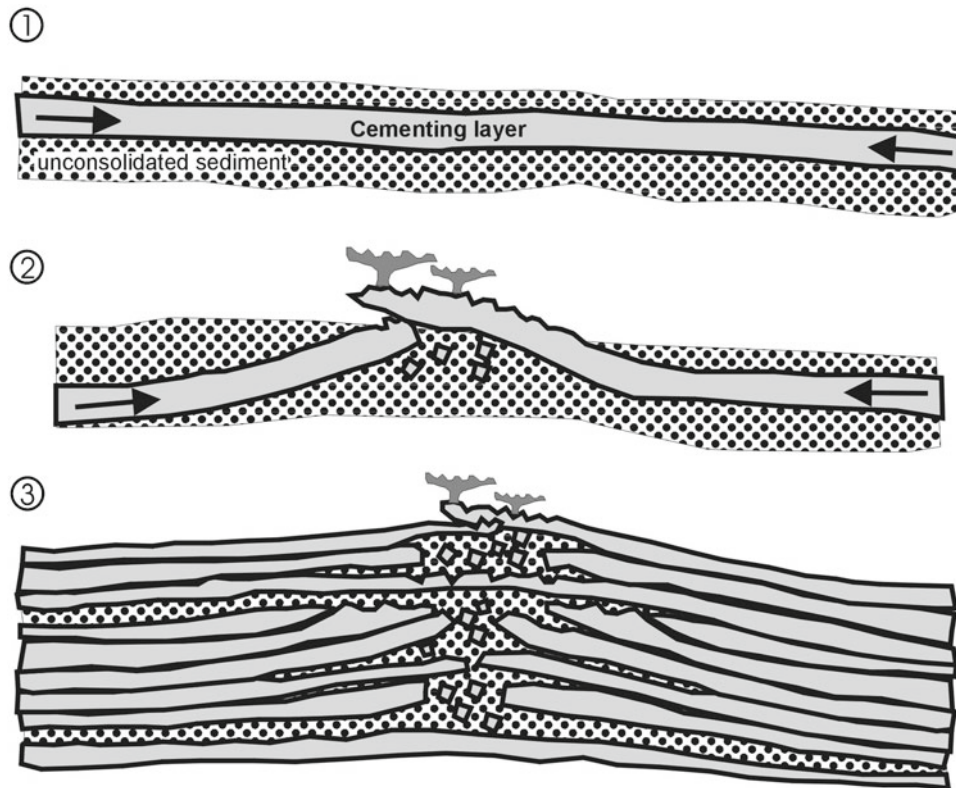
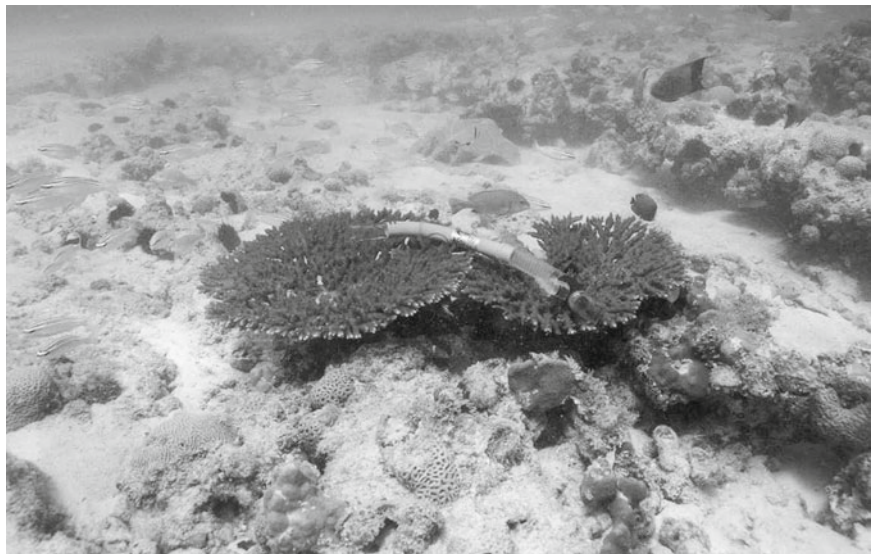


Fig. 2.23 Three stages in the evolution of a hardground ridge (Shinn 1969). (1) A cementing layer forms inside the sediment which eventually buckles up and (2) cracks, exposing a hardground ridge which frequently serves as a focal point for coral framework development. (3)

Several generations of hardground ridges can be formed. This explanation for the formation of ridges in the shallow Arabian Gulf complements the structural control theory for many such features by Lomando (1999) (Permission by Springer)

Fig. 2.24 The usual substratum for coral growth, particularly in the southern Gulf, is syndimentarily lithified hardground (Shinn 1969). Ledges, such as this overthrust teepee (clearly visible in the background, see Fig. 2.23) are locus of preferential coral recruitment



assemblages on the Iranian mainland coast (Shokri et al. 2000; Maghsoudlou et al. 2008), which can be due to runoff from the mountainous hinterland creating unfavorable conditions and insufficient records in literature available in the West.

Pleistocene (MIS 7 and 5e) reefs are known from several Iranian islands (Pirazzoli et al. 2004).

The total Gulf coral fauna is around 40 scleractinian (reef-building) species (Coles 2003) and 31 alcyonacean

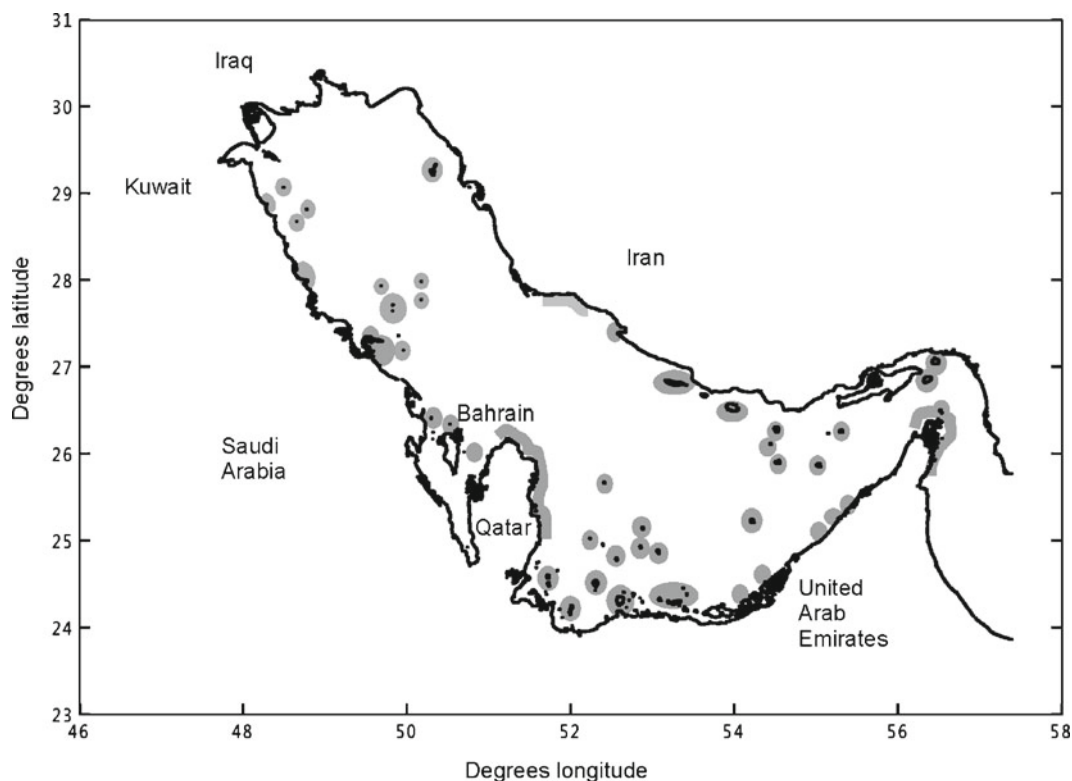


Fig. 2.25 The location of areas with extensive coral growth reported in the literature are indicated here by grey lines

(soft coral) species (Samimi Namin and van Ofwegen 2009), but local diversity is usually lower. The highest number of species was recorded from Saudi Arabian offshore islands (50 species, in Basson et al. 1977; Burchard 1979), which was maybe an over-estimation (Vogt 1996) and the UAE (34 scleractinian species, Riegl 1999). Iran has a rich coral fauna, probably the richest in the Gulf, due to more benign oceanographic conditions (Chap. 11). Local species richness in the Gulf is subject to temporal fluctuations caused by mass mortality events that preferentially affect the branching *Acropora* (Shinn 1976; Riegl 1999). Taxonomic composition of Gulf corals is typically Indo-Pacific (Chap. 11). Two *Acropora* species (*Acropora arabensis*, Hodgson and Carpenter 1995; *Acropora downingi*, Wallace 1999) and one endemic *Porites* (*P. harrisoni*, Veron 2000) are restricted to the Gulf and nearby Arabian and Red Sea. The closest faunistic proximity to other reefs of the Indo-Pacific is naturally to the Gulf of Oman and then the Red Sea (Sheppard and Sheppard 1991; Veron 2000) due to a shared paleoceanographic history of restriction during the last sea-level low stand and simultaneous flooding during the Holocene transgression (Sheppard and Sheppard 1991; Uchupi et al. 1996). While the Red Sea has marked endemism (18 species), the Gulf shares all its species with the Indian Ocean. (Hodgson and Carpenter 1995; Wallace 1999; Veron 2000). The coral fauna in the southern Gulf (Peninsular Arabian coast)

is characterized by rarity of alcyonacean soft corals and absence of reef building hydrozoa, which are common on other high latitude reefs in the Red Sea and the Indian Ocean.

2.5.2 Mollusca in Reefs

The molluscs are the most important sediment producers in the Gulf (Hughes Clarke and Keij 1973; Fig. 2.26). The bivalves, due to their high population densities in subtidal and intertidal sand make up many of the shallow sands that often develop into hardgrounds (Wagner and van der Togt 1973). The molluscan fauna is rich and varied and typically Indo-Pacific in character (Bosch et al. 1995). Oysterbeds (*Pinctada radiata*) cover extensive areas.

Bivalves overgrow substrates like dead corals (Chap. 5). Greiss and Riegl (2000) found that overgrowth of dead corals by first *Chama aspera* and *Spondylus marisrubris* (among others) increased carbonate mass almost two-fold. A clear succession in overgrowth was observed: within the first year, a dense cover by *Chama aspera* covered almost the entire skeleton. These original settlers then died in the second year and gave way to more encrustation by red algae, serpulids and mainly *Spondylus marisrubris*. Hassan (1998) found a similar pattern of original bioaccretion, and only later bioerosion, in the Red Sea.

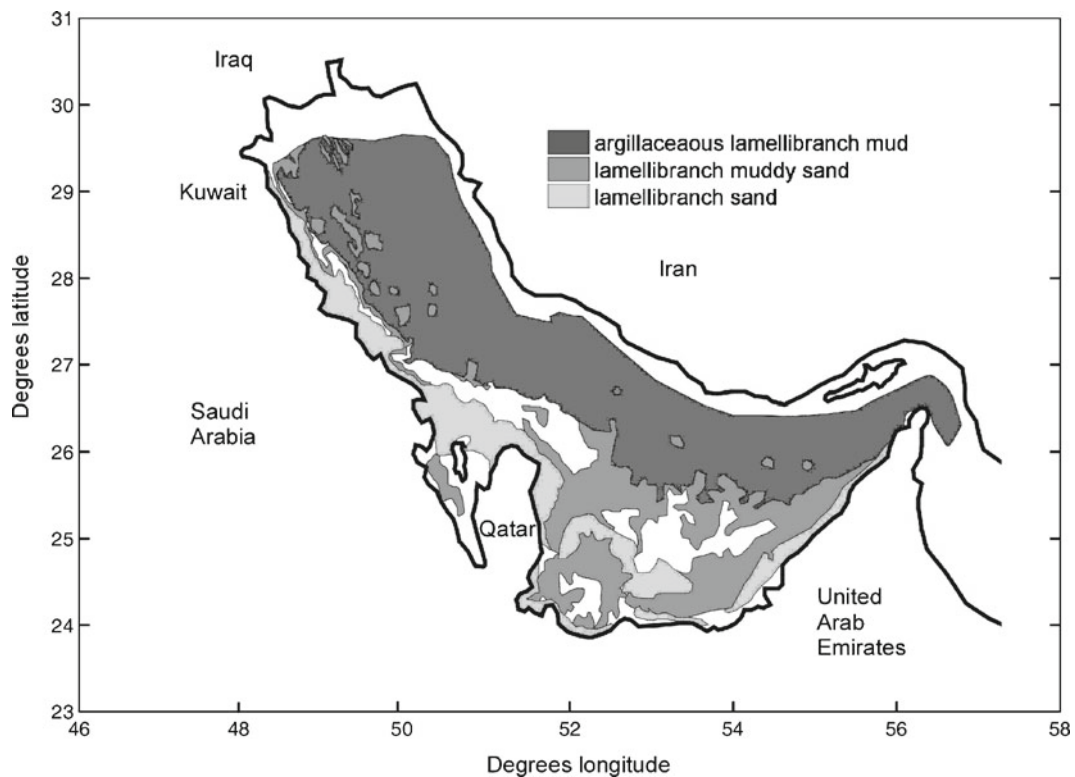


Fig. 2.26 Bivalves (lamellibranchs) are important sediment producers (Wagner and van der Togt 1973). White areas in southern Gulf are other sediment types (foraminiferan and mixed sands) Coralgal sands overlap with lamellibranch sands and are not shown (Permission by Springer)

No major gastropod predators of corals, such as *Drupella cornus*, that have denuded reefs in the Red Sea and Indian Ocean, occur in the Gulf. Local *Coralliophila* species also have not been reported to cause significant predation damage to corals, unlike in the Caribbean.

2.5.3 Echinoderms

Due to its shallow nature, the Gulf provides abundant habitat for echinoderms. Echinoids, asteroids, ophiuroids and holothuroids are common, although limited in species richness. The most common echinoids are *Echinometra mathai* and *Diadema setosum*, which occur mainly in areas with coral growth but also in oyster beds.

Echinoids in particular are important due to their activities as bioeroders, which makes them a major controlling factor for reef-framework production and its breakdown to fine sediment. Hughes Clarke and Keij (1973) quote Shinn (personal communication) as having measured a sand production rate of 0.5 g medium grained sand per echinoid per day when browsing on dead *Acropora* coral skeletons.

An interesting and important absence is that of the crown-of-thorns-starfish (*Acanthaster planci*), a voracious predator of coral that can denude entire reefs. So far, only two specimens have reliably been recorded in the Gulf, on Larak and Lesser Tomb Island (Price and Rezai 1996).

2.5.4 Calcareous Algae

Algae find detailed treatment in Chap. 14. The Gulf lacks many of the major algal sediment producers that are found in the Atlantic and Indo-Pacific like *Halimeda*, *Penicillus*, etc. Red algae do, however, occur as encrusters on reef corals. The branching red alga *Jania rubens* also occurs frequently. Red algae are important as encrusters of dead substrata and can enhance the settlement of larvae of other calcareous organisms, such as corals. Filamentous red algae like *Spyridia* associated with large brown algae cover shallow subtidal rocks (Basson et al. 1977). Filamentous red algae flourish in salinities of up to 100 ppt, while most other algae are not reported in water of salinities above 50 ppt. There is no carbonate production potential associated with these assemblages. The only calcareous algae among the rhodophyta are

Peyssonnelia simulans and four coralline genera (*Hydrolithon farinosum*, *Jania rubens*, *Lithophyllum kotschyianum*, *Sporolithum molle*), among the chlorophyta, *Acetabularia calyculus*. *L. kotschyianum* is common, particularly on reefs, and is a major producer of carbonate sediments. Both *L. kotschyianum* and *S. molle* occasionally form rhodoliths. However, not with the same frequency as rhodolith formation is observed in the Bahamas or in Belize. Hughes Clarke and Keij (1973) report characteristic algal oncoids from offshore shoals.

2.5.5 Green and Brown Algae on Rocky Reefs

The Gulf algal flora is as much determined by temperature extremes as the fauna and is an impoverished, but unique, subset of the Indian Ocean flora (Schils and Wilson 2006). Green algae do not play an active role in sediment production in the Gulf but green and brown algal weeds are widespread throughout the shallow water environment and host important epifaunal biota (Hughes Clarke and Keij 1973; Chap. 14). They occur both in the shallow subtidal, frequently forming dense cover on rocky reefs, or can also form dense assemblages on deeper subtidal hardground areas to ~10 m depth. Dominant species include *Hormophysa cuneiformis* and several species of *Sargassum* and *Cystoseira*. Many algae show a marked seasonality and are less common in summer. Their fronds form the substratum for locally dense calcareous assemblages, consisting of red algae, serpulid polychaetes, small bivalves and even coral recruits. *Sargassum* sometimes actively competes for space with reef-building corals. Particularly when corals die, due to temperature (and other) stresses, the area can become overgrown by dense *Sargassum* beds, which then makes re-settlement by coral larvae difficult to impossible (Chap. 14).

2.5.6 Blue-Green Algae and Stromatolites

As analogues to reefs, modern stromatolitic environments are known from the United Arab Emirates (Kendall and Skipwith 1968; Alsharhan and Kendall 1994; Kirkham 1998) and from Kuwait (Duane and Al-Zamel 1999). Stromatolites are found in tidal creeks where the algal mats are protected from direct wave impact by 1–3 km wide consolidated beach ridges. Stromatolites are being formed by *Microcoleus chthonoplastes*, *Lyngbya estuarii*, *Lyngbya limnetica*, and *Oscillatoria* sp. Six stages of stromatolite growth and burial were proposed which provide an alternate explanation (to p.ex. Hoffmann 1969) to the origin of domal stromatolites (1) growth of flat-topped stromatolites with laminated growth

until a bioherm is formed (2) spalling of the bioherm during weathering (3) development of fractures which are invaded by crinkle stromatolites which build microcolumns in a vertical framework (4) erosion and exposure of microcolumns (5) flat-topped stromatolites grow and regeneration of columnar bioherm structure (6) drowning by risen sea-level and preservation of fossilized bioherm.

2.6 Conclusion

In the Gulf well-developed reefal framestones are rare but at least temporary frameworks commonly occur. Development takes place in the most proximal reaches of the ramp, close to the mainland shore where extensive coast-fringing coral frameworks occur. In the more distal reaches of the Arabian homocline, coral frameworks are concentrated around topographic highs, where corals grow best on windward sides. The Gulf coral fauna, with about 40 species is essentially as rich as that in the Caribbean (Chiappone et al. 1996). Like in most other reef areas, the scleractinian genus *Acropora* is the most important framebuilder and dominates in the shallowest areas. Massive favids usually occur in slightly deeper water below the zone of *Acropora* dominance. The tabular *Acropora clathrata*/*A. downingi* group of species can form well-developed rigid frameworks. Framework production has been severely hampered by mass mortalities that killed large parts of the framebuilder populations. Cause of coral mass mortality are temperature anomalies, either negative or positive (Coles 1988; Coles and Fadlallah 1991; Fadlallah et al. 1995; Riegl 2001, 2003). The most important non-*Acropora* framebuilders belong to the genus *Porites*. In the Gulf, *Porites harrisoni* forms coherent, rigid frameworks. Especially in areas of more extreme salinities and temperature variations, these take the place of the *Acropora* frameworks. *Porites* frameworks are usually smaller than *Acropora* frameworks.

Framebuilding in the Gulf happens on a much smaller scale than in the Indo-Pacific or Caribbean. Frameworks in the Gulf are thin, if present at all. This is due to harsher climate (Riegl 2001; Riegl and Purkis 2009).

With regard to the reef associated flora, the important sediment-producing calcareous green algal genus *Halimeda* is absent. Also calcareous red algae have less taxonomic diversity. While in the Caribbean and Indo-Pacific red algae are being considered important and efficient binders, either of rubble or reef framework (Blanchon et al. 1997; Perry 1999) the same is not true in the Gulf, where red algae encrust and bind dead reef frameworks, but cannot prevent their break-down and do not appear to efficiently cement rubble (Riegl 2001; Rasser and Riegl 2002).

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Sam J. Purkis and Bernhard M. Riegl

3.1 Introduction

The Gulf, a subtropical epicontinental sea, is home to the northernmost coral reefs on the western boundary of the Indo-Pacific. The basin has an area of 250,000 sq. km and is shallow and semi-restricted, which combined with its high-latitude and the presence of mountainous plateaus and deserts nearby, make the Gulf's climate the most extreme endured by reef-building corals anywhere in the world (Riegl et al. 2011, Chaps. 2, 7, and 9). Despite the hostile conditions, the Gulf is home to about 40 species of scleractinian and 31 species of alcyonacean corals, representing an impoverished but typical segment of that of the Indo-Pacific. The Gulf is unique in many respects, most notably in terms of its water chemistry, inclement climate (hot summers but also cold winters), and the hardiness of the corals that inhabit it. These factors conspire to prevent the development of spectacular reef edifices, like those that exist in the adjacent Red Sea, but nonetheless the expression of coral growth is as varied and interesting as the prevailing climate. The Gulf marks the separation between the stable Arabian foreland, atop which the U.A.E. sits, and the unstable Iranian fold belt. This positioning generates a specific geological set-up which conveys primary control on the geomorphology of the basin and in turn, the opportunities for reef development. Of particular note is the influence that salt tectonics play in the creation of offshore banks and islands, all of which support coral communities. Secondary and more recent modification has been exerted by the flooding of the Gulf during the last transgression, with the majority of the basin having lain sub-aerially exposed for considerable periods in the last 100,000 years. This complex and rich genesis brings the Gulf to a crossroads in the present day; we witness an unprecedented level of coastal development and modification fueled by rising economic prosperity on the back

of vast hydrocarbon discoveries. Many areas of spectacular coral growth have been lost to construction, but some remain, for now. This chapter will detail the status of these ecosystems and the factors that have shaped them through time.

3.2 The Holocene Transgression in Arabia

Considerably lower sea-levels and even complete evaporation of the Gulf occurred in the Pleistocene. The period between 110,000 year BP and 30,000 year BP was characterised by considerable sea-level fluctuations within the range of 30 and 60 m below present (inset Fig. 3.1). As per Sheppard et al. (1992), these levels correspond to the depths of major wadis, best observed along the Red Sea coast. At the height of the Last Glacial Maximum (LGM), sea-level stood between 120 and 150 m below present, which implies that the entire Gulf was dry during this period. Since it has not been the subject of such intense study, sea-level rise following the LGM in the Gulf cannot be constrained as definitively as for the Atlantic or Pacific. Several relevant sea-level curves however do exist and once assembled, are largely in concert with one another (Fig. 3.1). It is reasonable to assume that the sea-level history for the Gulf is comparable to that of surrounding basins, such as the Red Sea, following the LGM - the transgression in both being driven by the sea-level fluctuations of the Indian Ocean. The tracing of the Holocene sea-level transgression in the Gulf is relevant to developing an understanding of present-day reef morphology in this young sea (Purser and Evans 1973; Purkis et al. 2010).

Flooding of the Gulf likely initiated shortly prior to 12,000 year BP as the ocean transgressed into the basin via the Strait of Hormuz (Lambeck 1996; Teller et al. 2000). With this sills overtopped, the Gulf witnessed a rapid rise in sea-level between 12,000 and 9,000 year BP from less than 90 m to less than 30 m below the present level. This was followed by a more gradual rise to a point between 3 and 6 kyr ago when today's sea-level was reached. Though the evidence remains contentious, sea-level may have overshoot to 1 m

S.J. Purkis (✉) • B.M. Riegl (✉)
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu; purkis@nova.edu

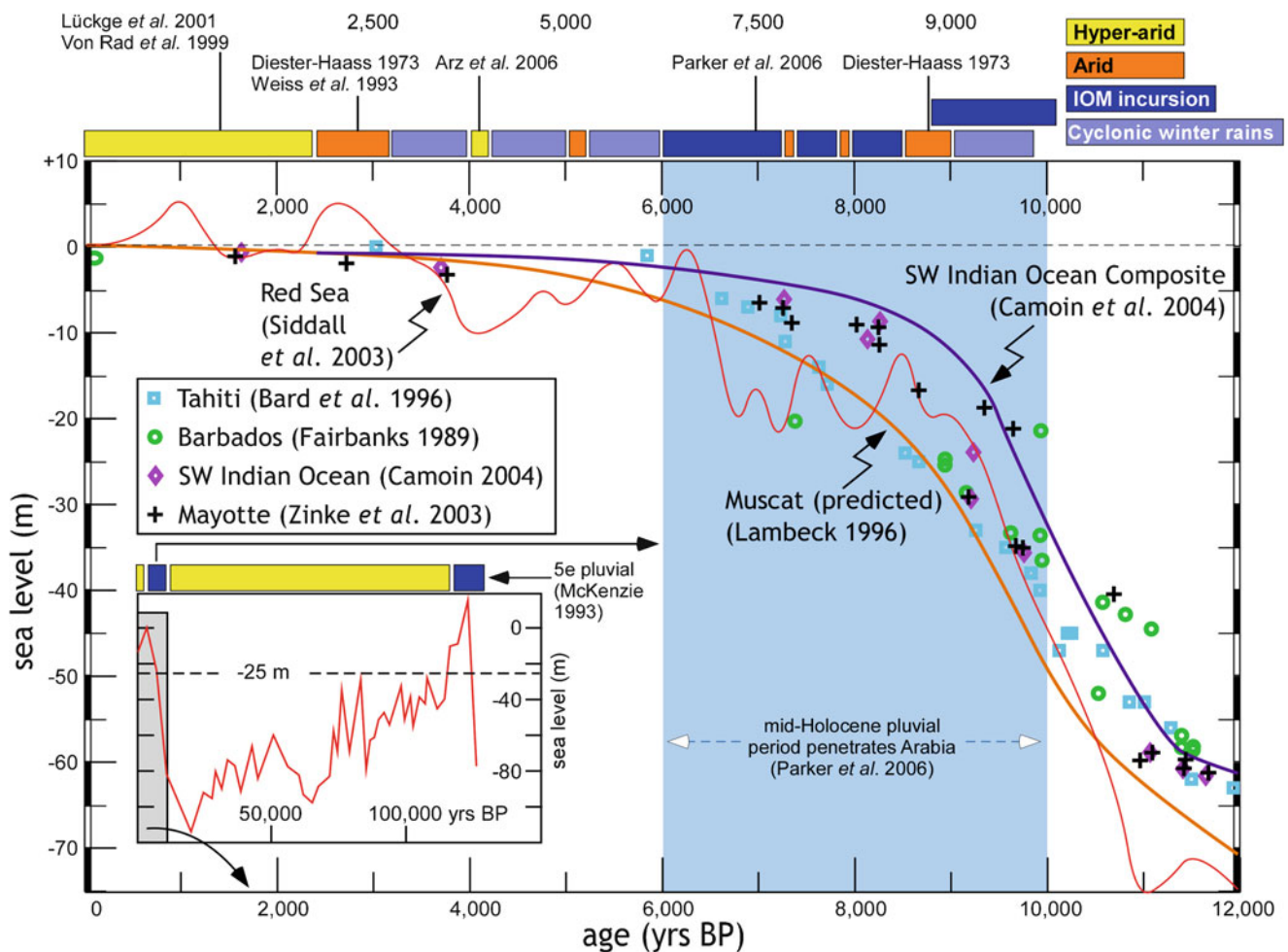


Fig. 3.1 Reconstructions of the Holocene transgression for Arabia and surrounding regions. The climate in the Gulf during this period is indicated by the coloured bars running along the top of the plot. Inset graphs sea-level for the past 125 kyr in the Red Sea (Siddall et al. 2003)

above present about 6 kyr ago prior to falling smoothly back (Chappell 1983). The Gulf's unique morphology conspired to deliver a rapid landward March of palaeoshorelines during the last transgression. The gentle basal slope of the Gulf, combined with a limited depth of only 90 m, are such that the postglacial transgression would have passed over parts of the shelf extremely quickly, the shoreline position routinely changing by as much as 5 km per century and certainly several orders faster as the homoclinal central shelf was inundated. Here, only an 18 m rise in elevation across a distance of about 500 km exists (Teller et al. 2000).

Figure 3.1 plots six sea-level curves relevant to the Arabian region. The inset to this figure shows that the floor of the Gulf was exposed for 100 kyr prior to the initiation of the most recent transgression. The rise predicted by Camoin et al. (2004) sees the earliest inundation following the LGM. The curve provided by Lambeck (1996) charts a more conservative transgression, flooding the -40 m contour 1 kyr later than Camoin et al. and the -15 m contour 1.5 kyr later. Lambeck's curve does not arrive at present sea-level until <4 kyr BP,

while Camoin reaches this point 1 kyr earlier. The curves of Lambeck and Camoin both assume that the sea-level rise up until $\sim 6,000$ yr BP was continuous without stillstands or regressions. Measures of the LGM transgression obtained elsewhere occupy the middle ground between Camoin et al. and Lambeck. This agreement is demonstrated by Fig. 3.1 which plots sea-level derived from dated corals in Barbados (Fairbanks 1989) and Tahiti (Bard et al. 1996) as well as coring from the Indian Ocean Island of Mayotte (Zinke et al. 2003). Also plotted is the high resolution sea-level reconstruction of Siddall et al. (2004) which, based on $d^{18}O$ isotopes from sediment cores obtained in the central Red Sea, offers centennial-scale resolution through the last glacial cycle. The sensitivity of the reconstructive model is affected by a lack of precise knowledge for temperature and net evaporation in the Red Sea during this period, and hence yields an uncertainty of ± 12 m for the sea-level estimates. We are cautious that the Siddall curve may overestimate highstand amplitudes since numerous previous studies pin sea-level in the Gulf at least to stand at $+2.5$ m 6,000 year BP (e.g. Lambeck 1996; Barth

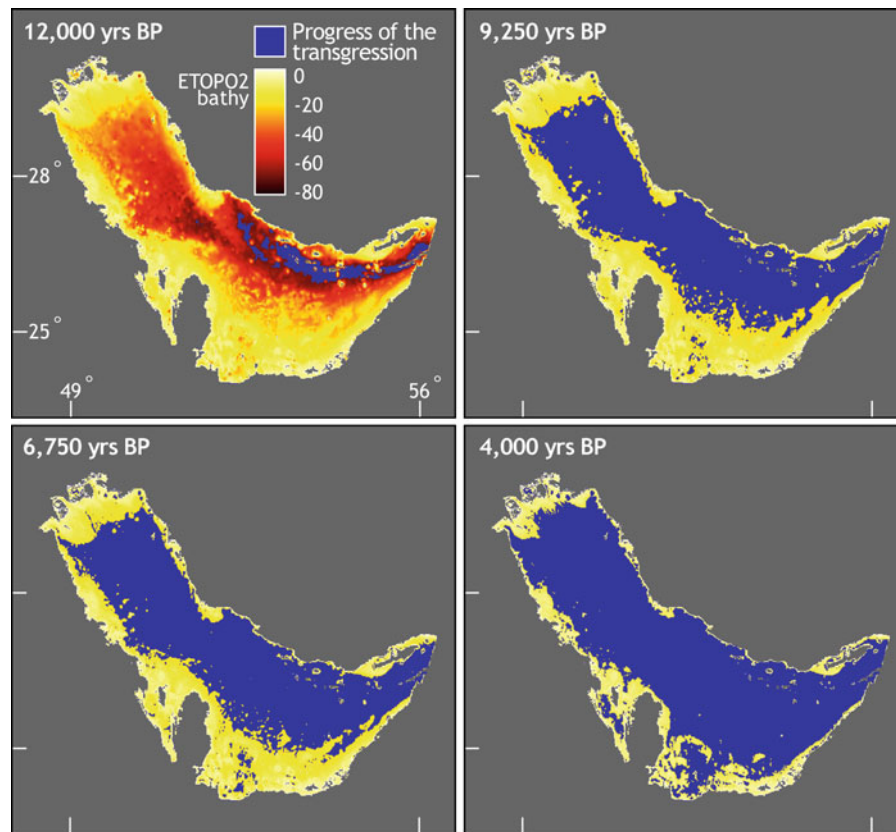


Fig. 3.2 Paleogeographic maps of the Gulf during the post-glacial transgression. The inundation, depicted in blue, tracks the sea-level curve of Siddall et al. (2003). The coloured base map is ETOPO2 digital seabed elevation data from the NOAA/NGDC Earth topography database

2001). Siddall, by comparison, reconstructs sea-level to lie at >-5 m below present in this period, and rising to $+6$ m as recently as 1,000 year BP. The latter estimate is somewhat corroborated by the existence of late Holocene beach deposits at $+6$ m elevation along the western part of the Makran coast (Vita-Finzi 1982), but for a considerably earlier time period. Despite the accepted vagaries, Siddall's curve is largely in concert with the other reconstructions of sea-level for the same period which are based on coral reef data and corrected for hydro-isostatic contributions. Shoreline position can not be unequivocally derived from Fig. 3.2 due to glacio-hydro isostatic adjustments that proceeded unabated even through periods of relative sea-level stasis. These adjustments can account for an uncertainty of several metres (Lambeck 1996; Mitrovica and Milne 2002), which equates to a several tens of kilometres fluctuation in shoreline position for the shallow incline of the Gulf's central shelf.

3.3 Holocene Climate of Arabia

Evidence for the Late Pleistocene and early Holocene climate of the region is rather contradictory. In the Gulf the prevalence of aragonitic sediments from this period suggest a more

arid climate than today's (Sarnthein 1972). For these sediments to have persisted, rivers, such as the Zagros, must have been virtually inactive. By contrast, the Late Pleistocene of the Red Sea shows evidence of erosion and deposition of alluvial material resultant from periods of heavy rainfall between 35 and 17 kyr BP (Jado and Zoetl 1984). Given their proximity, the discrepancy is best explained by the fact that the late-Pleistocene Arabian climate was variable, alternating between dry and wet before settling into early-Holocene humidity.

The available Holocene palaeo-archives fall into unison for the Gulf and Red Sea by 10,000 yr BP. Lacustrine sediments, cave records, and radiocarbon chronology from southeastern Arabia unequivocally point to the onset of wet conditions that peaked around 9,000 year BP and persisted until at least 6,000 year BP (McClure 1976; Al-Sulaimi et al. 1995; Neff et al. 2001; Parker et al. 2006; Lézine 1998). This abrupt switch to a tropical climate, the mid-Holocene pluvial period, corresponds to a change in the strength and duration of the Indian Ocean Monsoon (IOM).

The hyper-arid Arabian region that encompasses the Red Sea and Gulf is today located outside the range of the IOM. The onset of the pluvial phase was caused by the northward migration of the IOM over Arabia (Gasse et al. 1990; Gasse and Van Campo 1994; Clemens et al. 1996; Lézine 1998;

Liu et al. 1998). The shift can be attributed to an increase in solar heating during this period across the Northern Hemisphere during the early- to mid-Holocene which caused the intertropical convergence zone (ITCZ) to pull northwards. This extended the limit of the monsoon rainfall belt far north of its modern location, which today is the southern shoreline of Arabia (deMenocal et al. 2000; Neff et al. 2001; Fleitman et al. 2003; Davies 2006; Parker et al. 2006). Proposed by Staubwasser (2006), an alternative hypothesis proposes that rainfall during the summer monsoon was derived from local convection, possibly augmented by local orographic effects (both the Red Sea and Gulf are fringed by mountain ranges) and not solely through a shift of the ITCZ. Though the IOM penetrated northwards into Arabia, the rainfall may not have been particularly pronounced in the northern reaches of the region, however, here there exists evidence for equally wet conditions but the onset of Westerly winter rainfall originating in the Mediterranean is implicated (Arz et al. 2003).

Whether southern Arabia's wet-phase can be attributed more to monsoon or local effects, or whether the north of the region owes its rainfall to the IOM or Mediterranean weather systems, there is abundant evidence that the region was subjected to an episode of high rainfall through the early- to mid-Holocene (Fig. 3.1). At the same time that sea-level approximated its present position only 3–6 kyr ago, there was a widespread weakening in monsoon strength and the climate of the Gulf shifted to become extremely hot and dry (Morrill et al. 2003; Arz et al. 2006). These hyper-arid conditions persist today with annual average rainfall less than 10 cm in the Gulf (Purser 1973; Sheppard et al. 1992).

Though Arabian wet-phases were generally short in duration, there is reasonable evidence that they have occurred several times through the Pleistocene during transitions from glacial to interglacial conditions. Just as for the penultimate glaciation, the trigger would have been rapid global warming at the tail-end of an ice age inducing a temporary alteration of atmospheric circulation with an intensification of the southwest monsoons (McKenzie 1993). With sea-level considerably lower than today, meteoric processes such as pluvial episodes would have sculpted the topography of the present-day seafloor of the Gulf. For example, Kassler (1973) makes reference to the bedrock below the Holocene of the Gulf as being extensively leached and altered by fresh water, evidence the author takes to be “probably indicative of sub-aerial exposure”. In the same vein, Kassler recognizes the presence of paleo-drainage patterns offshore Abu Dhabi and the Musandam Peninsula. The presence of structures created by Neogene and Quaternary climate fluctuations is relevant for understanding the configuration of contemporary benthic ecosystems in the Gulf. Once flooded by the Holocene transgression, topographic highs would have been preferentially settled by corals, while lows are sediment filled, offering poor habitat to corals in the absence of hardground

formation. As recognized elsewhere, the distribution and morphology of coral dominated areas may be controlled by pre-existing topography, to the point that seabed architecture has very little to do with modern marine processes. Modern reef growth serves to accentuate these underlying patterns (Purkis and Kohler 2008; Purkis et al. 2010).

The corals of the Persian/Arabian Gulf display unusual resilience to temperature stress (bleaching). Summer daily-mean temperatures routinely top 32°C while winter winds can chill the water to 12°C (Sheppard 2003; Sheppard et al. 2010). Catastrophic bleaching only occurred in the summers of 1996, 1998, and 2002 when water temperature exceeded 35°C (Purkis and Riegl 2005; Sheppard et al. 2010), well above the 25–29°C range of thermal tolerance for corals elsewhere in the world (Buddemeier and Wilkinson 1994). While these radical temperature excursions in the Gulf impart mortality on coral species such as *Acropora*, dominant frame-builders persist with death-rates much lower than would be predicted elsewhere in the Indo-Pacific (Baker et al. 2004). Indeed, such is the ability of the Gulf system to rebound from severe temperature events, that the coral community can regenerate to a fully healthy state in only a handful of years (Purkis and Riegl 2005; Riegl and Purkis 2009). At the time of writing and even withstanding the again anomalously hot summer temperatures of 2010, many coral-rich areas in the region boast dense, interlocking, frameworks of *Acropora* surrounded by and indeed overtopping, vigorous growth by faviids and *Porites* (personal obs.).

This resilience implies that the corals of the Gulf and their algal symbionts have been capable of acclimatization and selectively adapt to elevated temperatures (Baker et al. 2004; Obura 2009; Rowan 2004). Such genetic plasticity is in line with recent observations that regions of maximal evolutionary potential exist on the geographic periphery of reef growth, such as the isolated high-latitude regime of the Gulf (Budd and Pandolfi 2010). The existence of bleaching-resistant populations is pertinent considering the dire predictions for reefs under projected increases in temperature due to global warming (Hughes et al. 2003; Veron et al. 2009). Since many corals can distribute their larvae widely, their dispersal is mediated by oceanic currents and the heat-adapted trait can be imparted to reefs further afield through genetic connectivity. The Gulf therefore represents a potential source of temperature-capable corals that could spread through the adjacent Indian Ocean, a region that has heretofore shown very little adaption to high water temperatures (Sheppard 2003). If such a prophecy is to be fulfilled, the corals of the Gulf must maintain a large and healthy population into the far-future to provide an effective battery of larvae to nourish the migration.

While the unique temperature resilience of the Gulf's corals stands them in good stead to prosper in the near-term heating delivered by climate change, there remains the risk

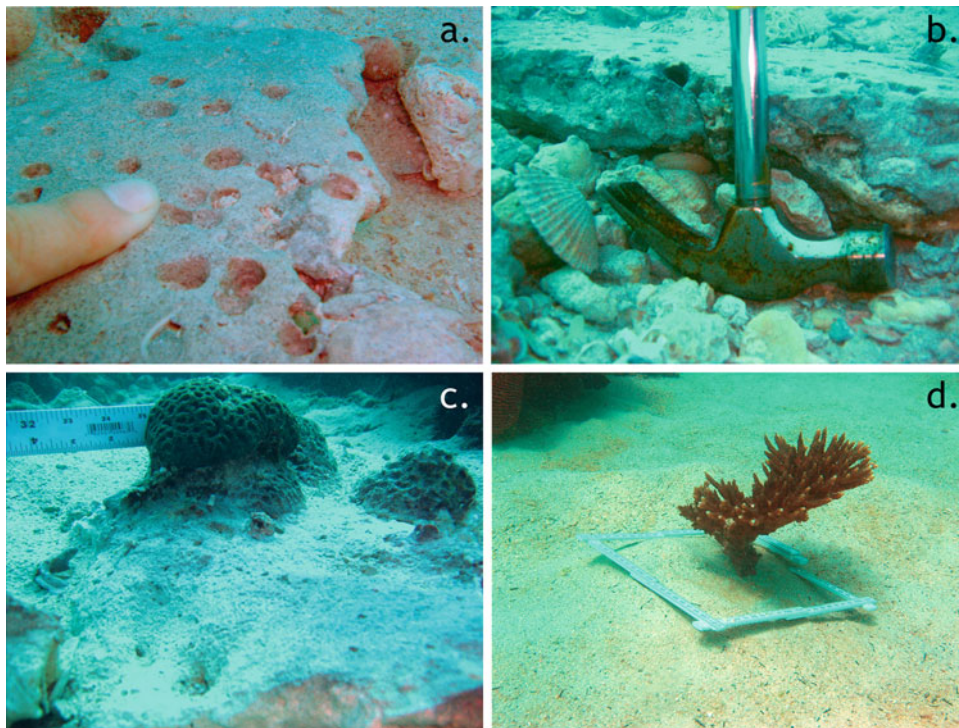


Fig. 3.3 (a) shows the smooth surface of a lithified Gulf hardground. The circular pits are bored by lithophagous bivalves. This hardground crust is only several centimeters thick and underlain by a conglomerate of unconsolidated coarse material that accumulates at the growing face of the sheet and is subsequently overtopped and preserved (b) – hammer for scale. (c) depicts juvenile faviid corals

that have recruited onto a patch of hardground, while (d) shows an *Acropora* coral that has settled on lithified substrate and survived the temporary incursion of a sand wave. These mobile sands are typically only a few centimetres deep and their constant planing imparts the smooth upper surface of the hardgrounds observed in (a), (b), and (c)

that their ability to prosper in the longer-term may be curtailed by the loss of the cemented seafloors that the strongly rely on for habitat. While seabed lithification is possible with the present seawater chemistry, the process will deteriorate, perhaps even halt, under future conditions of acidification-driven lowering of CaCO_3 saturation state, a further consequence of raised atmospheric CO_2 . Laboratory experiments pin this change to occur with a pCO_2 of approximately 1,900 ppm (Purkis et al. 2011). This CO_2 concentration will be reached around the year 2300 according to the IPCC IS92a emission scenarios coupled with a logistic function for burning of fossil fuels beyond 2,100 (Caldeira and Wickett 2003).

3.4 Seawater Chemistry and Hardground Formation

The Gulf is located in a subtropical, hyper-arid region. Average salinity is 37–40 ppm though can exceed 50 ppm in shallow waters and 70 ppm in some coastal embayments (Purser 1973). The Gulf is shallow and the high salinity and summer temperatures lead to the super-saturation of seawater with calcium carbonate (CaCO_3). The carbonate system

of the Gulf is hence rich in meta-stable minerals and seafloor lithification through abiotic precipitation is widespread and rapid (Shinn 1969; Sheppard et al. 2010). Though it is typical that reefs contain some proportion of CaCO_3 cement that stiffens the seabed (Manzello et al. 2008), the Southern Gulf is unique in that the precipitation of cement directly from the water column is by far the dominant mechanism creating hard seafloor. Hardgrounds in the Gulf form exceptionally smooth bedding planes as sand sheets moving across them plane off topographic irregularities (Shinn 1969) (Fig. 3.3). As depicted in Fig. 3.4, the regional extent of Gulf hardgrounds are reasonably well constrained (Shinn 1969; Uchupi et al. 1996; Purkis et al. 2011) and with the exception of the deeper waters along the Iranian coast, it is clear that the majority of the basin floor is lithified.

The carbonate cements responsible for binding the seafloor are typically isopachous fibrous aragonite fringes around grains. With these fibers growing at rates in the range of 30 mm per year, unconsolidated sand can be converted to modern rock in a matter of a few years (Grammer et al. 1993). Cementation starts near-instantaneously, requiring only a brief cessation of grain movement for a few hours between tides for the grains to become bound. As has

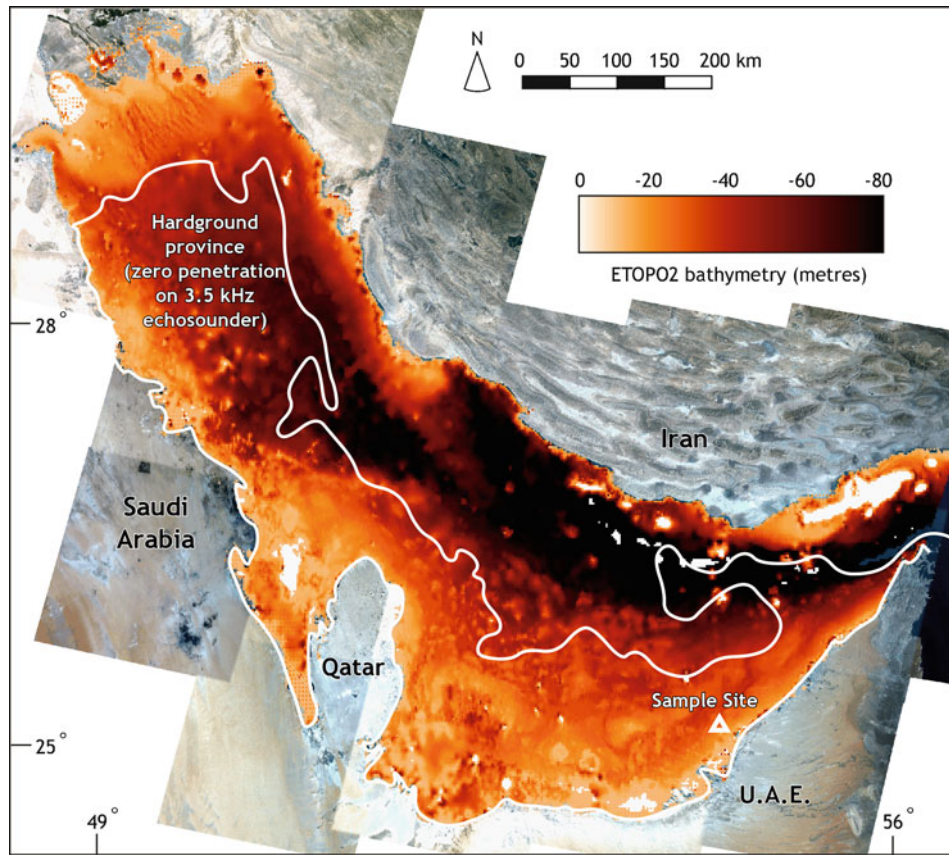


Fig. 3.4 The Gulf as depicted by a mosaic of Landsat ETM+ images blended with ETOPO2 digital seabed elevation data from the NOAA/NGDC Earth topography database (orange). Overlain is the boundary of the Gulf hardground province (white line), a ~90,000 sq. km area of diagenetically cemented seafloor fringing the southern margin of this

epicontinental sea. This hardground province is defined by Uchupi et al. (1996) as preventing penetration of a 3.5 kHz echosounder. This distribution broadly agrees with the rock samples presented by Shinn (1969). Location of the sample depicted in Fig. 3.5 is given with a white triangle

previously been reported (Shinn 1969), thin section petrography and scanning electron microscopy reveal the hardground samples to be composed of sand grains, foraminifera, as well as mollusc and red algae fragments, bound to a rock-matrix by fibrous aragonite cement (Fig. 3.5a). These grains and fragments display a dark micritic envelope, likely resultant from microbial boring by endolithic algae (Kobluk and Risk 1977). The cement is composed of densely packed aragonite needles with sharp chisel-shaped ends (Fig. 3.5b). Observations by diving show the only difference between hardground and overlying loose sediment is the addition of cement (Shinn 1969).

Many of the ‘coral reefs’ described for the Gulf are areas of hard substratum which are not actively accreting but are modern veneers of living coral on much older limestone domes or recently formed diagenetic hardgrounds (Sheppard et al. 2010). Indeed, with the exception of the Iranian coastline, the Gulf lacks any significant rocky outcrops to offer prime habitat for the development of coral communities. There is hence a strong reliance on the availability of lithified

seafloor as a firm habitat for corals and in the southern margin of the Gulf, hardgrounds can be considered the principal substrate supporting reef development (Figs. 3.3 and 3.4).

3.5 Salt

The Gulf is a flooded foreland basin at the position where the stable Arabian plate meets the unstable Iranian (Zagros) fold belt (Zagros Suture, Fig. 3.6). The U.A.E. finds itself atop this stable Arabian foreland. The Zagros province is an Early Proterozoic to Late Tertiary sedimentary basin (Haghpour and Aghbanati 1985; Edgell 1996). It is intricately folded largely due to thrust and reverse faulting and consists of elongated whaleback and anticlinal mountains, which generally trend NW-SE, parallel to the Gulf’s axis and constrain its northern shoreline. During the Late Paleozoic to the Cenozoic Eras, the vast Arabian platform lay along the southern margin of the Tethys Ocean. From the Late Permian to the Late Tertiary mainly epeiric shelf carbonates associated

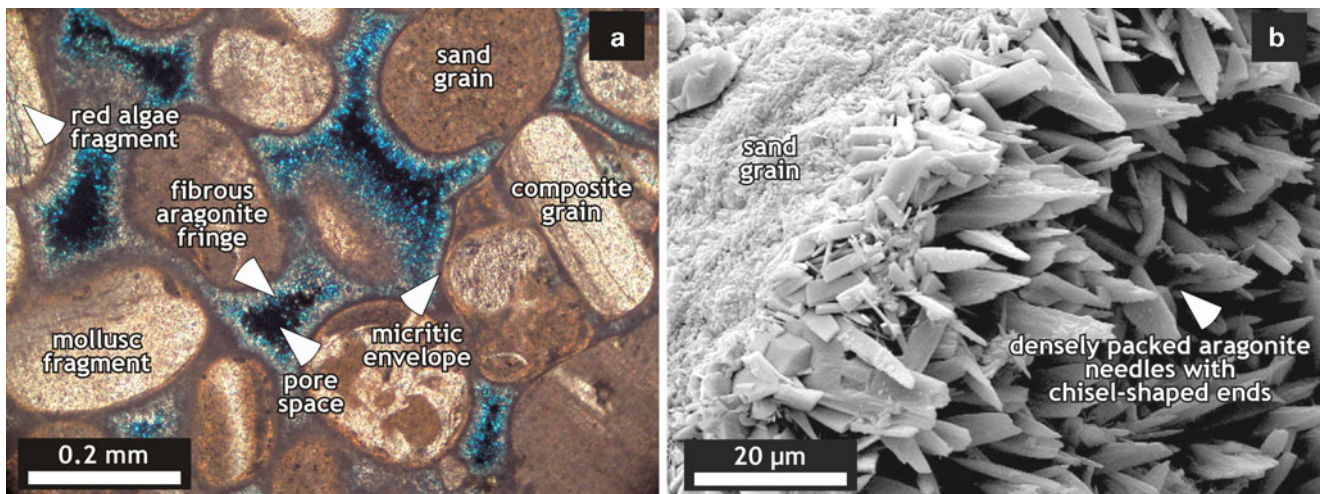


Fig. 3.5 (a) is a photograph of a thin-section (crossed nicols, 10×) cut from a sample of hardground collected offshore Abu Dhabi (*white triangle* – Fig. 3.4). The fibrous aragonite cement that fringes the grain fragments is dyed *blue* and pore spaces are *black*. (b) is an electron

micrograph image obtained from a. The ×3,000 magnification reveals the chisel-shaped needle structure of the individual fibrous aragonite crystals that compose the cement

with only minor clastics and evaporites were deposited (Alsharhan and Salah 1997; Konyuhov and Maleki 2006). Sedimentation patterns were controlled by many factors such as epeirogenic vertical shifts due to basement tectonism, deep seated salt growth, climatic variations, and, most importantly, fluctuations in sea-level. The Gulf's geology is most famous for the vast hydrocarbon resources that it has delivered. Abundant oil and gas reservoirs have been discovered in the Jurassic (Araej and Arab formations), Cretaceous (Thamama Group: Habshan, Lekhwair, Kharair, Shuaiba, Mishrif, and Simsim formations), and the Tertiary (Asmari and Gachsaran formations) carbonates. These fields, all related to structural traps, make the Gulf basin the richest in the world in terms of hydrocarbon resources, perhaps containing 55–68% of recoverable oil reserves and greater than 40% of gas reserves (Konyuhov and Maleki 2006). Gas has also been discovered in the Pre-Permian sandstones and in Upper Permian carbonates in offshore Abu Dhabi, the source-rock for which is likely the Silurian Qasaiba Formation.

Like the southern reaches of the neighboring Red Sea, salt diapirs strongly control contemporary carbonate sedimentation in the Gulf. These are described as “bathymetric highs” and “salt-dome islands” by Purser (1973) because they are circular highs that rise from the surrounding seafloor. Sub-surface salt is a mobile, non-rigid, substrate that flows. Inelastic creep is the dominant deformation mechanism and deformation rates are rapid; it is not uncommon that diapiric uplift is measured in centimeters per year. In cases where the salt plug breaches the ground surface, major sub-aerial or submarine dissolution is possible inducing collapse, termed a ‘doline’, though unlike the neighboring Red Sea, such features are not observed in the Gulf. As depicted in Fig. 3.6, the basement topography in the Gulf serves to guide and

constrain salt deformation. As outlined by Edgell (1996), the main types of salt structures in the Gulf Basin are salt domes, salt pillows, salt walls, salt piercements, rim anticlines, turtleback structures, disharmonic folds, orogenic fold fillings and dissolution drapes.

The best studied examples of true diapiric islands in the Gulf are the eight found offshore of the U.A.E.; Dalma, Zirkouh, Qarnain, Das, Sir Bani Yas, Arzana, Sir Abu Nuwair and Abu Musa. These, along with the Jebel Dhanna Peninsula (see Fig. 3.6), owe their relief to the diapiric movement of salt which has pierced the overlying strata (Alsharhan and Salah 1997). All comprise concentrically arranged carbonate facies belts around a central diapirs; the evidence for a salt core comes from exposed salts on some islands and ‘exotic’ lithoclasts mixed within the modern skeletal carbonates down-current from the seafloor highs. For example, the dark colored cores in the center of Sir Bani Yas Island and Jebel Dhana are Paleozoic diapiric Hormuz material that has penetrated the surrounding younger lithologies (Figs. 3.6 and 3.7). In other cases, such as Arzana and Qarnain, despite having been created by salt tectonism with diapirs at their core, the salt is not visible due to its relatively slow uplift velocity, but the morphology of the islands (flat, domal structure) identifies the diapir (Purser and Evans 1973; Alsharhan and Salah 1997; Pirazzoli et al. 2004). Halokinesis can be considered as a secondary ‘local’ control on the architecture of the sedimentary set-up in the Gulf. Primary control is afforded by the foreland margin which exerts regional-scale influence over the region's tectonic setting. The Gulf hosts about 200 salt diapirs, the diameter of which varies between 1 and 17 km (Kent 1970; Bruthans et al. 2009). Density is greatest on the southern carbonate shelf of the Gulf, though diapiric influence stretches north into Iran (Alsharhan and Salah 1997; Talbot 1998).

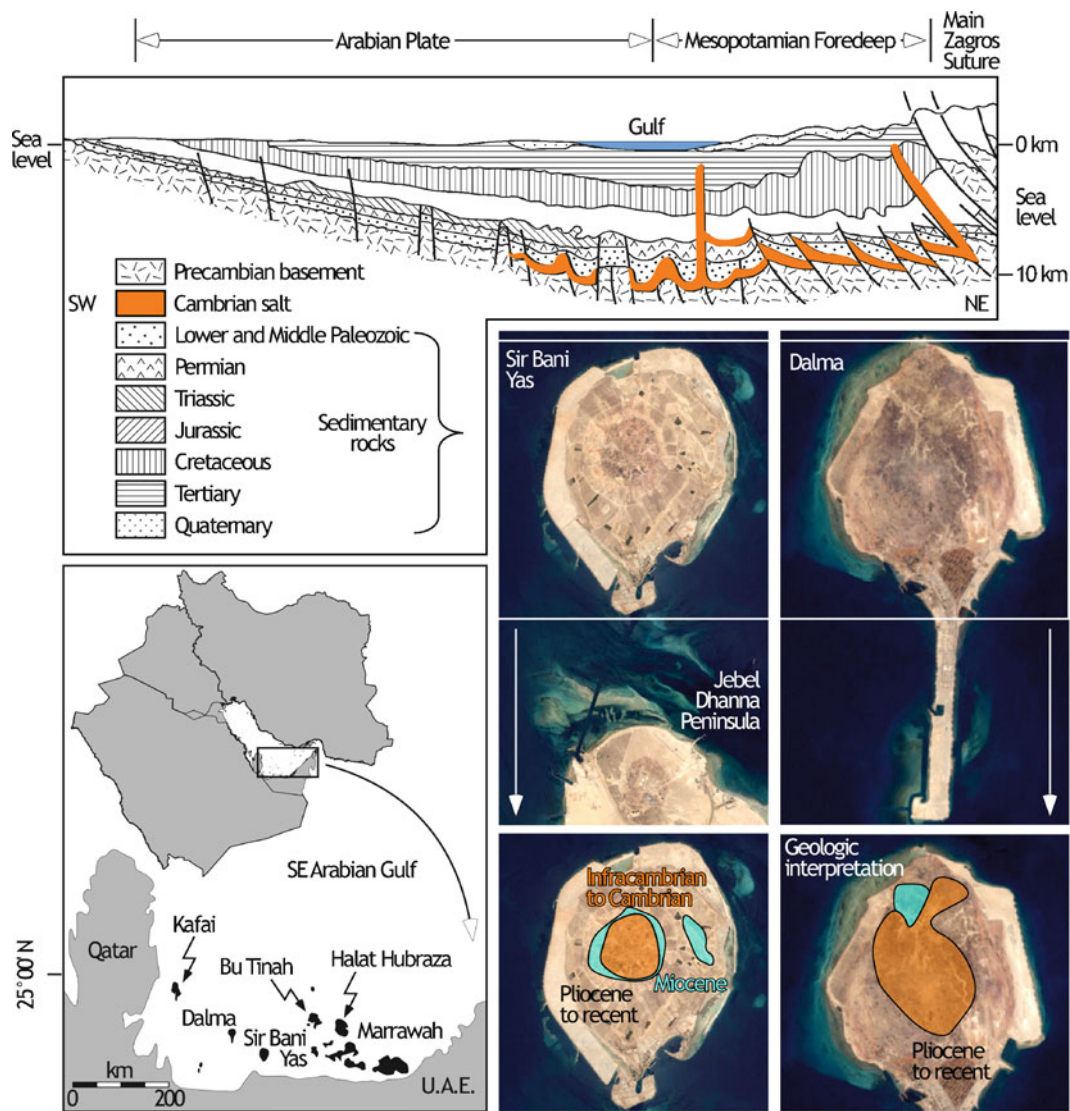


Fig. 3.6 (Top) Structure and sedimentary cover in the central Gulf Basin, including the Arabian Plate and Zagros fold belt. (Modified after Konyuhov and Maleki (2006)). (Bottom) Locations and examples of salt diapirs controlling the placement of offshore bathymetric highs and

salt-dome islands. Satellite images are of Sir Bani Yas and Dalma, both true diapiric islands, where Infracambrian-Cambrian salt (orange) has pierced the overlying strata, carrying with it Miocene sediments (blue). The periphery of the islands are of Pliocene to Recent in age

The salt is part of the Hormuz Complex (hence often termed ‘Hormuz Salt’) and of Upper Precambrian (Riphean-Vendian) to Middle Cambrian age, when it was deposited in large evaporitic basins (Bosak et al. 1998; Bruthans et al. 2009). Halokinesis transported blocks up to 2 km to the surface, which consist of beds of salts, other evaporites, carbonates, siliciclastics and volcanic sediments (Fig. 3.6).

3.6 Reef Morphology

Since the Gulf is so shallow with relatively high water clarity even in the coastal areas, the seabed supports productive habitats, such as extensive seagrass and algal meadows,

mangroves, and coral reefs. Though the extreme temperature regime of the Gulf depresses diversity of corals as compared to the neighboring Indo-Pacific, the morphologies created by coral growth are varied. The diversity in morphology however, more often than not arises from the underlying structural complexity of the seafloor, than from the construction of ornate limestone edifices. Because of a dearth in the investigation of the shallow-subsurface of the Gulf, details on the underlying fabric are sparse, but presumably often wadi-related detritus accumulated at the mouths of paleo-drainage features. Blast excavations offshore Qatar conducted by Shinn (1969) show a common depositional motif through the late Holocene to be multiple stacked sheets of hardground, each several centimeters thick,

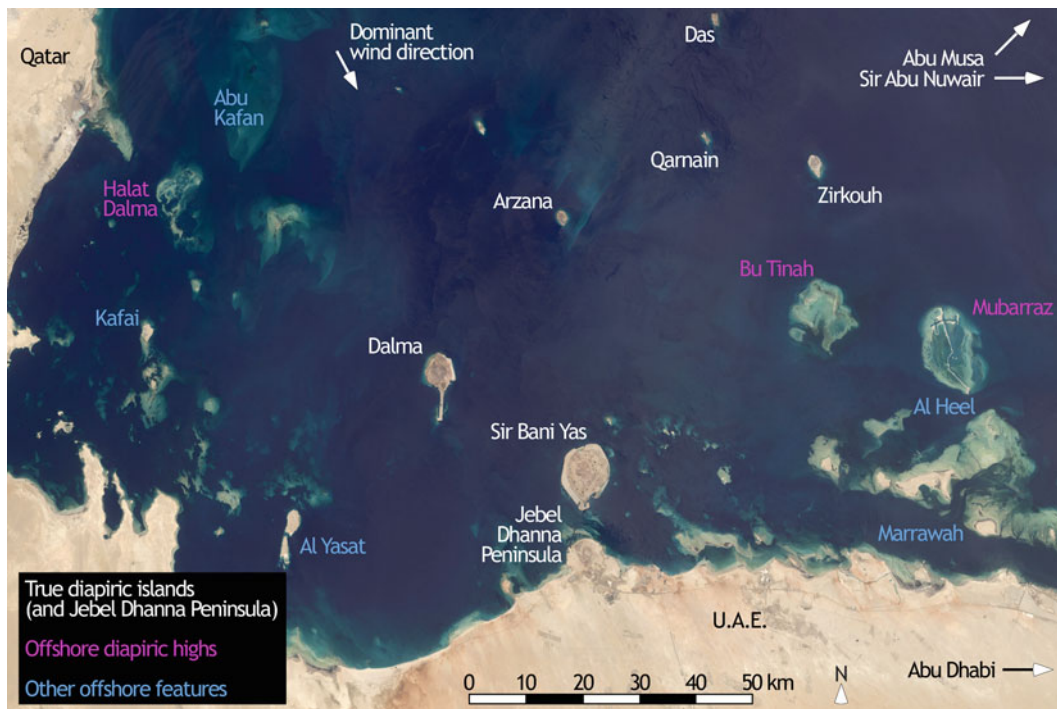


Fig. 3.7 The location of true diapiric islands and offshore diapiric highs in the southeastern Gulf

interleaved with similarly thick layers of unconsolidated carbonate sand.

As for all reefal settings, many other calcareous organisms, both animal and plant, contribute more to the volume of reefs in the Gulf, than do the corals. Corals remain the architects however, and in the numerous places where growth is sufficiently dense, the spaces between them become in-filled by many kinds of smaller calcareous organisms, both entire skeletons and fragments broken up by wave action, and boring animals and plants. Small pieces of mollusc shells, sea urchins, foraminifera, and calcareous plants are among the most important detrital ingredients of the filler. Providing there is sufficient ventilation of the sediment through the action of waves and currents, the CaCO_3 supersaturated waters of the Gulf aid the rapid lithification of this unconsolidated loose filler to a stiff boundstone facies. This stiffened structure constitutes ideal settlement substrate for the next generation of corals. Conversely, in areas where coral growth is insufficiently dense to hold detritus, the same combination of water chemistry and ventilation causes the formation of hardgrounds (i.e. Fig. 3.3), which at the very least tend to support a 'sparse' coral community comprised of solitary colonies spaced by several meters. While these hardgrounds are intermittently planed flat by the passage of mobile sand sheets, which creates clean settlement substrate, the migrating sands also periodically smother corals and by doing so, retard the development of framebuilding communities. Differences in topographic set-up for the coastal inshore

versus the offshore highs, offer a convenient means of partitioning the discussion of coral growth.

3.6.1 Coral Growth in the Nearshore

The best studied nearshore coral areas in the Gulf are those found along the gently sloping bathymetry off the U.A.E. coast, frequently referred to as the Arabian Homocline (Purser and Seibold 1973). Here, coastal and nearshore sedimentology has been shaped by rapidly changing sea-level throughout the Pleistocene and Holocene (Lambeck 1996; Uchupi et al. 1996; Kirkham 1998) and in the shorter term by wind. Daily onshore afternoon breezes and especially the prevailing (though largely seasonal) northerly Shamal wind, influence the local wave-induced currents, which in turn are important for coastal sedimentology (Kirkham 1998; Alsharhan and El-Sammak 2004). The northwest-trending coastline of the eastern U.A.E. is particularly influenced by Shamal events, because it lies oblique to the characteristic north wind blowing from the Iranian highlands and, apart from the Qatar Peninsula, lacks any shelter from offshore barriers. The shallow seafloor throughout the southeastern margin of the Gulf is above the storm wave-base typical for Shamal conditions, which can extend to a depth of at least 20 m (Purser and Seibold 1973). The best studied shallow-water carbonate environment in the Gulf is that in the vicinity of Abu Dhabi. This system consists of seaward reefs,

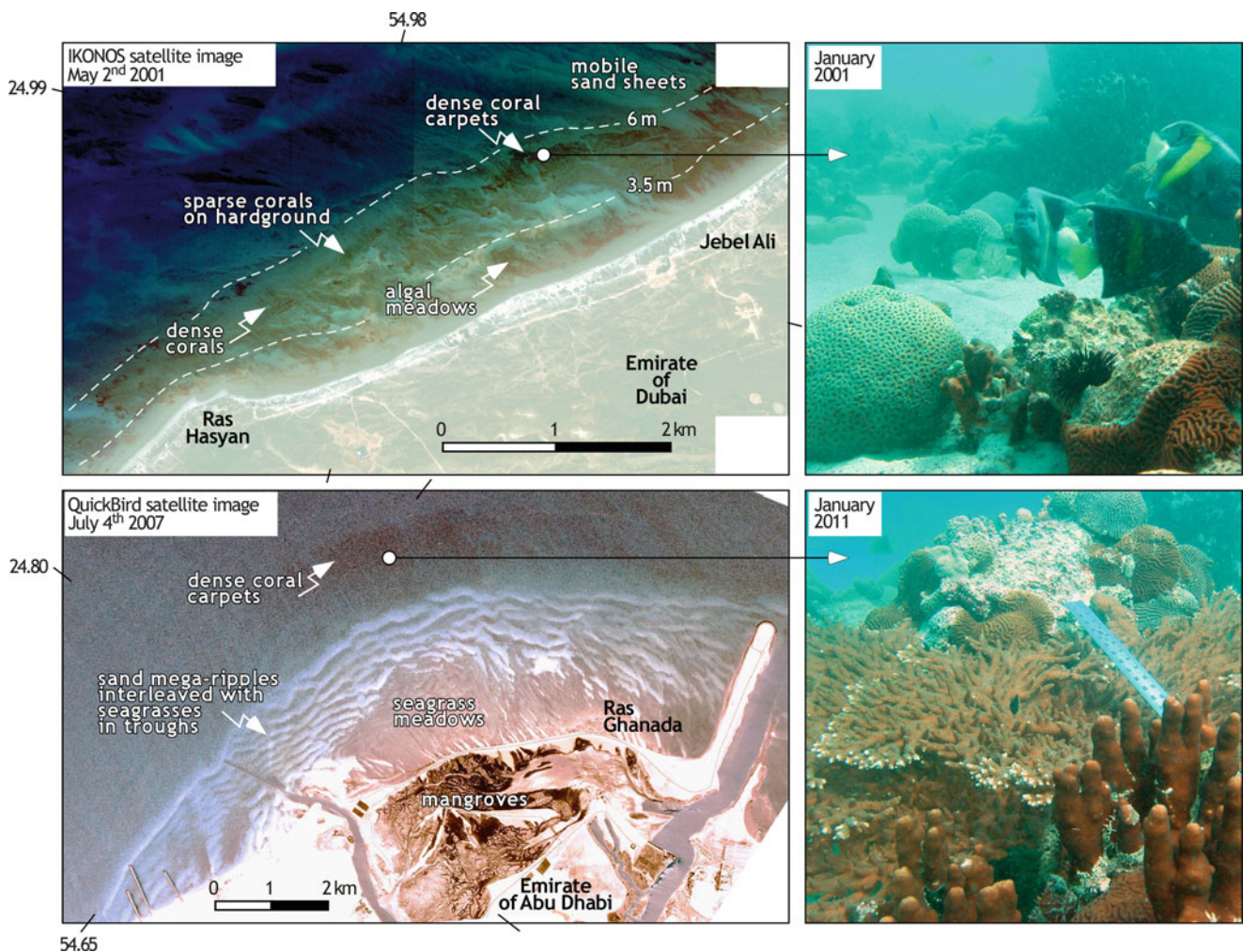


Fig. 3.8 Two of the richest near-shore Gulf coral communities. *Top* panes show Jebel Ali (Dubai, U.A.E), healthy in 2001, but shortly after destroyed by the construction of a ‘Palm Island’ (*inset*, Fig. 3.9). *Lower* panes show coral growth offshore Ras Ghanada (Abu Dhabi, U.A.E),

which at the time of writing remain in good health, despite the construction of the Khalifa Port just two kilometres to the west of the dense coral area (Modified after Purkis, 2005)

barrier islands, and expansive tidal flats. In eastern Abu Dhabi, ooid grains collect on inter-island tidal deltas while reefs are generally restricted to small patches along channels and on the seaward margins of islands (Evans et al. 1964). To the west, coral reefs grow along the northern edges of most of the offshore banks north of the Khor al Bazam, also termed the ‘Great Pearl Bank’.

The most common instance of dense coral communities in the nearshore of the southeastern Gulf is in the form of ‘coral carpets’, also termed ‘biostromes’. As depicted in Fig. 3.8 and until recently, two of the most vibrant examples of this motif could found offshore the headlands of Jebel Ali (Emirate of Dubai) and Ras Ghanada (Emirate of Abu Dhabi). The construction phase of the Jebel Ali Palm, which stretched from 2002 through 2008, however all but obliterated the former, while the corals of Ras Ghanada remain in good health at the time of writing, despite the nearby placement

of the Khalifa Port and Industrial Zone (KPIZ) at Taweelah. Coral carpets consist of laterally thin, but continuous frameworks of coral that do not reach the water surface, but may sustain several meters of topographic relief from the surrounding seabed. While extensive, carpets do not develop into true ‘reefs’ because of (1) underlying flat topography, and (2) disturbance history of the local coral assemblage. The initiation of coral carpets may be governed by both bottom topography and exposure. For instance, the fractured peripheries of hardground sheets offer an attractive point of nucleation for coral growth. These structures, termed overthrust-teepees (Shinn 1969), have sufficient relief to offer substrate free of mobile sediment that would otherwise retard coral growth. The location of dense nearshore coral carpets can also be somewhat linked to prominent headlands, which in turn likely have a tectonic origin. In the U.A.E. for example, the headlands of Ras Ghantoot, Ras Ghanada, and the

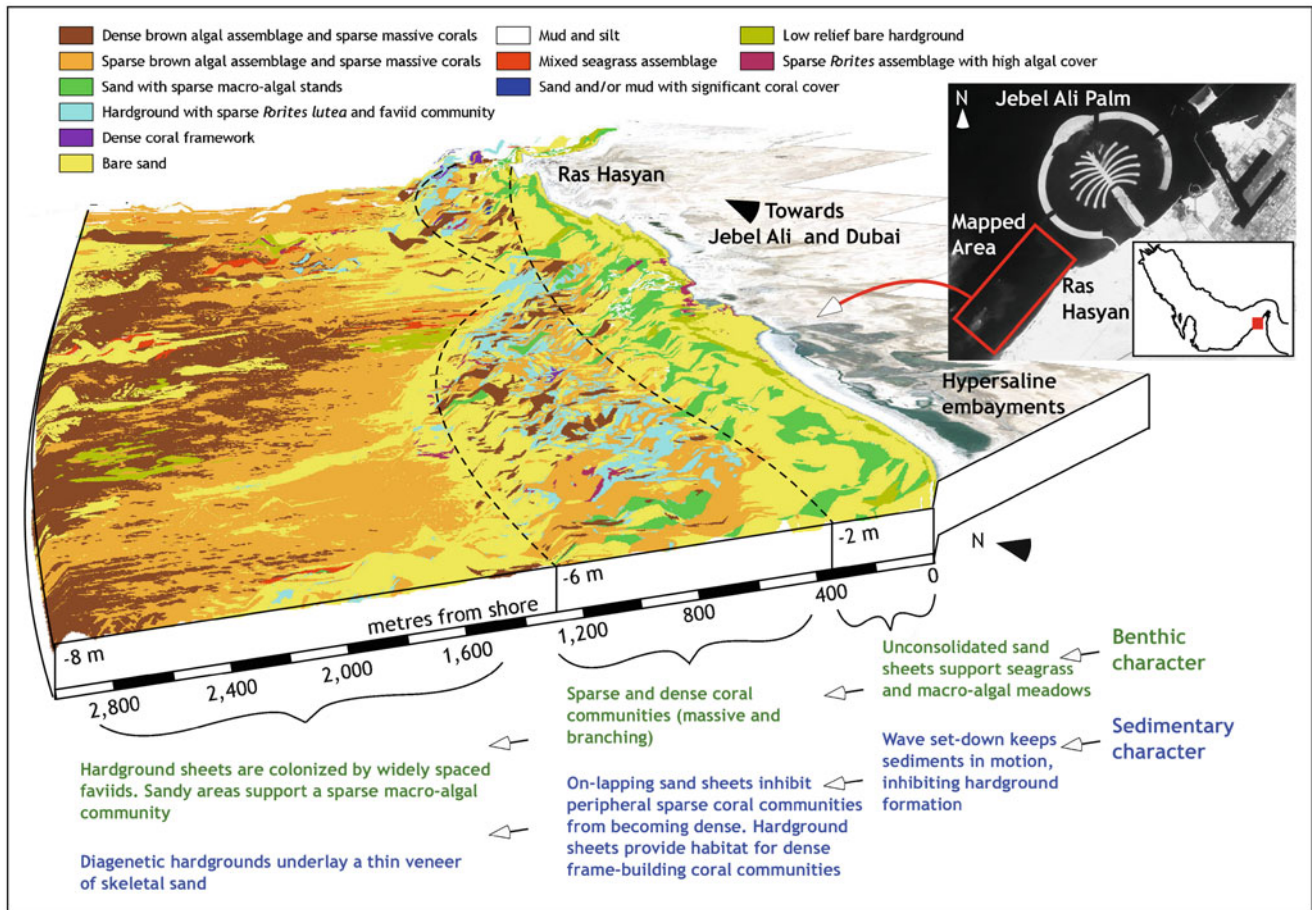


Fig. 3.9 Typical succession of near-shore habitats in the southeastern Gulf. Habitat and bathymetric mapping were conducted in 2006. Three depositional zones are present offshore Ras Hasyan, but the concept can be equally applied to all near-shore coral areas of the southeastern Gulf

Jebel Dhanna Peninsula, have all boasted rich coral areas in the last decades, though as previously discussed, coastal development has brought with it degradation and habitat loss. It has further been postulated that because of the near-horizontal coastal topography, even minor rises in future sea-level will serve to mobilize vast volumes of muddy, highly saline, sediment seaward from the supratidal flats, or ‘sabkhas’, that line the coast (Riegl 2003). This influx of sediment could serve to reset near-shore reef growth for several centuries. It should be noted however that coastal development in the last decade has seen thousands of square kilometers of sabkha removed or ‘filled’, while also strong shamal winds from the north serve to temporarily raise sea-level on the southeastern margin of the Gulf by up to 5 cm, flooding the sabkha for many kilometers inland (Thoppil and Hogan 2010). These short-lived flood-events do not seem to convey any detrimental effects to near-shore coral communities.

The nearshore ecological and sedimentary zonation of the southeastern Gulf is pronounced, but different, to the traditional environments of deposition adopted by “true” coral reefs (e.g. Wells 1954, 1957; Goreau 1959; Stoddart 1969;

Glynn 1973; Done 1983). Instead, the zonation is a blend of that produced by an actively accreting reef, with that of a purely sedimentary coastline. A hallmark of the southeastern Gulf is the shallow homoclinal slope of the shelf which serves to deliver broad, shore-parallel zonation of the near-shore. Here, and as for true reefs, it is the differing energy regimes imposed by wave-influence of the seabed, that set-up the zonation. On the basis of satellite mapping conducted offshore Ras Hasyan, the nearshore can be partitioned into three shore-parallel submarine zones (Fig. 3.9). Moving from the beach seaward, the first encountered zone has a breadth of several hundred metres and is dominated by unconsolidated sand sheets that may be colonized by algal and seagrass meadows. Here, the shallow water is not conducive to coral growth; stress from ultra-violet light will be high, sedimentation will be great because of sand mobilization by waves, and there is a general lack of stable substrate (hardground) for coral settlement.

The next zone encountered may be coral rich, supporting dense carpets (see for example Purkis 2005; Purkis and Riegl 2005; Riegl and Purkis 2005). Here, in water depths of

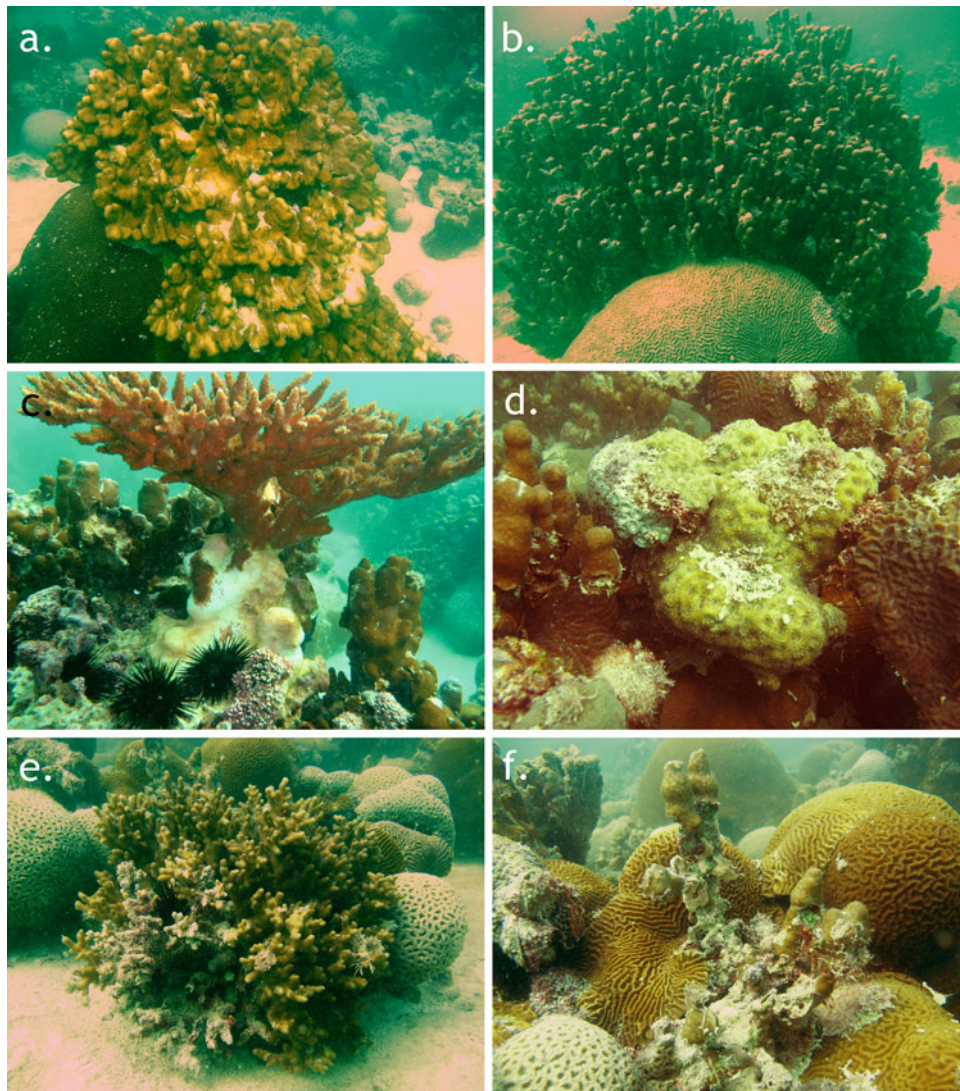


Fig. 3.10 Components of the typical dense coral assemblage encountered offshore Abu Dhabi. (a) *Porites lobata*, a relatively rare coral. (b) *Porites harrisoni*, the dominant species. (c) *Acropora clathrata* with a diseased stalk, but fully recovered from summer 2010 bleaching. (d)

Acanthastrea echinata, a rare coral. (e) *Stylophora pistillata*, an uncommon species. (f) A group of *Platygyra daedalea* with *Porites harrisoni* in the middle

2–5 m, surface waves have neither strong nor negligible effects on the sand bottom during a typical year; hardground formation is at its most vigorous and there is ample availability of suitable substrate for coral settlement. The main impediment to the formation of dense carpets is the impingement of mobile sand sheets, but, providing that a slight topographic irregularity (often associated with coastal headlands) serves as a nucleation-point for a coral community, the resulting framework will provide clean stable framework going forward. In this intermediate zone which is typically a kilometre or so in breadth, light levels are high because of the limited water depth, and oppressively hot summer temperatures maybe somewhat mitigated by the long-shore currents typical to this shelf. Here, algal biomass tends to be low, partly due to grazing-pressure from the herbivorous fish

community that associates itself with the coral frameworks, and also because very dense coral communities out-compete the algae for space (corals in Fig. 3.10 are diverse, dense, and over-topping). Providing that corals remain dense and healthy, the only algal incursions tend to be seasonal when winter storms deliver high nutrient concentrations to the nearshore, facilitating a spring/summer bloom of the brown benthic alga *Padina boergenseni* (personal obs.). This influx typically is well advanced by May, becoming absent by October. If the dense corals suffer significant mortality, fleshy algae are capable of rapidly monopolizing the available space (Purkis and Riegl 2005; Riegl and Purkis 2009).

The third and final zone depicted in Fig. 3.9 begins approximately 1.5 km from the beach and may extend for several kilometres further, down to depths of tens of metres.

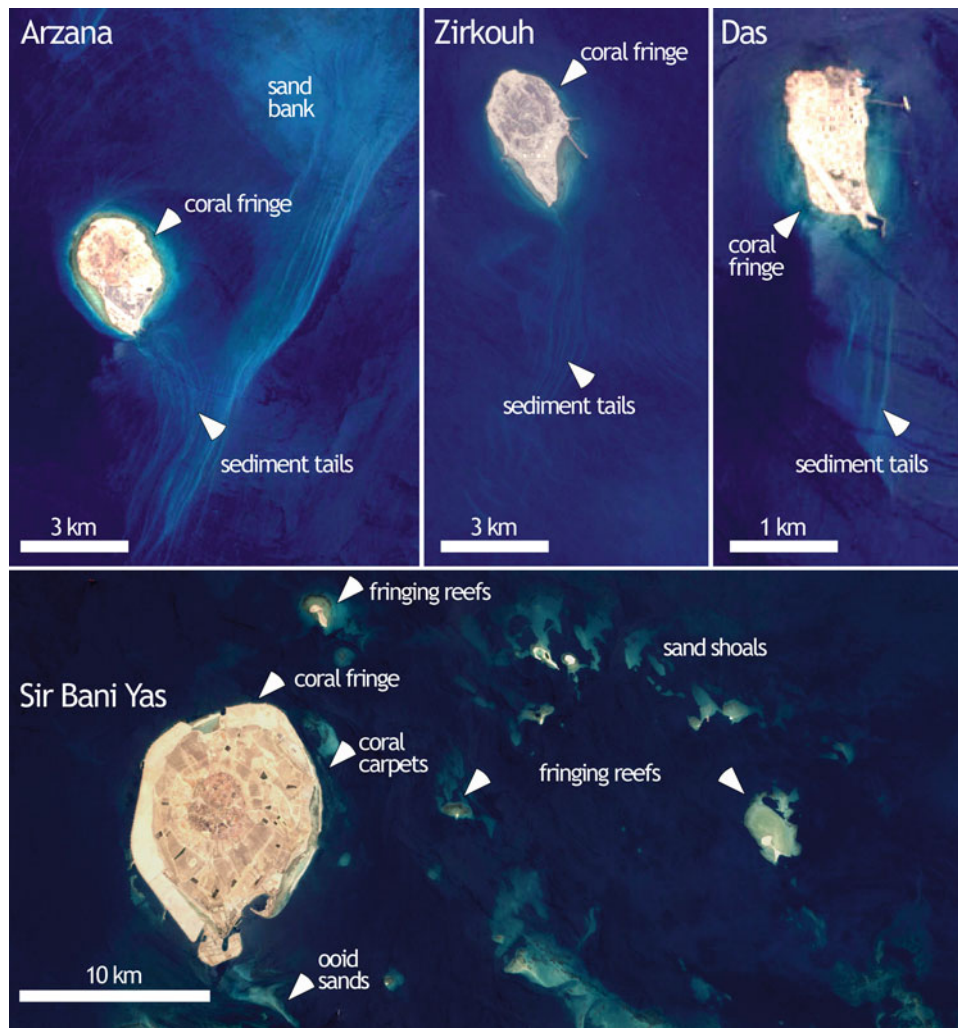


Fig. 3.11 Fringing reefs surrounding the Gulf's true diapiric islands are *pale green* when viewed in these Landsat satellite images. The fringes tend to best developed on the northern (windward) margins. The

imagery also shows the presence of extensive sediment 'tails' extending from the lee of the islands. North is *top*, prevailing wind is from the *upper-left*

Here, hardground formation does provide habitat for corals, but the community is typically sparse since sediment stress becomes chronic with the lack of seabed topography and light levels are low. Energy from surface waves is minimal in all but the most severe storm events. It is the hardy Faviid corals that are most successful in this deeper offshore zone, which may support sparse macro-algal communities. Unlike the nearshore, light levels are insufficient to allow the development of seagrass meadows.

3.6.2 Coral Growth on Offshore Islands and Highs

The majority of offshore diapiric islands (see Fig. 3.7) in the Gulf host fringing reefs. The best developed of which tend to be found on their windward (northern) margins, but even

here and as for those in the nearshore, they are best classified as incipient, or at least very young, fringing reefs. This stands in stark contrast to more traditional reef provinces, such as the adjacent Red Sea. Remnants of incipient fringes surround Sir Bani Yas and Dalma (Fig. 3.11), where, as is presently so common, coastal modification has served to bury previously extensive reefal areas. For instance, the runway for Dalma airport, built on the eastern coast of the island, lies atop a fringing reef (Fig. 3.6). Since the water surrounding the offshore islands and banks is only several tens of meters deep, the angle of repose of the flanks is slight, yielding large areas suitable for the development of coral frameworks (Fig. 3.11). At the time of writing, however, the majority of these appear to be in poor health, mostly dead, and in the process of conversion to algal-covered rubble mounds.

Reef growth also occurs on offshore platforms, such as Bu Tinah and Mubarraz. Both host islands, but these are

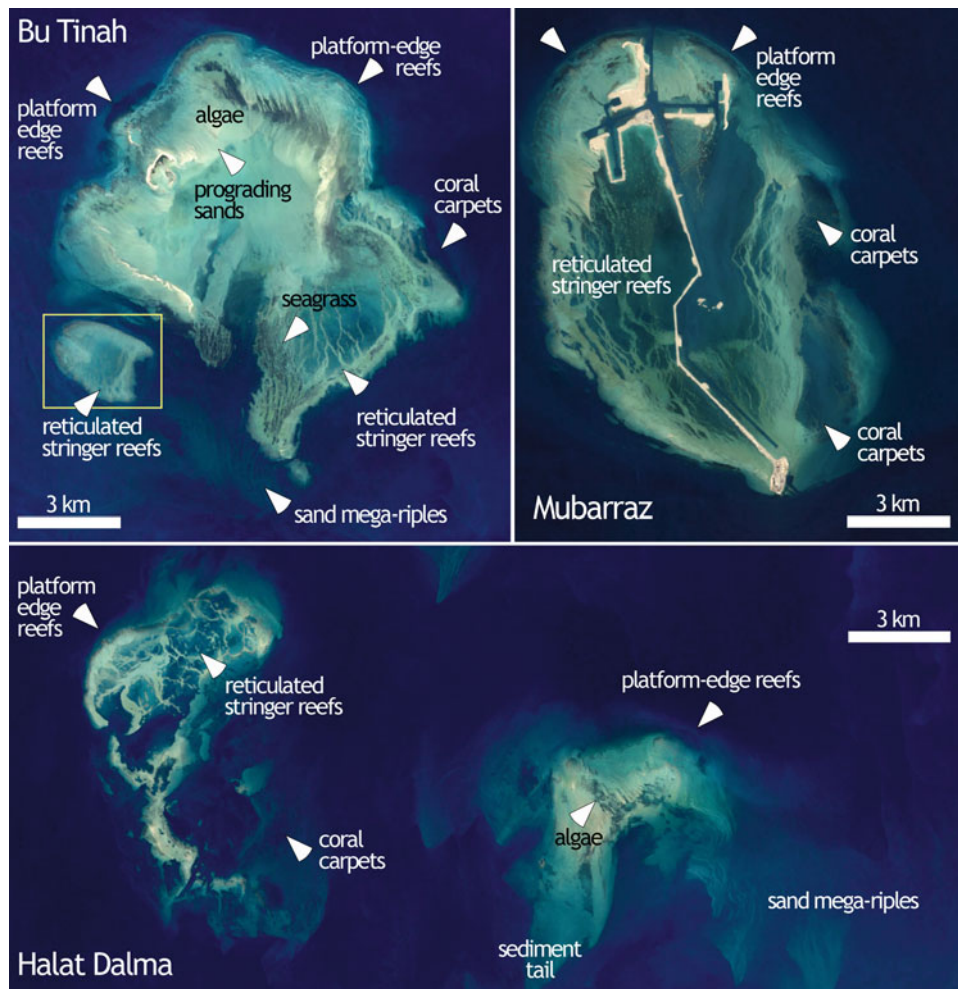


Fig. 3.12 A collection of offshore diapiric platform reefs captured by Landsat imagery. Here, islands, if present at all, are sandy and differ from those depicted in Fig. 3.11 by not possessing a bed-rock core. All

of these platforms host reticulated ‘stringer’ reefs. The *yellow rectangle* adjacent to Bu Tinah highlights the area considered by Fig. 3.13

sand-islands atop salt-domes and should not be considered as true diapiric islands in the same vein as Dalma and Sir Bani Yas. Adopting the nomenclature of Hopley (2007), platforms such as Bu Tinah and Mubarraz are best classified as lying somewhere between an ‘unmodified antecedent platform reef’ and a ‘crescentic reef’. Their morphological expression is that of the underlying salt-dome, but Holocene reef growth has provided a partially aggraded windward margin of sufficient width for a sediment apron to develop in the lee (Fig. 3.11). Since this margin is perforated and unable to sufficiently extend around the system, a true lagoon cannot develop and thus nor do complexes of lagoonal patch reefs. The platform centres are however not devoid of framework and instead populated by ‘stringer reefs’ (Fig. 3.12). These are elongated structures, which may develop to a reticulated maze-like pattern, such as observed on the small platform adjacent to Bu Tinah (Fig. 3.12-inset). In traditional nomenclature, this patterning is similar, but not identical, to

the ‘compound mesh reef’ of Maxwell (1970), though the mechanism of development may be rather different. If not reticulated, stringer reefs tend to be arranged in parallel to one another and aligned with the dominant axis of the host-platform and may be several kilometres in length (see the platform-top of Mubarraz, Fig. 3.12).

A mechanism for the formation of stringer reefs is poorly constrained and there likely exist several as composition varies between settings. For instance, excavation on the reticulated structures of Bu Tinah reveal construction of the stringers to be by coral frameworks (Fig. 3.13), whilst those in the center of Mubarraz appear to be more sediment-dominated. By developing a Pleistocene-Holocene chronology of sea-level and climate for the Arabian region, Purkis et al. (2010) concluded that the reticulated reef structures (termed Type-2) to be indicative of a brief period of sub-aerial chemical erosion followed by submergence and the initiation of reef growth. The work provided evidence that the

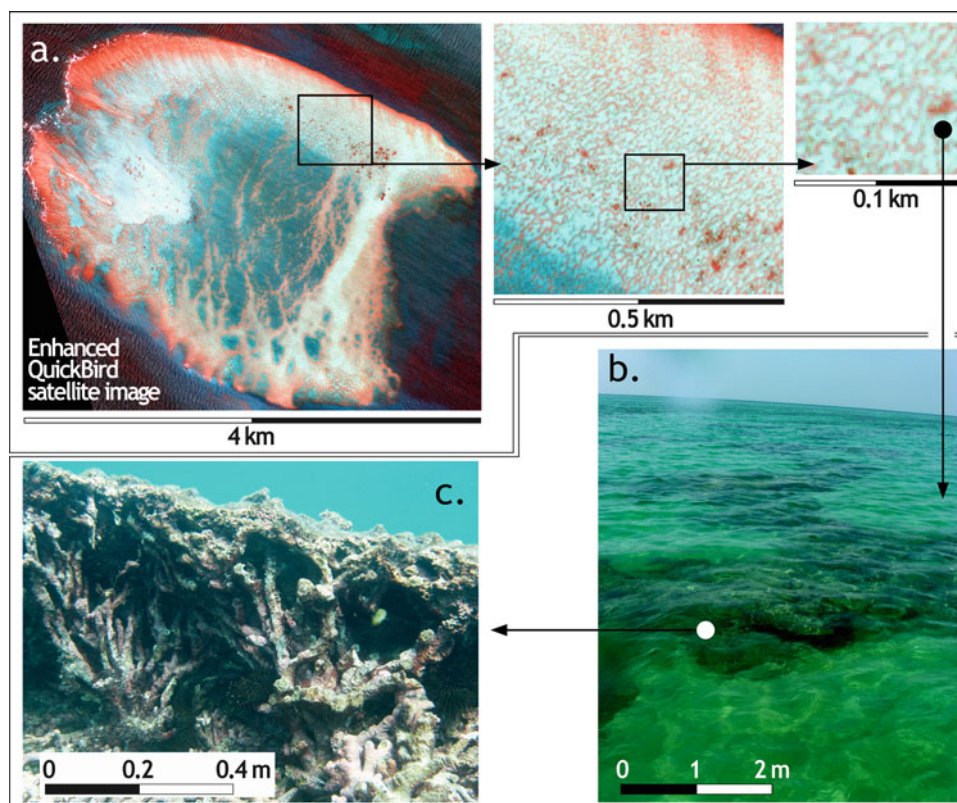


Fig. 3.13 An enhanced QuickBird satellite image reveals reticulated networks atop Bu Tinah Shoal (Abu Dhabi) that consist of a maze of sills that surround sand-filled depressions (a) (see yellow rectangle in Fig. 3.12 for area depicted). The pattern is ‘scale-invariant’, similar in

form, regardless of the level of magnification. The tops of the sills rise to sea-level (b) and exposed at low-tide. The internal structure of the sills consists of branching coral frameworks infilled with coralline algae, rubble, and debris (c)

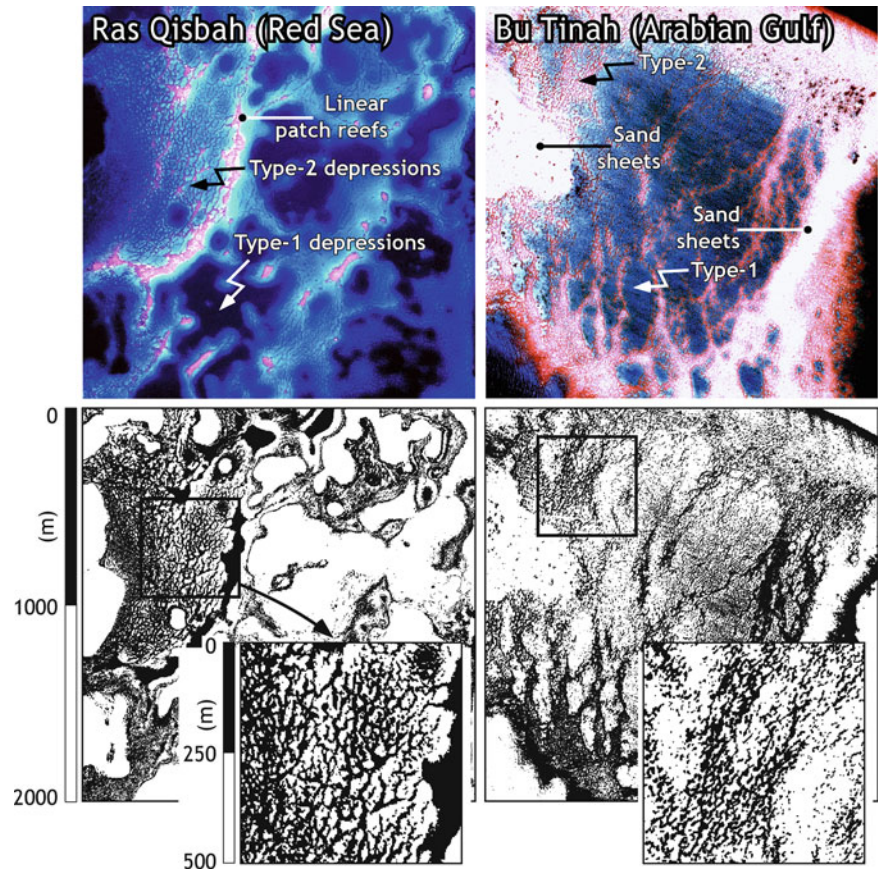
timing of this short episode of karst weathering occurred during the Holocene pluvial period in Arabia. If correct, this mode of formation demonstrates that aspects of the reef morphology in the Gulf are controlled by antecedent topography formed as recently as the mid-Holocene. Shinn and Purser (2010) propose an alternative hypothesis, ascribing the reticulated structures to arise from expansion of rapidly cementing seafloor hardgrounds. Here, expansion of lithifying subsea sediment produces bending and folding, and overthrusting of layers best explained by force of crystallization. This lateral expansion was postulated to develop polygonal patterns, the reverse of, but similar to, mud cracks in dried mud layers (Kendall and Skipwith 1969; Shinn 1969; Purser and Evans 1973). This latter explanation is however at odds with the observation that geometrically similar patterns are observed in the Red Sea, which unlike the Gulf, does not boast the necessary supersaturated seawater mineralogy to promote substantial hardground formation. This accordance in patterning between the Gulf and the Red Sea (Fig. 3.14) is hard to reconcile with the buckled hardground hypothesis. Further plausible methods for the formation of reticulated patterning come in the form of growth structures (Wyrwoll et al. 2006), but if these were to

be at play in the Gulf, the strong relationship between depth distribution of the reticulates and sea-level would not be anticipated (Purkis et al. 2010). In addition, the fact that reticulated topography can form via karst has been adequately demonstrated by Purdy (1974).

3.7 Summary

This chapter frames the present day coral systems of the Gulf with the geological development of the basin, as well as sea-level and climate variation since the last glacial maximum. It is revealed that the motif of coral development differs considerably between the inshore and offshore islands and banks. In all cases, fringing reefs are best classified as incipient, or at least, very young, which stands in contrast to the extensive development of non-framebuilding coral carpets (biostromes), which represent the richest coral ecosystems in the Gulf. Coral growth on offshore banks, which owe their existence to underlying salt domes, adopts a conspicuous reticulated ornamentation of ‘stringer’ reefs. Despite its inhospitable conditions, the Gulf displays considerable diversity in coral species and reef morphology alike.

Fig. 3.14 Stringer reefs have comparable morphology in the Red Sea (*right*) and Gulf (*left*), indicating a common mechanism of formation. Purkis et al. (2010) provides a statistical treatment of these images



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Environmental Setting and Temporal Trends in Southeastern Gulf Coral Communities

Kristi Foster, Greg Foster, Ashraf S. Al-Cibahy, Suaad Al-Harathi, Sam J. Purkis, and Bernhard M. Riegl

4.1 Introduction

The majority of coral reefs are found in tropical environments between 25°N and 25°S, where typical seawater temperatures and salinities are between 18°C and 31°C and 34–37 ppt, (Kleypas et al. 1999; Veron 1986). The marine environment of the southeastern Arabian Gulf is singularly harsh; the coral communities in this high-latitude region (i.e. between 24°09'N and 25°40'N) are exposed to natural conditions that exceed threshold limits of corals elsewhere in the world, with temperature ranges between 14°C and 36°C (Kinzie III 1973; Shinn 1976) and salinities above 40 ppt. Less than one-third of the scleractinian species that are found in the neighboring Gulf of Oman have adapted to survive in the Arabian Gulf (e.g. *Acropora* spp., *Porites* spp., faviids and siderastreids) (Riegl 1999; Coles 2003; Rezai et al. 2004; Claereboudt 2006). Other benthic taxa that are common in the Gulf of Oman but are absent from the Arabian Gulf include the coral genera *Montipora*, *Pocillopora*, and *Goniopora* spp., fungiids, oculinids, alcyonaceans, and massive sponges. The adaptations of some taxa to extremes of temperature and salinity and the exclusion of other taxa are of interest to scientists studying the impacts of global climate change on coral reefs and other marine organisms.

The southeastern Arabian Gulf encompasses the coastal and offshore environments of the United Arab Emirates (UAE) and eastern Qatar (Fig. 4.1). The shallow-water coral communities are situated on discontinuous patches along the Qatari and Emirati coasts, near offshore islands and atop limestone domes. Assessments of the coral communities and their respective marine environments were conducted

between 2005 and 2009 at multiple sites within Study Area “A”, located offshore Qatar and Abu Dhabi (Fig. 4.1, Table 4.1a). These assessments have provided data that describe (i) the typical environmental regimes to which the corals are exposed and (ii) the structure of the recovering coral communities a decade after the mass mortality associated with the 1996 elevated temperature anomaly (Riegl 2002, 2003; Sheppard and Loughland 2002). Similar assessments were conducted in the adjacent northwestern Gulf of Oman within Study Area “B” (Fig. 4.1, Table 4.1b) where the same coral species as those in the Arabian Gulf, along with 60–70 additional species, are found.

4.2 Environmental Setting

4.2.1 Temperatures

Temperature extremes have been recorded at various locations around the Arabian Gulf (Table 4.2), but little information is available regarding the “normal” conditions to which coral communities are exposed. As part of the assessments described herein, temperature recorders were deployed within Study Areas “A” and “B” approximately 0.5 m above the benthos. Daily mean temperature profiles for ten sites in the southeastern Arabian Gulf and two sites in the northwestern Gulf of Oman are shown in Figs. 4.2, 4.3, and 4.4. The data for the individual sites were combined to provide regional temperature profiles for the southeastern Arabian Gulf and the northwestern Gulf of Oman (Figs. 4.5 and 4.6). Spring cooling rates, autumn warming rates, maximum summer temperatures and minimum winter temperatures are listed in Table 4.3. Results indicated the following with respect to normal temperatures at sites in Study Area “A”:

- Minimum daily means varied between the individual sites during the winter season (December 21–March 20), ranging from 16.5°C to 19.5°C (Figs. 4.2 and 4.3). The minimum daily mean for the southeastern Arabian Gulf region was 16.5°C, although this was not reached every year

K. Foster (✉) • G. Foster • S.J. Purkis • B.M. Riegl
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: kfoster@nova.edu; fjohn@nova.edu; purkis@nova.edu;
rieglb@nova.edu

A.S. Al-Cibahy • S. Al-Harathi
Environment Agency-Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: aalcibahy@ead.ae; salharthi@ead.ae

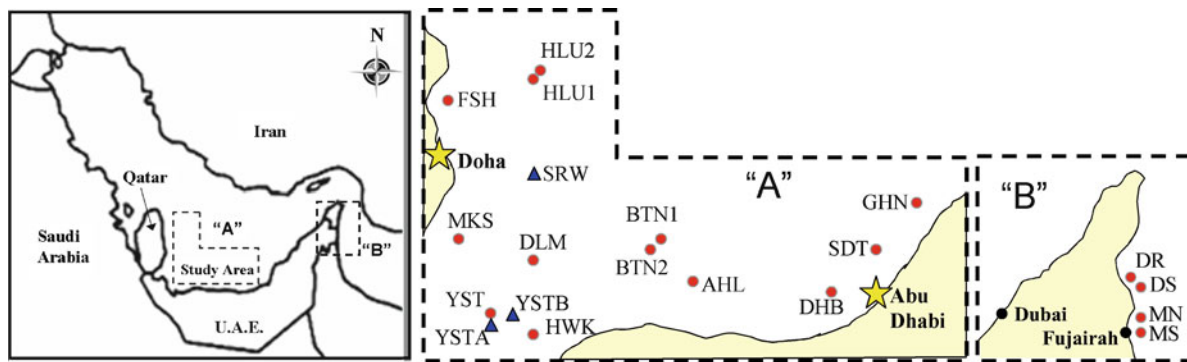


Fig. 4.1 Map of monitoring station locations. (left) Map of Arabian Gulf and surrounding region, study areas are outlined; (center) Study area “A” locations in the southeastern Arabian Gulf; (right) Study area

“B” locations in the northwestern Gulf of Oman. Circles indicate monitoring station locations. Triangles indicate sites with temperature recorders only

Table 4.1 Descriptions of monitoring station locations

Station	Site name	Location	Territory	Depth (m)
(a) Southeastern Arabian Gulf				
HLU2	Halul East	Island	Qatar	4.8–5.2
HLU1	Halul South	Island	Qatar	4.5–5.3
FSH	Fasht Al-Ghabi	Coastal	Qatar	3.5–3.9
SRW	Shra’aw	Island	Qatar	5.0–5.5
MKS	Makaseb	Island	Abu Dhabi, UAE	2.1–5.5
YST	Yasat Ali	Island	Abu Dhabi, UAE	3.0–4.7
YSTA	Yasat Asfl	Island	Abu Dhabi, UAE	5.0–5.5
YSTB	Yasat Buoy #B-08	Offshore	Abu Dhabi, UAE	31
HWK	Hawksbill Reef	Limestone Dome	Abu Dhabi, UAE	7.0–8.5
DLM	Delma	Island	Abu Dhabi, UAE	5.3–5.6
BTN1	Bu Tinah North	Island	Abu Dhabi, UAE	1.8–3.6
BTN2	Bu Tinah West	Island	Abu Dhabi, UAE	2.0–3.5
AHL	Al Hiel	Island	Abu Dhabi, UAE	2.6–4.2
DHB	Dhabiya	Coastal	Abu Dhabi, UAE	6.4–7.2
SDT	Saadiyat	Coastal	Abu Dhabi, UAE	5.7–7.2
GHN	Ras Ghanada	Coastal	Abu Dhabi, UAE	7.6–8.5
(b) Northwestern Gulf of Oman				
DR	Dibba Rock	Coastal	Fujairah, UAE	5.1–7.1
DS	Dibba South	Coastal	Fujairah, UAE	6.7–8.1
MN	Mirbah, North	Coastal	Fujairah, UAE	4.5–6.9
MS	Mirbah South	Coastal	Fujairah, UAE	2.5–3.6

Table 4.2 Temperature extremes recorded from Arabian Gulf coral communities

Location	Latitude	Min (°C)	Max (°C)	Range (°C)	Source
Kuwait	29 N	13.2	31.5	18.3	Downing (1985)
Saudi Arabia	27 N	11.4	36.2	24.8	Coles and Fadlallah (1991)
Abu Dhabi	25 N	16.0	36.0	20.0	Kinsman (1964)
Qatar	24 N	14.1	36.0	21.9	Shinn (1976)
Abu Dhabi (Al Hiel)	24 N	14.9 (2008)	37.2 (2007)	22.3	This study – hourly records
Qatar (Shra’aw)	25 N	18.7 (2006)	35.4 (2006)	16.7	This study – hourly records

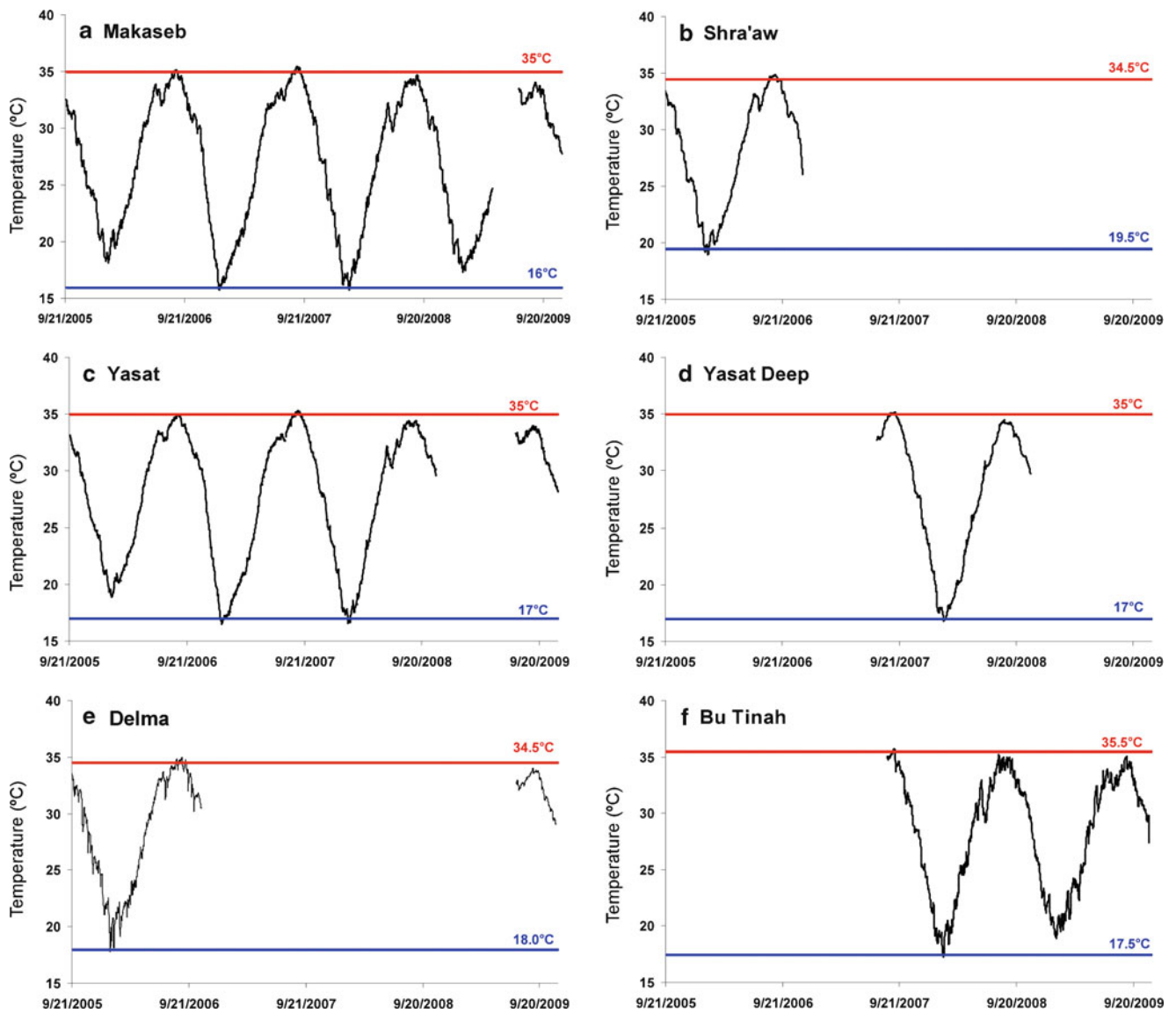


Fig. 4.2 (a–f) Daily mean temperature profiles (2005–2009) – sequential. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines*

indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at Abu Dhabi offshore islands (a, c, e, f); at a Qatar offshore island (b); and at a buoy marking the Yasat marine protected area boundary in Abu Dhabi waters (d)

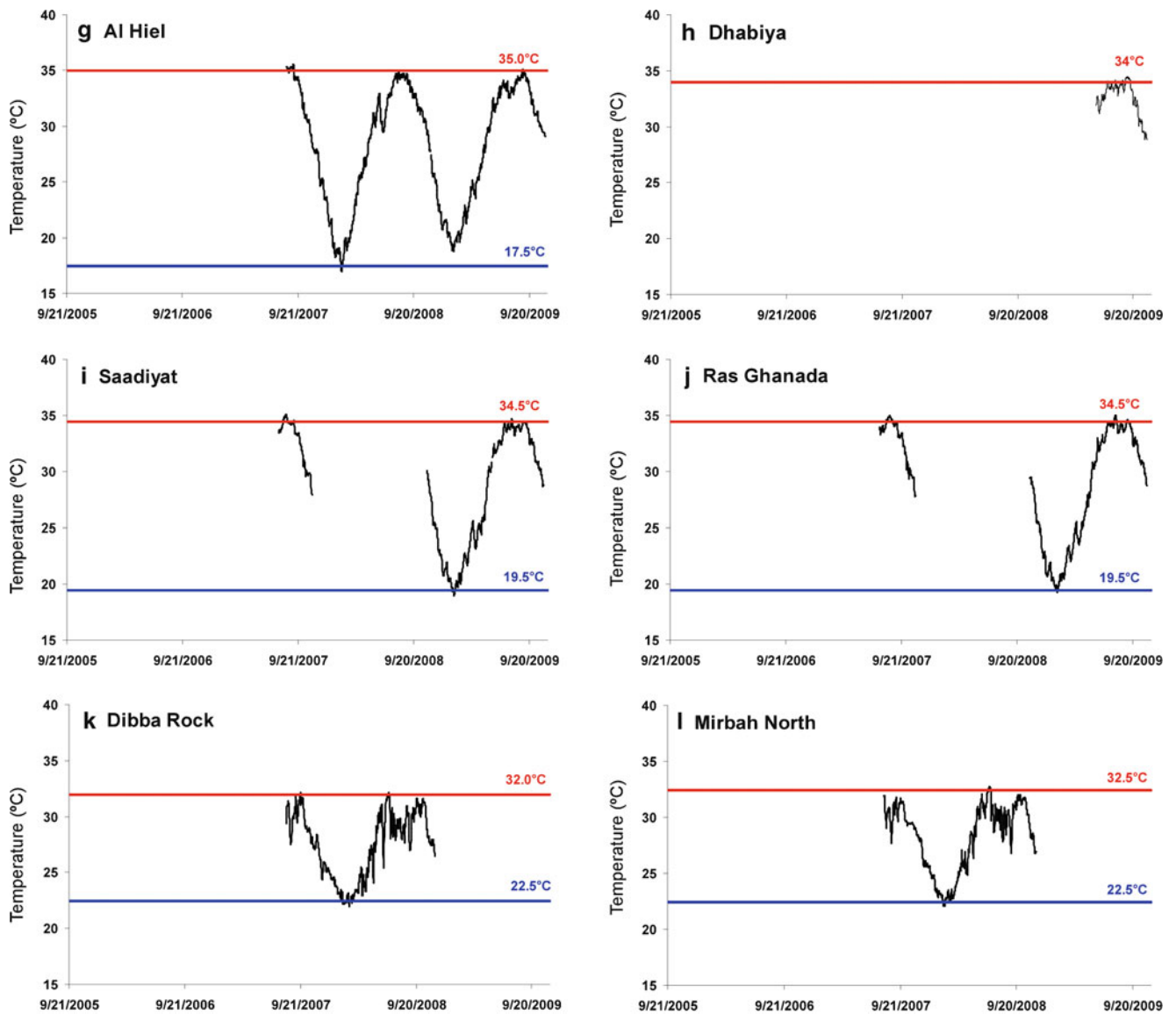


Fig. 4.2 (continued) (g–l) Daily mean temperature profiles (2005–2009) – sequential. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures.

Lower lines indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at an Abu Dhabi offshore island (g); along Abu Dhabi coasts (h–j); and along Fujairah coasts (k, l)

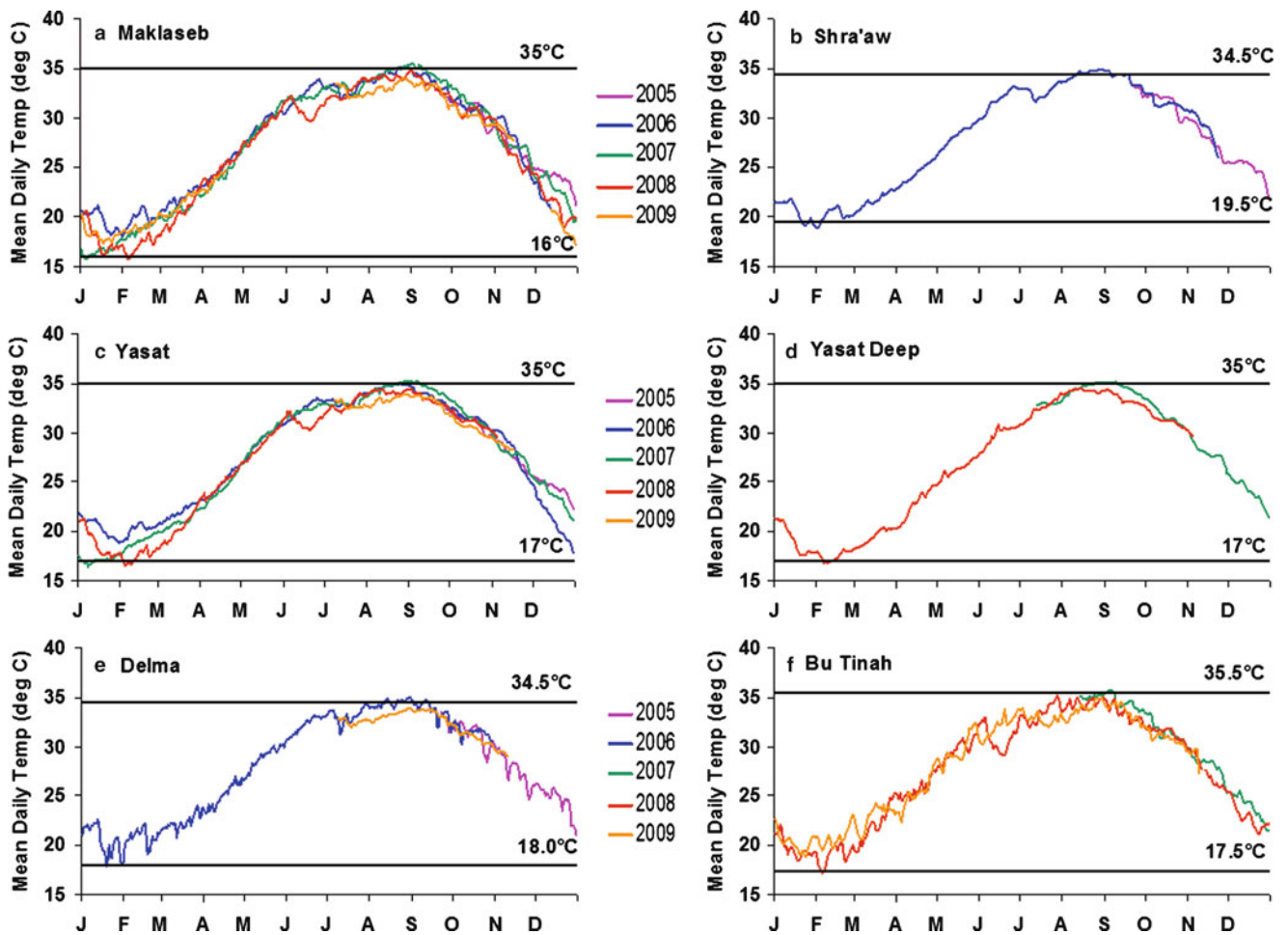


Fig. 4.3 (a–f) Daily mean temperature profiles (2005–2009) – overlapping. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures. *Lower lines*

indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at Abu Dhabi offshore islands (a, c, e, f); at a Qatar offshore island (b); and at a buoy marking the Yasat marine protected area boundary in Abu Dhabi waters (d)

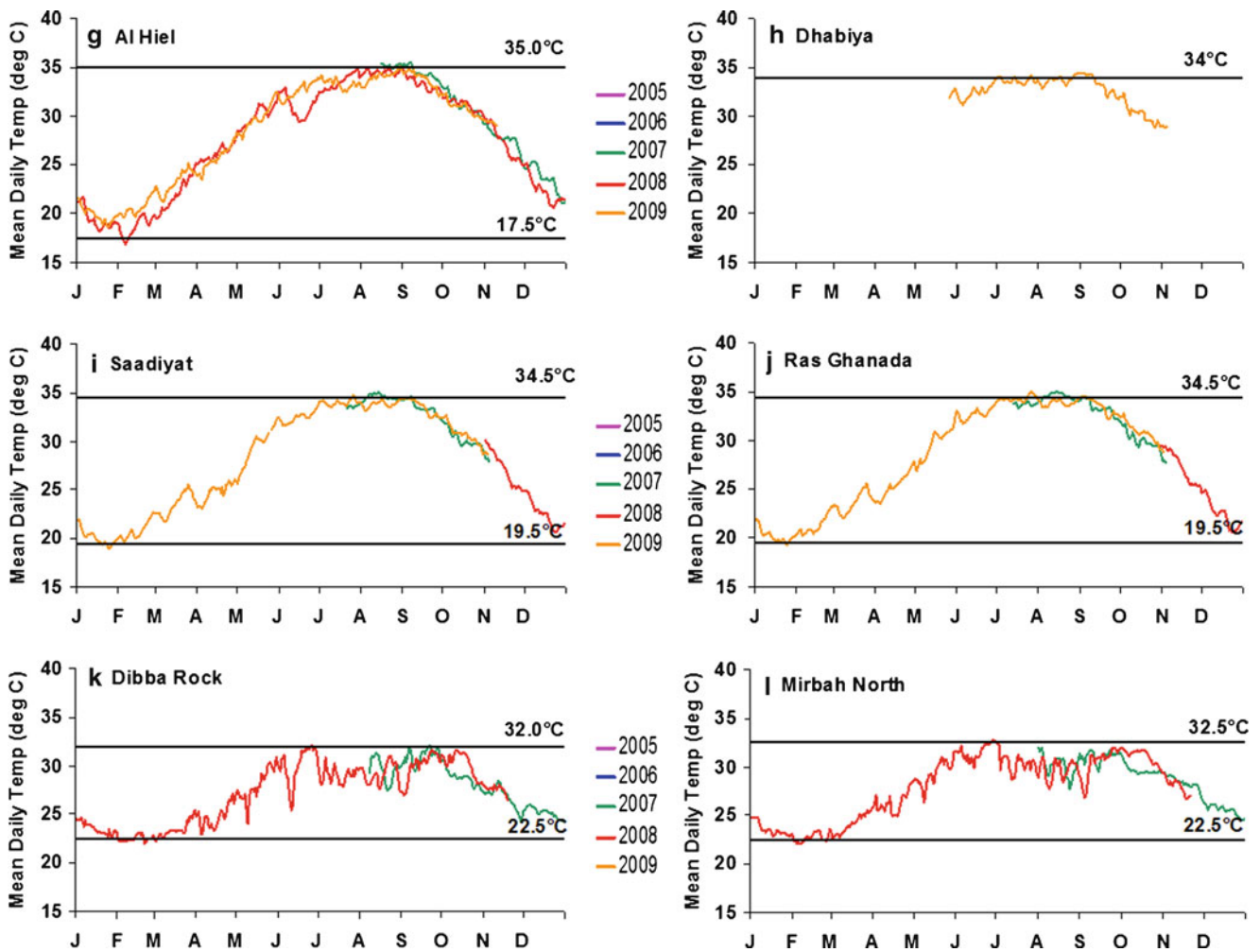


Fig. 4.3 (continued) (g–l) Daily mean temperature profiles (2005–2009) – overlapping. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day. *Upper horizontal lines* indicate the normal summer (June 21–September 20) maximum temperatures.

Lower lines indicate the normal winter (December 21–March 20) minimum temperatures. Temperature loggers were deployed at an Abu Dhabi offshore island (g); along Abu Dhabi coasts (h–j); and along Fujairah coasts (k, l)

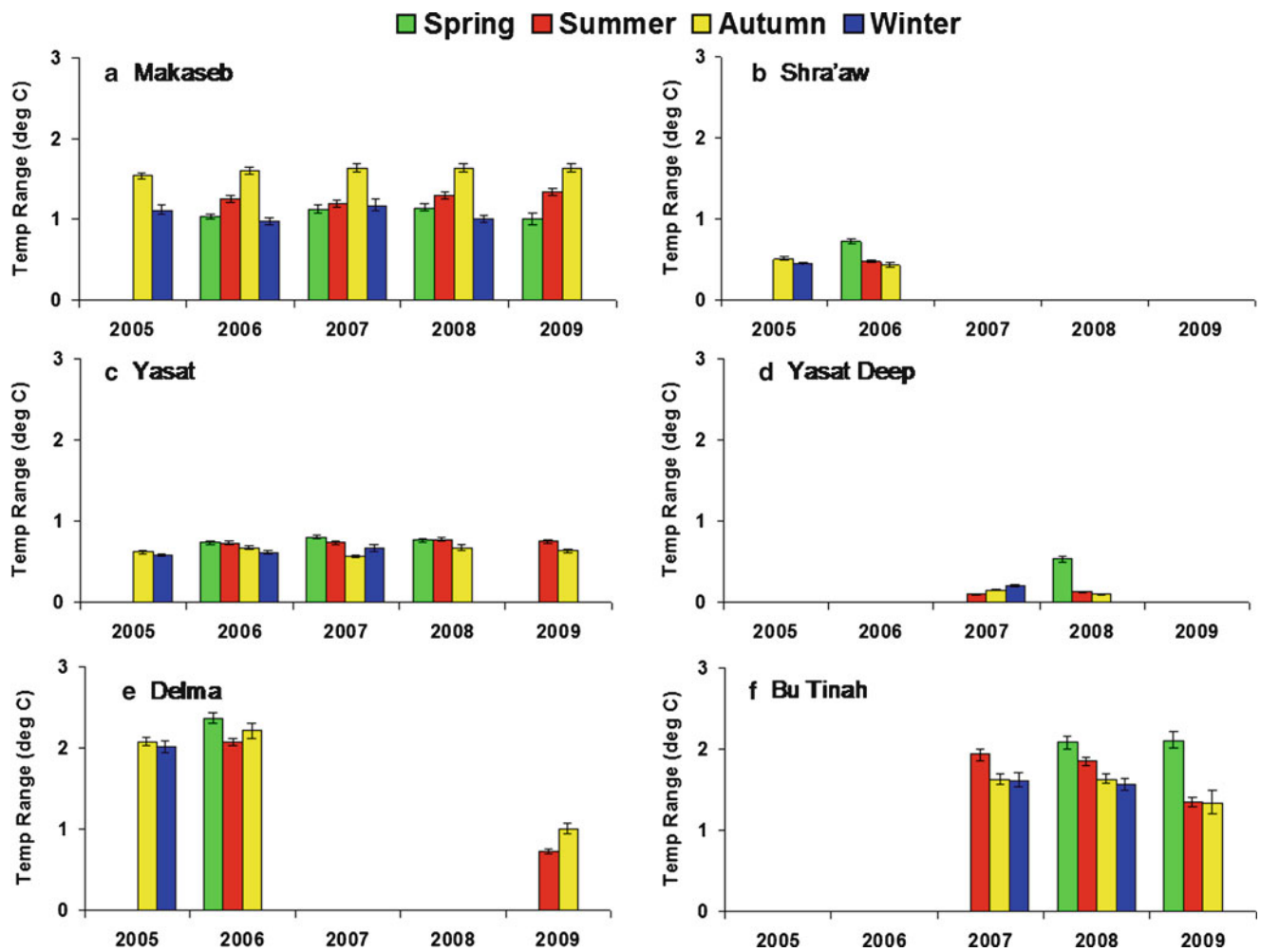


Fig. 4.4 (a–f) Mean daily temperature ranges by season (2005–2009). Temperature range is the difference between the maximum and minimum hourly records between 00:00 and 23:59 for each calendar day. Seasons are defined as spring (March 21–June 20); summer (June 21–September

20); autumn (September 21–December 20); and winter (December 21–March 20). Temperature loggers were deployed at Abu Dhabi offshore islands (a, c, e, f); at a Qatar offshore island (b); and at a buoy marking the Yasat marine protected area boundary in Abu Dhabi waters (d)

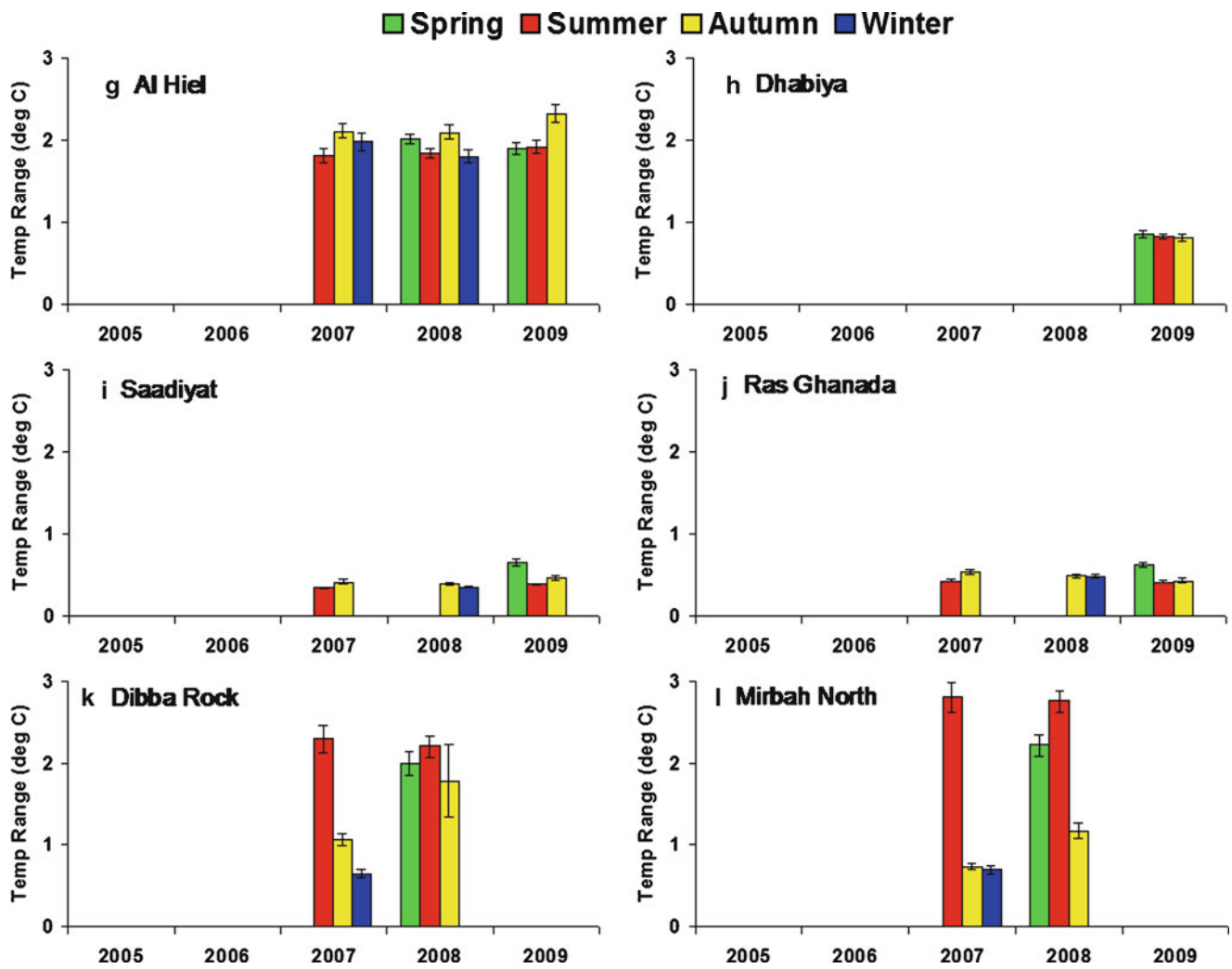


Fig. 4.4 (continued) (g–l) Mean daily temperature ranges by season (2005–2009). Temperature range is the difference between the maximum and minimum hourly records between 00:00 and 23:59 for each calendar day. Seasons are defined as spring (March 21–June 20); summer

(June 21–September 20); autumn (September 21–December 20); and winter (December 21–March 20). Temperature loggers were deployed at an Abu Dhabi offshore island (g); along Abu Dhabi coasts (h–j); and along Fujairah coasts (k, l)

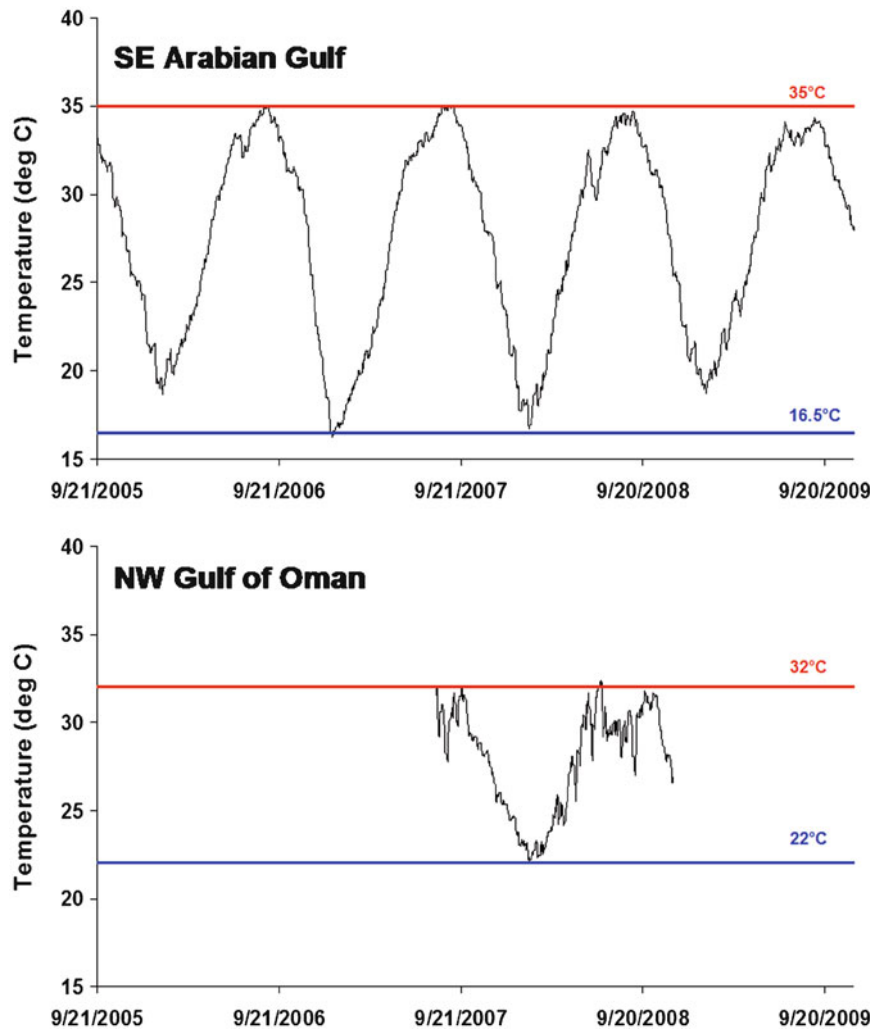


Fig. 4.5 Regional daily mean temperature profiles (2005–2009) – sequential. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day, averaged across all sites (Arabian Gulf = 10 sites; Gulf of Oman = 2 sites). *Upper horizontal lines* indicate

the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures

- (Figs. 4.5 and 4.6). These data suggests that the southeastern Arabian Gulf gets colder in the winter than does the central Gulf for which Sheppard et al. (2010) presented HadSST1 data indicating a lower temperature limit of 20°C.
- Daily mean temperatures for the southeastern Arabian Gulf region during the winter season were typically within the range of 18.5–21.0°C (Table 4.3).
 - The minimum hourly temperature recorded during this study was 14.9°C at Al Hiel in February 2008 (Table 4.3).
 - The mean warming rates during the spring (March 21–June 20) were typically 0.09–0.13°C per day. The warming rates were nearly uniform across the individual sites in a given year. (Table 4.3)

- Temperature data collected near Yasat Island indicated that a thermocline formed during Spring 2008 as shallow waters warmed faster than deeper waters (Fig. 4.7). The lower water layer was 1–4°C colder than the upper water layer. Mixing of the thermally stratified layers was evident by rapid temperature declines in the upper layer during the late spring/early summer, after which the thermocline was no longer present. Similar rapid reductions in temperature occurred at the other sites during the same timeframe (June–July 2008) and during the other years (Fig. 4.2), indicating that the mixing of warmer surface waters with cooler deeper water is an annual and regional phenomenon.
- Maximum daily means varied between the individual sites during the summer season (June 21–September 20),

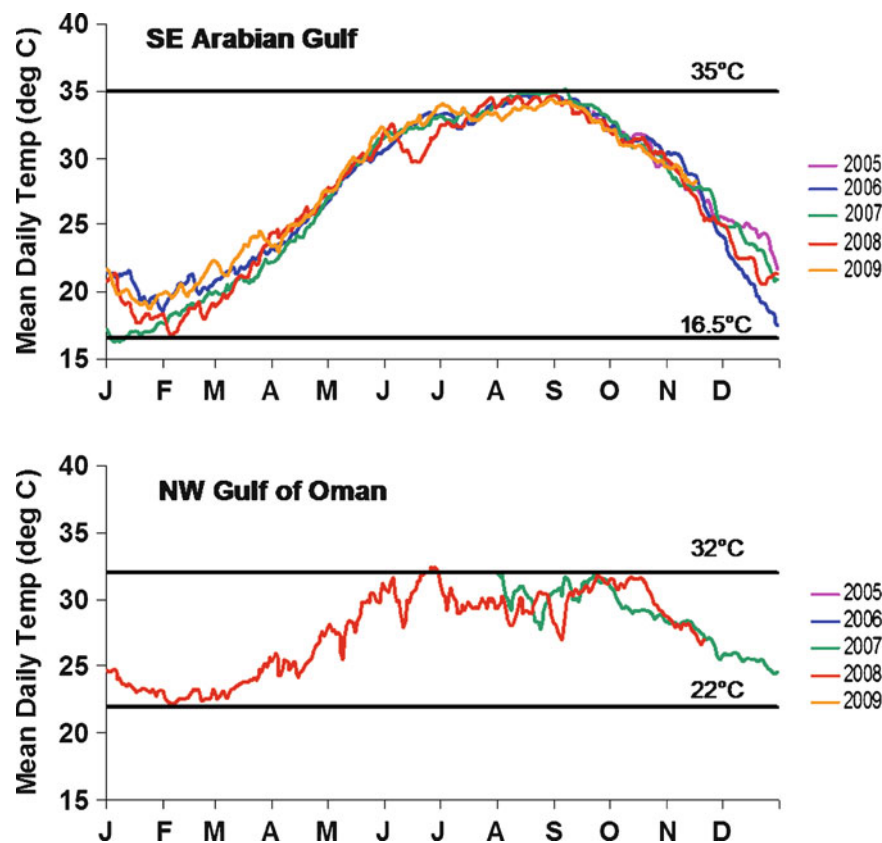


Fig. 4.6 Regional daily mean temperature profiles (2005–2009) – overlapping. Daily mean temperatures based on hourly records between 00:00 and 23:59 each calendar day, averaged across all sites (Arabian Gulf = 10 sites; Gulf of Oman = 2 sites). *Upper horizontal lines* indicate

the normal summer (June 21–September 20) maximum temperatures. *Lower lines* indicate the normal winter (December 21–March 20) minimum temperatures

ranging from 34.0°C to 35.5°C (Figs. 4.2 and 4.3). The maximum daily mean for the southeastern Arabian Gulf region was 35°C, although this was not reached every year (Figs. 4.5 and 4.6). These data suggests that the southeastern Arabian Gulf gets hotter than does the central Gulf which Sheppard et al. (2010) presented HadSST1 data indicating an upper temperature limit of 33°C.

- Daily mean temperatures for the southeastern Arabian Gulf region during the summer season were typically 33.4–33.9°C (Table 4.3).
- The maximum hourly temperature recorded during this study was 37.2°C at Al Hiel in August 2007 (Table 4.3).
- The mean cooling rates during the winter (December 21–March 20) were typically 0.10–0.15°C per day (Table 4.3). The cooling rates were nearly uniform (i) among the individual sites within a given season (Table 4.3) and (ii) throughout the water column (Fig. 4.7).
- The annual temperature ranges at the individual sites and for the southeastern Arabian Gulf region were 15–19°C and 18.5°C, respectively (Figs. 4.2 and 4.3). These ranges

are wider than the 13°C range recorded in the Central Gulf (Sheppard et al. 2010).

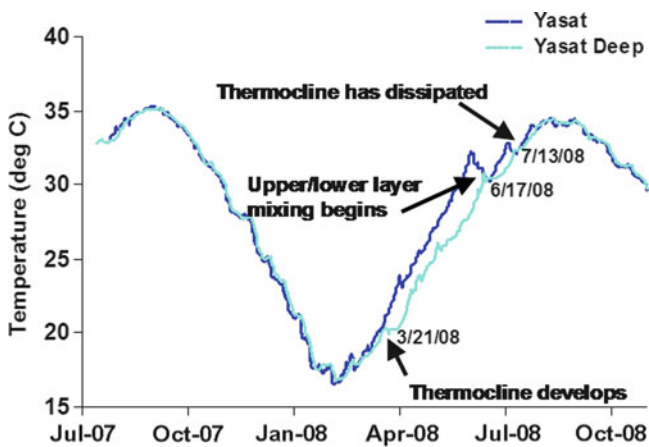
- Daily temperature ranges of less than 1°C were recorded at the coastal Abu Dhabi sites (i.e. Dhabiya, Saadiyat, Ras Ghanada), one of the Abu Dhabi offshore islands (Yasat) and the Qatari offshore island (Shra'aw). The other Abu Dhabi offshore islands (Makaseb, Delma, Bu Tinah, Al Hiel) experienced daily temperature ranges between 1.0°C and 2.5°C. (Fig. 4.4)

The coral communities in the southeastern Arabian Gulf did not experience mass mortalities during exposure to the lower and upper temperature limits described above, indicating acclimatization to these conditions. Small-scale bleaching and disease were observed on individual corals during the summer months (Fig. 4.8) but subsequent visits in late autumn, when water temperatures had cooled, indicated that (i) bleached corals had returned to normal coloration without mortality and (ii) disease resulted in mortality of affected polyps while the remainder of the colonies survived.

The Gulf of Oman has a different temperature regime compared to the Arabian Gulf (Figs. 4.2, 4.3, 4.4, 4.5, and

Table 4.3 Spring warming rates, autumn cooling rates, maximum summer temperatures and minimum winter temperatures (2005–2006)

(a) Spring cooling and autumn warming rates				
Year	Mean warming rates (°C per day)		Mean cooling rates (°C per day)	
	Arabian Gulf	Gulf of Oman	Arabian Gulf	Gulf of Oman
2005			0.10–0.11	
2006	0.11–0.12		0.15	
2007	0.13		0.12–0.13	0.06–0.08
2008	0.10–0.11	0.08–0.09	0.13–0.15	
2009	0.09–0.10			
(b) Maximum summer temperatures				
Summer	Region	Mean daily temp (°C)	Max daily temp (°C)	Max hourly temp (°C)
2006	Arabian Gulf	33.8	34.9	36.2 (Makaseb, 23Aug2006)
2007	Arabian Gulf	33.9	35.1	37.2 (Al Hiel, 29Aug2007)
2008	Arabian Gulf	33.4	34.7	36.8 (Al Hiel, 23Jul2008)
2009	Arabian Gulf	33.5	34.3	36.6 (Al Hiel, 07Aug2009)
2008	Gulf of Oman	29.9	32.8	35.5 (Mirbah North, 01Jul2008)
(c) Minimum winter temperatures				
Winter	Region	Mean daily temp (°C)	Min daily temp (°C)	Minx hourly temp (°C)
2005–2006	Arabian Gulf	21.0	18.6	16.2 (Makaseb, 31Jan2006)
2006–2007	Arabian Gulf	18.5	16.3	15.1 (Makaseb, 04Jan2007)
2007–2008	Arabian Gulf	19.4	16.7	14.9 (Al Hiel, 06Feb2008)
2008–2009	Arabian Gulf	20.7	18.7	15.9 (Makaseb, 24Jan2009)
2007–2008	Gulf of Oman	23.4	22.2	21.2 (Dibba Rock, 21Feb2008)

**Fig. 4.7** Shallow and deep temperature profiles – Yasat (2007–2008). Thick line represents temperatures at the reef (3.0–4.7 m depth). Thin line represents temperatures in deep water (31 m)

4.6, Table 4.3). The temperature extremes are milder in the Gulf of Oman, where daily mean temperatures range between 22°C and 32°C throughout the year. However, the coral communities in the Gulf of Oman may be exposed to extreme daily temperature oscillations, especially during the summer when temperatures can fluctuate up to 9°C within a single day due to the rise and fall of a strong thermocline that forms

between the heated surface and cool upwelling waters (Rezai et al. 2004). The data collected between 2007 and 2008 indicated that “normal” mean daily temperature ranges in the Gulf of Oman were less than 3°C, with a maximum daily range of 7.1°C recorded. The coral communities did not experience mass mortalities during exposure to these daily temperature fluctuations, indicating acclimation to these conditions.

4.2.2 Sea Urchins

Algal turfs can limit the free space that is available for coral settlement and can increase mortality of recruits by overgrowth, shading, and abrasion (Sammarco 1980, 1982). Sea urchin grazing of algal turf has been positively correlated to coral recruitment and survival (Birrell et al. 2005; Carpenter and Edmunds 2006). Sea urchin densities (*Diadema* and *Echinometra* spp.) were determined as part of the site assessments described herein (Figs. 4.9 and 4.10). Sea urchin densities were typically less than 7 urchins per m² in both the southeastern Arabian Gulf and in the northwestern Gulf of Oman. The exception to this was at Al Hiel, where densities up to 12 urchins per m² were measured. Al Hiel has a noticeably higher macroalgae cover than the other sites, which can support its slightly larger population of sea urchins.

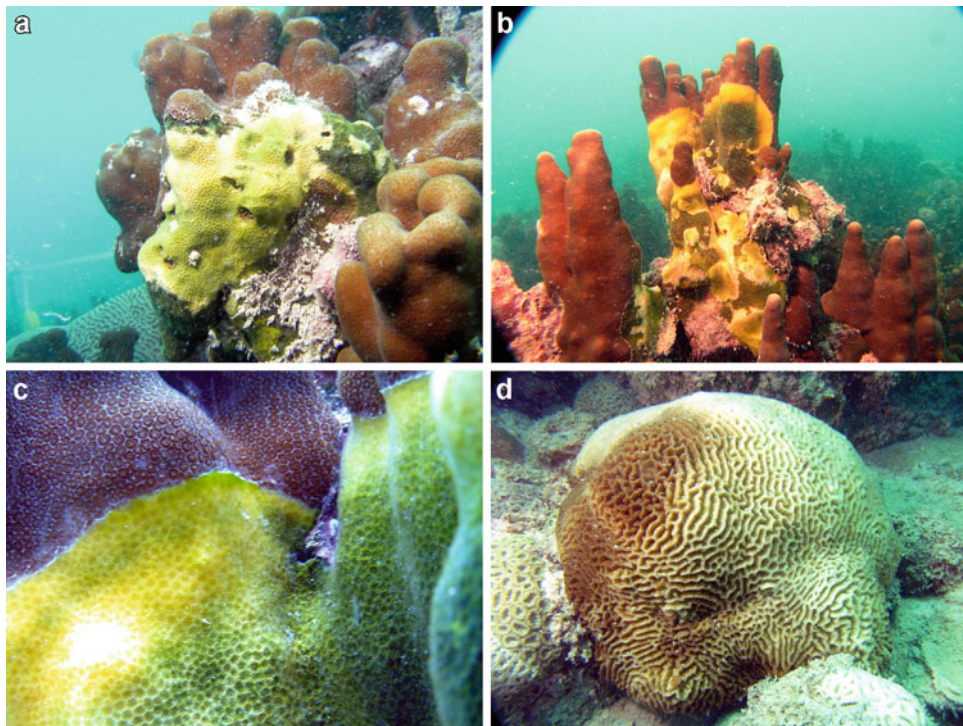


Fig. 4.8 Examples of individual diseased and bleached corals. (a–c) Yellow band disease in Saadiyat, July 2007; (d) bleaching at Abu Dhabi breakwater, July 2007

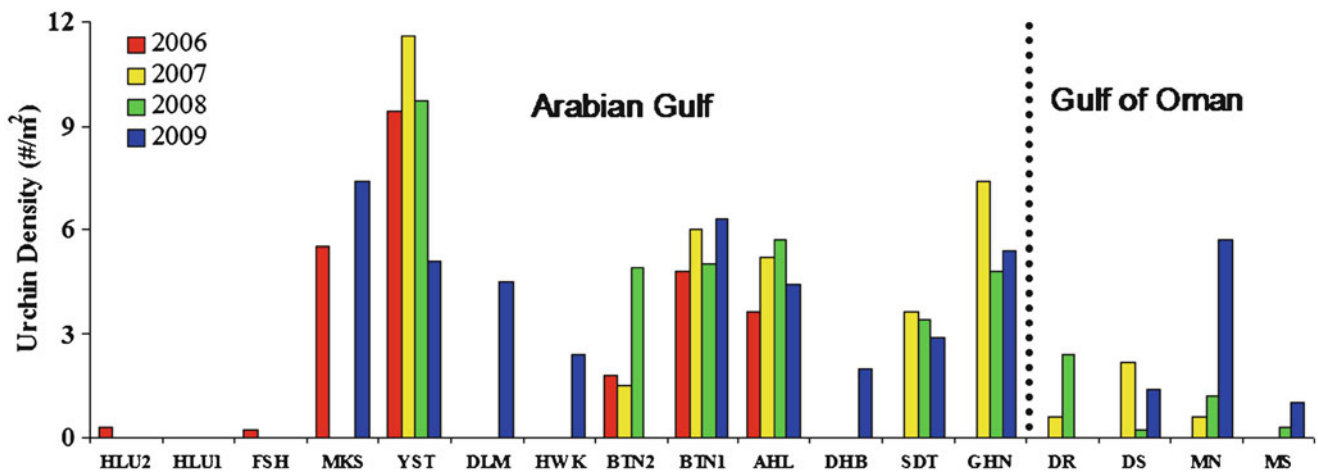


Fig. 4.9 Sea urchin densities (2006–2009). Sea urchins densities include *Diadema* and *Echinometra* spp. (site codes in Table 4.1)



Fig. 4.10 Sea urchins around Yasat Island

4.2.3 Topographical Complexity

Rugosity is a measure of topographical complexity, defined as the ratio of the reef surface contour distance to linear distance (Fig. 4.11) (e.g. a completely flat substrate would have a rugosity of 1.0). Changes in rugosity may be used to quantify reef growth or decline (e.g. increases in rugosity may be the result of coral colony growth; decreases in rugosity may be the result of bioerosion). Rugosities in Study Area “A” ranged between 1.2 and 1.8 (Fig. 4.12).

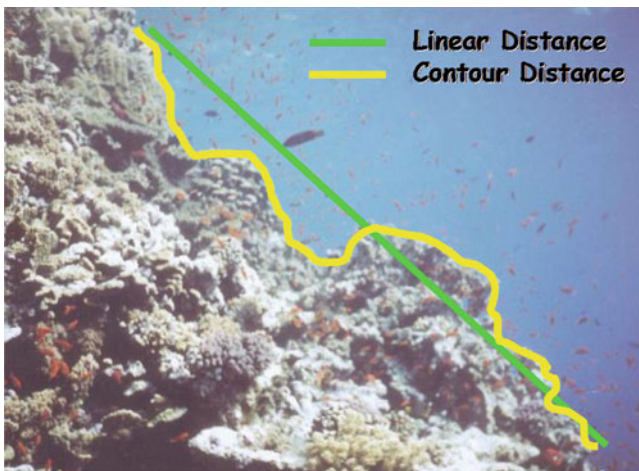


Fig. 4.11 Rugosity: ratio between contour distance and linear distance

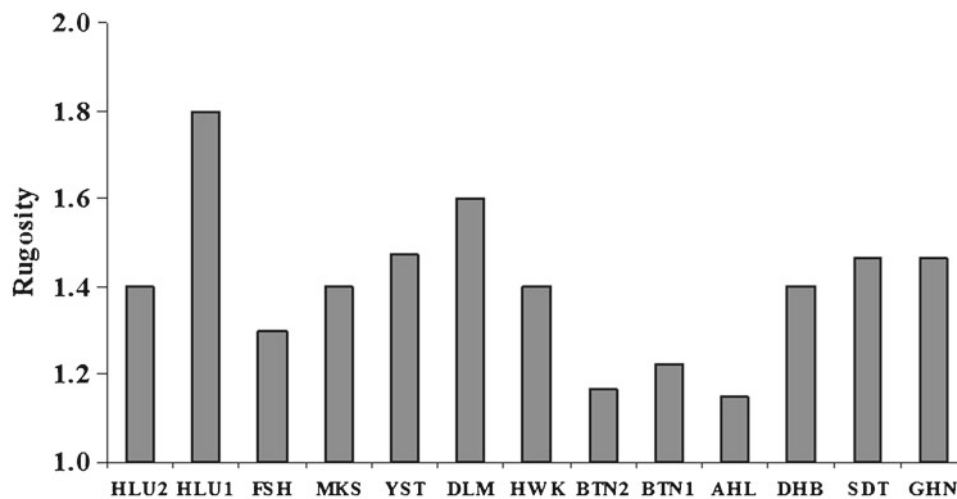


Fig. 4.12 Rugosities of coral communities in the southeastern Arabian Gulf (site codes in Table 4.1)

4.3 Coral Community Structure

Elevated sea surface temperature anomalies impacted the southeastern Arabian Gulf region in 1996, 1998 and 2002; during which temperatures were 2–4°C above the typical summer maximum (Sheppard and Loughland 2002; Riegl 2003). The 1996 event caused widespread coral bleaching and mortality, with a subsequent reduction of 98.7% of framework-building *Acropora* corals in some areas (Riegl 2002). The 1998 and 2002 anomalies had only minor effects on the remaining coral communities, possibly because the surviving colonies were not susceptible to the elevated temperatures (Riegl 2002). The coral communities in Study Area “A” (Fig. 4.1) were monitored between 2006 and 2009 (i.e. 10–13 years after the mass coral mortality event and 3–7 years after the most recent elevated temperature anomaly). Similar assessments were conducted in the adjacent northwestern Gulf of Oman within Study Area “B” (Fig. 4.1), which did not experience the elevated temperature anomalies or the associated coral mortality.

4.3.1 Taxa Inventories

Nine genera of coral were observed during taxa inventories within the southeastern Arabian Gulf (Table 4.4) between 2006 and 2009. Taxa were inventoried by genus to allow rapid and repeatable identification, regardless of the taxonomic

Table 4.4 Taxa Inventories at each Monitoring Station. Taxa observed within the belt transects at each monitoring station are indicated by “Y” (yes). “Other(s)” category includes *Pocillopora*, *Stylophora*, *Montipora*, *Goniopora* spp.

	Arabian Gulf													Gulf of Oman			
	HLU2	HLU1	FSH	MKS	YST	HWK	DLM	BTN1	BTN2	AHL	DHB	SDT	GHN	DR	DS	MR	MS
<i>Porites</i> spp.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
<i>Favia/Favites</i> spp.		Y		Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
<i>Platygyra</i> spp.		Y		Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
<i>Cyphastrea</i> spp.		Y		Y	Y			Y		Y	Y		Y		Y		
<i>Leptastrea</i> spp.		Y			Y			Y	Y	Y	Y			Y	Y	Y	Y
<i>Acropora</i> spp.	Y	Y					Y				Y	Y	Y	Y	Y	Y	Y
<i>Siderastrea</i> spp.		Y								Y		Y	Y	Y	Y	Y	Y
<i>Coscinaria</i> spp.	Y	Y											Y		Y		Y
<i>Turbinaria</i> spp.											Y	Y	Y				
Other(s)														Y	Y	Y	Y

knowledge of those executing the monitoring program. Results indicated the following with respect to taxa inventories at sites in Study Area “A”:

- *Porites* spp. were found at all sites. The most abundant species was *P. harrisoni*. Other species included *P. nodifera*, *P. lutea* and *P. solida*.
- Two sites (Fasht Al-Ghabi and Hawksbill Reef) were comprised solely of *Cyphastrea* sp. and *Porites* spp. Other genera occurred, but were rare and outside the monitoring sites.
- *Favia*, *Favites* and *Platygyra* spp. were common coral taxa found at all sites except at Halul East, Fasht Al-Ghabi and Hawksbill Reef.
- *Acropora* spp. were found at both Qatar sites (Halul East and Halul South), around Delma Island and at the three Abu Dhabi coastal sites (Dhabiya, Saadiyat, and Ras Ganada) (Fig. 4.13). Acroporids were not observed in the vicinity of any of the other Abu Dhabi sites.
- Three species of acroporids were observed; *A. clathrata*, *A. downingi*, and *A. arabensis*. Other subordinate *Acropora* species (e.g. *A. tenuis*, *A. valida*, *A. pharaonis*, *A. florida*) remain unobserved in the southeastern Arabian Gulf, including in waters offshore Dubai (Burt et al. 2008), suggesting local extirpation.
- Other coral taxa that have been reported offshore Dubai after the elevated temperature anomalies (i.e. *Acanthastrea*, *Psammacora*, *Psuedosiderastrea* spp. (Burt et al. 2008)) were not observed at the Qatari or Abu Dhabi sites.
- Other benthic taxa were found among the coral communities including crustose coralline algae, macroalgae, sponges and bryozoans (Fig. 4.14).

4.3.2 Live Coral Cover

Photo transects were taken at each site for subsequent image analysis. Coral Point Count (CPCe) (Kohler and Gill 2006)

was used to trace the colony perimeters and calculate surface areas (Fig. 4.15). Average surface areas at the sites ranged from 62 to 500 cm². The largest colonies are *Porites* spp., followed by *Platygyra* spp.

The surface area data for all images within a given year were combined to provide percent live coral cover within the belt transects at each site (Fig. 4.16). Results indicated the following with respect to live coral cover at the sites in Study Area “A”:

- The offshore island sites (Halul, Makaseb, Yasat, Delma, Bu Tinah, Al Hiel) (Fig. 4.17) were sparsely populated, with live coral cover ranging from 1.9% to 17.1%.
- Fasht Al-Ghabi, the only site surveyed along the coast of Qatar, had a sparsely populated coral community (1.3% live cover) consisting of small *Cyphastrea* spp. on old dead coral that was partially covered by crustose coralline algae (Fig. 4.18).
- The sites along the Abu Dhabi coast (Dhabiya, Saadiyat, Ras Ghanada) (Fig. 4.19b–d) were moderately populated, with live coral cover ranging from 27.5% to 46.5%. The sites most closely resembled the live cover at the northwestern Gulf of Oman sites (Fig. 4.16), which ranged from 23.0% to 44.9%.
- Hawksbill Reef, the only site situated on a limestone dome, had a densely populated coral community (62.2% live coral cover) comprised solely of *Porites harrisoni*.

The majority of the coral communities were comprised of several common families; poritids, faviids, acroporids, and siderastreids. Other families were either uncommon or unobserved at the sites. The composition of a particular family may be described as dominant (>50% of the coral cover), common (20–50%), uncommon (<20%) or unobserved. Results indicated the following with respect to the composition of live coral cover at the sites in Study Area “A”:

- Poritids were dominant at all sites except around the Qatar sites. Poritids were common at Halul South, Halul

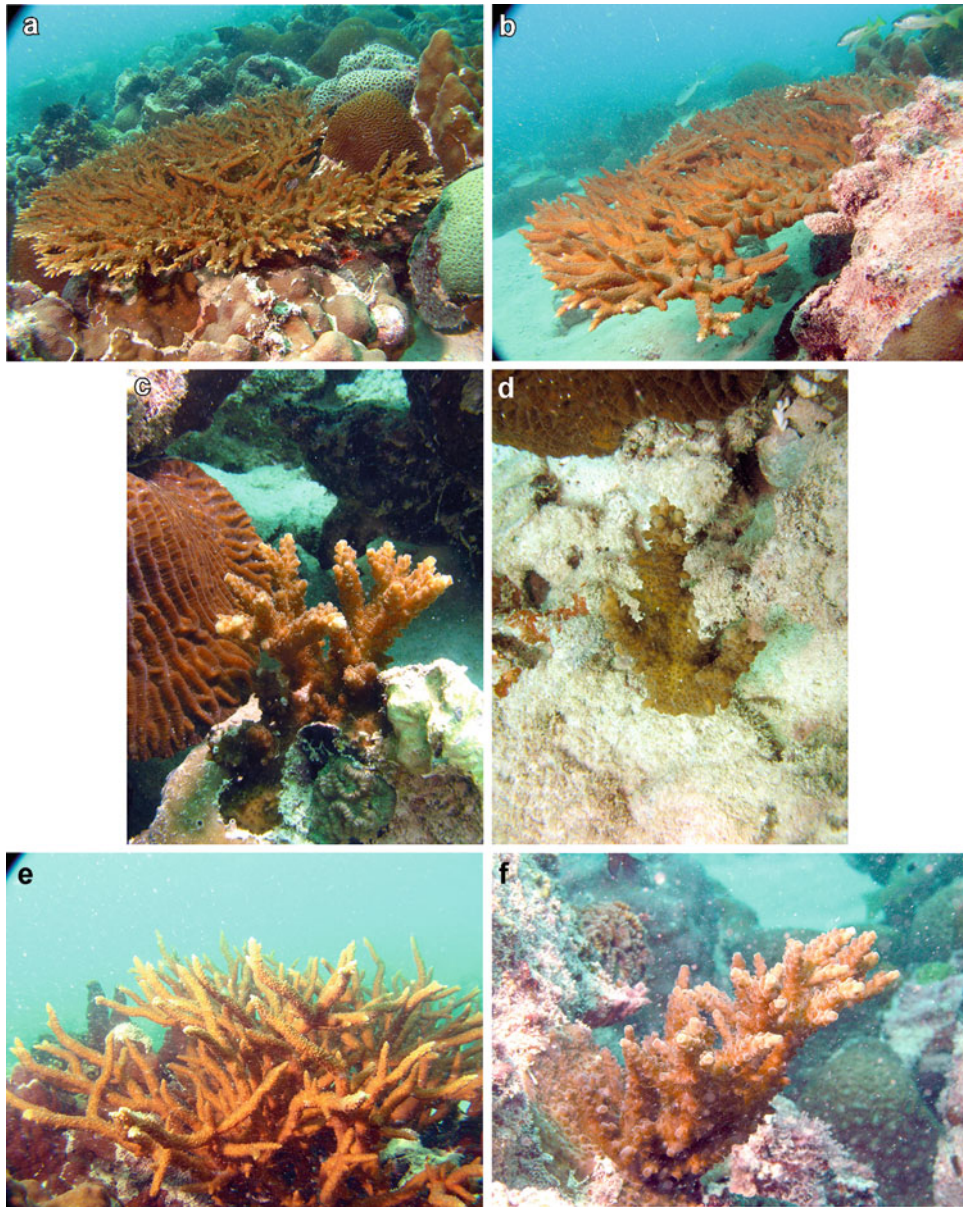


Fig. 4.13 Examples of *Acropora* spp. in the southeastern Arabian Gulf (see also Chap. 11, for taxonomic information). (a–b) *A. clathrata* near Halul Island; (c, d, f) juvenile colonies at Ras Ghanada; (e) *A. arabensis* near Saadiyat

- East. Poritids comprised 100% of the coral cover at Hawksbill Reef.
- Faviids were (i) dominant at Halul South and Fasht Al-Ghabi, (ii) common at Al Hiel and Ras Ghanada and (iii) uncommon or unobserved at the remaining locations.
 - Acroporids were present at six of the thirteen sites: they were (i) dominant at Halul East; (ii) common at Halul South; and uncommon at Delma, Dhabiya, Saadiyat and Ras Ghanada.
 - Siderastreids were uncommon at five sites (Halul East, Halul South, Al Hiel, Saadiyat and Ras Ghanada) and unobserved at the remaining locations.
 - Corals in the “Other families” category were uncommon at three sites (Dhabiya, Saadiyat and Ras Ghanada) and unobserved at the remaining locations. The “other” corals were all from the dendrophyllid family, specifically *Turbinaria* spp. No other coral families were observed.

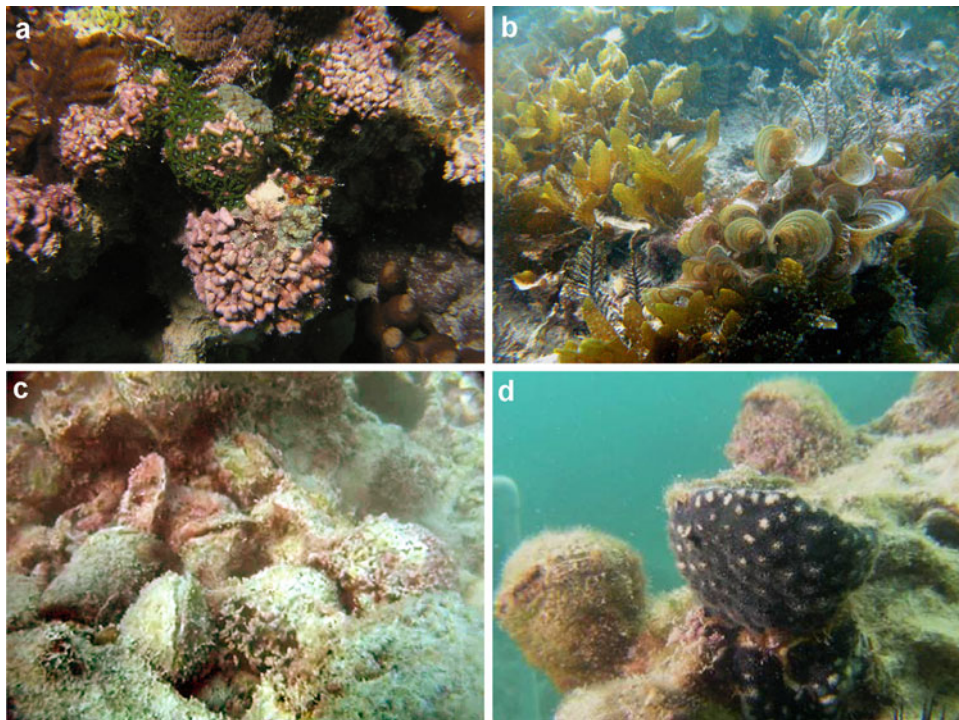


Fig. 4.14 Examples of other benthic taxa: (a) crustose coralline algae, Ras Ghanada; (b) macroalgae, Al Hiel; (c) oysters, Al Hiel; (d) bryozoans (see also Chaps. 13 and 14 for taxonomic information and species identifications)

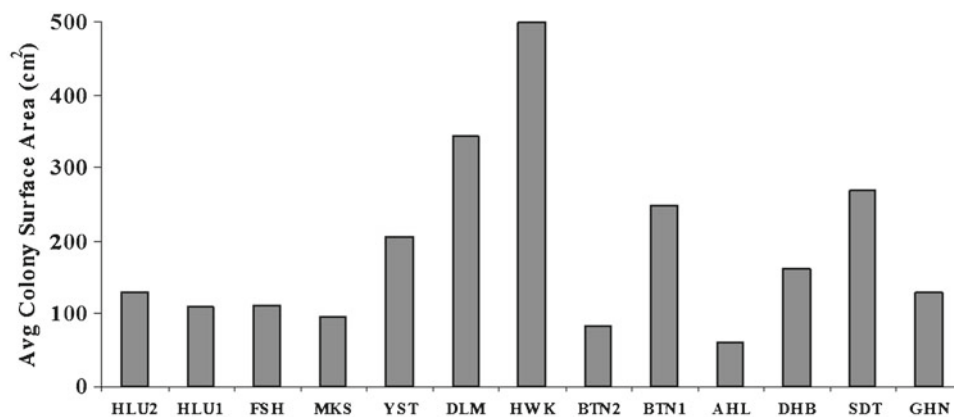


Fig. 4.15 Average coral colony surface areas (site codes in Table 4.1)

4.3.3 Coral Density

Digital photos were taken along belt transects at each site for subsequent image analysis. The number of corals within the belt transects were combined provide coral density (i.e. the number of corals per m²) for each site (Fig. 4.20). Results

indicated the following with respect to coral density at the sites in Study Area “A”:

- The offshore island sites (Halul, Makaseb, Yasat, Delma, Bu Tinah, Al Hiel) (Fig. 4.17) were sparsely populated, with coral densities for these sites range from 1.2 to 8.0 corals per m².

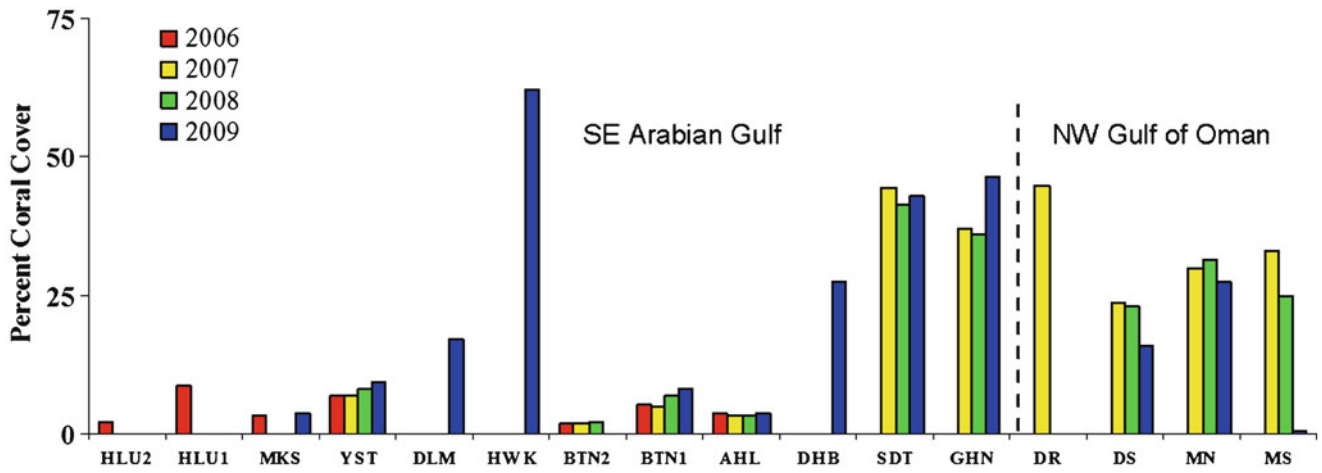


Fig. 4.16 Percent live coral cover (2006–2009) (site codes in Table 4.1)

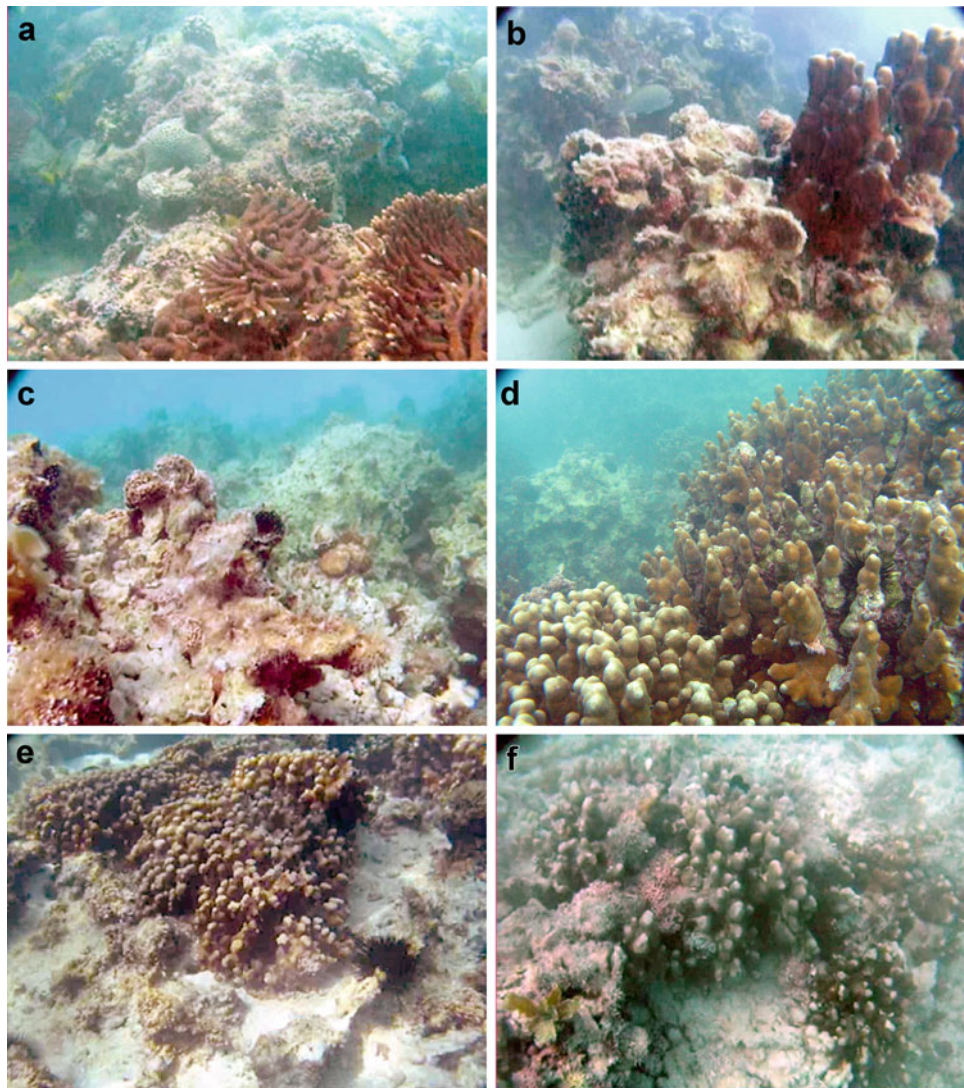


Fig. 4.17 Landscape views of sparsely-populated “near-island” sites. (a) Halul South; (b) Makaseb; (c) Yasat; (d) Delma; (e) Bu Tinah North; (f) Al Hiel



Fig. 4.18 *Planar view* of sparsely-populated coastal site (Fasht Al-Ghabi, Qatar)

- Fasht Al-Ghabi, the only site surveyed along the coast of Qatar, had a sparsely populated coral community with a coral density of 1.1 corals per m^2 .
- Two of sites along the Abu Dhabi coast (Dhabiya, Saadiyat) and Hawksbill Reef were moderately populated, with coral densities ranging from 12.5 to 16.9 corals per m^2 .
- Ras Ghanada, the third site located along the Abu Dhabi coast, was a densely populated coral community with a coral density >24 corals per m^2 .

4.4 Conclusions

The information presented in this chapter described (i) the typical environmental setting to which the Arabian Gulf corals were exposed and (ii) the structure of the recovering coral

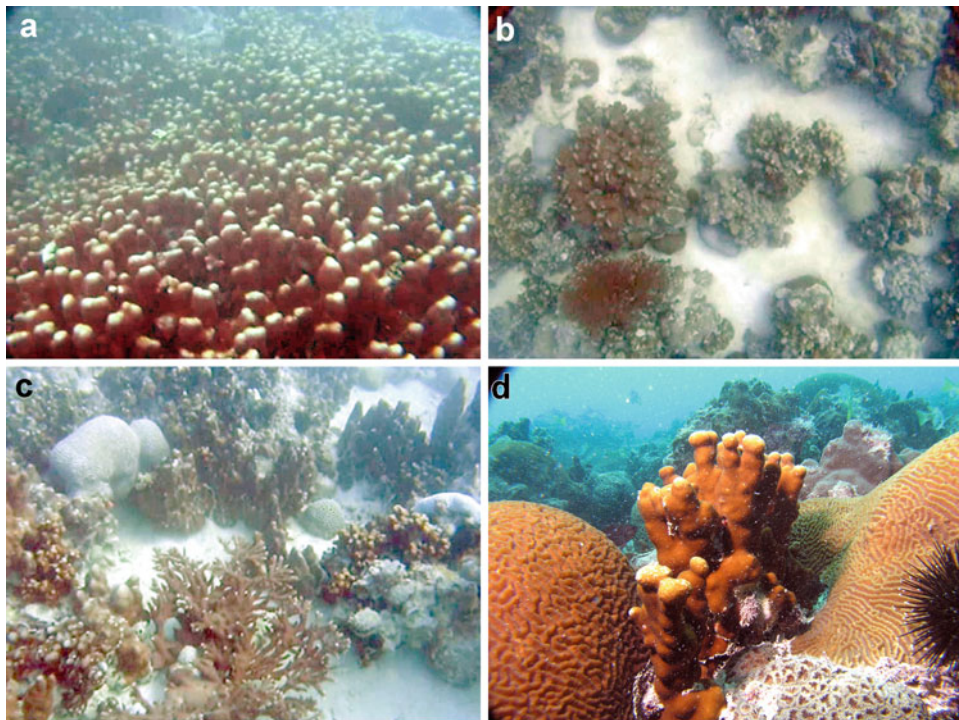


Fig. 4.19 *Landscape views* of densely- and moderately-populated sites. (a) Hawksbill Reef; (b) Dhabiya; (c) Saadiyat; (d) Ras Ghanada

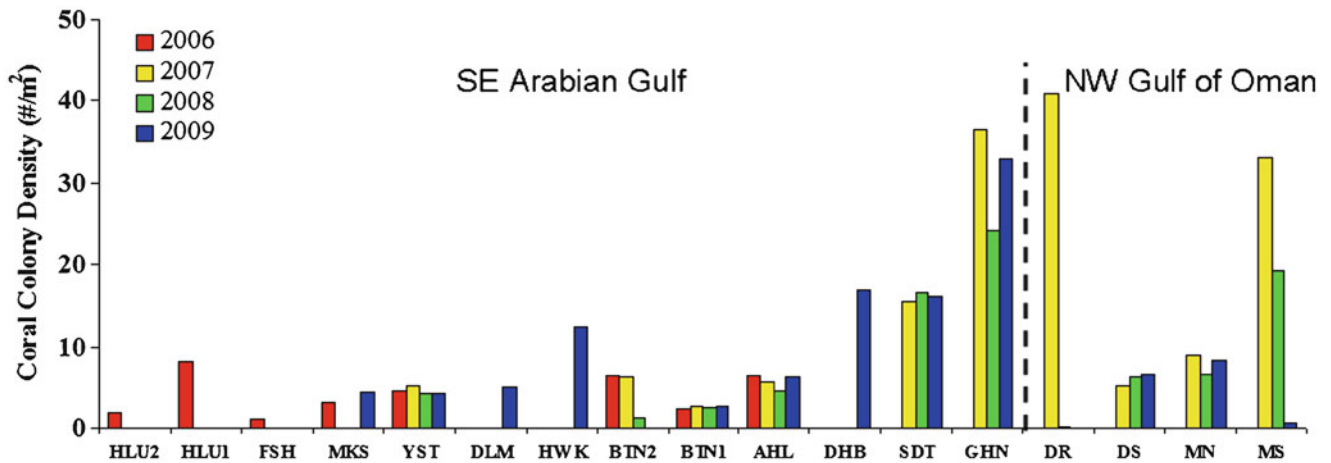


Fig. 4.20 Coral colony densities (2006–2009) (site codes in Table 4.1)

communities a decade after the mass mortality associated with the 1996 elevated temperature anomaly. These descriptions, as summarized below, may serve as baselines for normal conditions within the southeastern Arabian Gulf and as benchmarks of extreme conditions to which certain coral species are capable of adapting.

- The normal temperature range within the southeastern Arabian Gulf was 16.5°C–35.0°C. Temperature anomalies may, therefore, be defined as conditions that are 2–3°C below this minimum or above this maximum.
- The spring warming and autumn cooling rates were uniform across the region, ranging between 0.09–0.13°C per day and 0.10–0.15°C per day, respectively. A 1–4°C thermocline formed in the spring and dissipated in early summer. Autumn and winter thermoclines have not been recorded.
- The mean daily temperature range in the southeastern Arabian Gulf was <2.5°C. The same coral species found in the Arabian Gulf withstood normal daily temperature fluctuations up to 7.1°C, as measured in the adjacent Gulf of Oman.
- Sea urchin densities were typically below 7 urchins per m².
- The coral communities exposed to the above conditions were dominated by *Porites*, followed by *Favia/Favites* and *Platygyra* spp. Each of the six other coral genera that were inventoried within the communities comprised <1% to the regional population.
- Three species of acroporids were observed in the region following the 1996 mass mortality event; *A. clathrata*, *A. downingi*, and *A. arabensis*. The live coral cover for these species represented <1% of the coral cover in the southeastern Arabian Gulf, indicating that recovery to pre-event levels (>40%) had not occurred more than a decade later. The coral community structure has shifted from *Acropora* to *Porites* dominance. Other acroporid

species that were recorded prior to 1996 were not observed and may now be regionally extinct.

- Live coral cover and coral density varied among sites, with ranges of 1.9–62.2% and 1.1–36.5 colonies per m², respectively. The locations near the Abu Dhabi coast and Hawksbill Reef (on top of a limestone dome) had higher live coral covers and densities than those locations near the Abu Dhabi and Qatar islands and the Qatar coast.

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Dynamics of Gulf Coral Communities: Observations and Models from the World's Hottest Coral Sea

5

Bernhard M. Riegl and Sam J. Purkis

5.1 Introduction

Coral reefs are adapted to a relatively narrow band of environmental optima and the harsh Gulf environment tests the physiological and ecological limits of reef corals. The environmental variability (minimal and maximal annual temperatures, salinity extremes, etc.; Chap. 2; Sheppard et al. 1992, 2010) are outside the range of typical tropical reefs. Regular summer temperatures are several degrees above the bleaching and mortality thresholds of some regions in the Great Barrier Reef and the Caribbean (Baker et al. 2008; Chap. 6). Yet, corals thrive in the Gulf. However, they have recently been exposed to severe temperature anomalies at a recurrence faster than in any other coral reef region (Riegl 2002, 2003; Sheppard and Loughland 2002; Riegl and Purkis 2009; Sheppard et al. 2010) and it appears that hot-anomalies are increasing in severity and frequency (Nasrallah et al. 2004). Thus, corals in the Gulf already exist in a thermal environment that is equal to, or even worse than, what is predicted (IPCC 2007) to occur throughout the tropical oceans by 2099 and recognized as likely causing problems for coral reef persistence. Clearly, important lessons can be learned from Gulf corals about environmental extremes that corals can survive and, given the high frequency of disturbances, maybe even lessons in adaptability. Since the world is getting warmer and extremes are becoming more pronounced, the study of such extreme reef systems gains increased relevance.

It is well-demonstrated that temperature anomalies cause coral bleaching and death, but also that variability in levels of susceptibility, adaptation and acclimation among species exists (Coles and Brown 2003). Variable resistance to bleaching (Loya et al. 2001) may either be genetically determined at species-level or by distribution and environmental

variability within any given reef (McClanahan et al. 2007). Among the more susceptible species, the genus *Acropora* has been a dominant reef framework-builder in the Gulf, Indo-Pacific and until fairly recently also in the Atlantic. Bleaching and diseases have caused dramatic declines in Caribbean as well as Gulf *Acropora*, their recent decline in the Gulf (Riegl 1999; Purkis and Riegl 2005; Riegl and Purkis 2009) trailing that in the Caribbean by about two decades. Worldwide, the alarm has been sounded for many *Acropora* species (Carpenter et al. 2008). After Caribbean *Acropora* decline, the next-dominant *Montastraea* species were decimated by bleaching and diseases as well, a situation that would be echoed in the Gulf if *Porites harrisoni* began to die-back since it takes a similar ecological place as the *M. annularis* group in the Caribbean. A decline or, worse, loss of dominant species would have important biological and geological implications stretching from changes in community structure to the near-cessation or switch-off of reefbuilding.

It is unclear whether reef corals will be able to adapt to bleaching (Baker et al. 2004) or whether constantly upward-inching temperature-excursions will cause extinction of species (Sheppard 2003; McClanahan et al. 2007). Against this ecological background and scenarios of impending global warming (Sheppard 2003), we describe Gulf coral community structure and will model the dynamics of Gulf coral assemblages to demonstrate competition, population dynamics and how assemblage structure is maintained or altered. We will forecast changes in various disturbance scenarios. Due to its extreme temperature environment, the Gulf has been presented as an ideal laboratory to evaluate coral reef persistence in global change conditions (Riegl 2003). In the Gulf, reef corals already persist at temperatures forecast to affect many more temperate areas (Sheppard 2003). Therefore, the models from the Gulf have relevance beyond the regional scope since the predicted rates and patterns of regeneration or collapse will be similar in other systems.

In this study we (1) describe coral community structure in the Gulf (2) use ODE (ordinary differential equation)-based

B.M. Riegl (✉) • S.J. Purkis
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu; purkis@nova.edu

mathematical models of population and species-interactions to capture population and competitive dynamics (3) use habitat maps to estimate some key population parameters of a model (N of corals at specific time-step, carrying capacity) (4) evaluate likely shifts or persistence of community patterns in a warming climate with increasingly frequent temperature-mediated bleaching events.

5.2 Methods

5.2.1 Study Area

Several reefal systems, from which we extrapolate dynamics to the Gulf in general, were studied in detail. Spatial patterns in coral communities were investigated both by in situ surveys and by remote-sensing, most notably acoustic ground discrimination (Riegl and Purkis 2005) and satellite imagery (Purkis 2005; Purkis and Riegl 2005; Riegl and Purkis 2009). A fine-scale study covered several square-kilometers that were investigated with Ikonos satellite imagery. The details of the imagery and of image processing are given in Purkis et al. (2005); Purkis (2005). This system is situated in several distinct patches near Ras Hasyan, Ras Ghantoot and Ras Ghanada in the U.A.E. (Fig. 5.1). The corals cover a shore-parallel belt until ~1.5 km offshore, a region with a typical depth of 8 m beneath lowest astronomical tide (mean slope

angle 0.5°). It is typical of fringing systems (dense coral areas that, due to an absence of coral-built framework should not necessarily be referred to as “reefs”) that occur on the Arabian (southern) shores of the Gulf from Kuwait to Musandam (Chaps. 2 and 3). Previous studies (Riegl 1999, 2002; Riegl et al. 2001) had identified coral carpets (= biostromes), areas covered by unconsolidated carbonate sand, macro-algae and seagrass, underlain in wide areas by hard-grounds consisting of early diagenetically cemented calcarenites (Shinn 1969; Evans et al. 1973).

As a second study area, a major island/shoal complex associated with the Great Pearl Bank (Purser 1973) was investigated using Landsat imagery at the Murrawah and Al Gharbi shoals complex, which includes shoals around the islands of Murrawah, Al Hila, Fiyya and Al Gharbi. The shoals are roughly circular or oblong, with a fringe of reefal sediments, followed by grainstones and a largely muddy interior (Purser 1973; Schlager 2005). This system is representative of the offshore shoals occurring throughout the Gulf from Iran and Kuwait to the UAE.

A third study area, representative of the high offshore Islands of the southern and northern Gulf was studied quantitatively at Halul in Qatar. Additional qualitative observations to allow for comparison were obtained by us from Arzanah, Qarnein, Das, Sir Abu Nuair and from Larak, Hengam, Qeshm, Kish, Greater and Lesser Tomb by Samimi-Namin (personal communication).

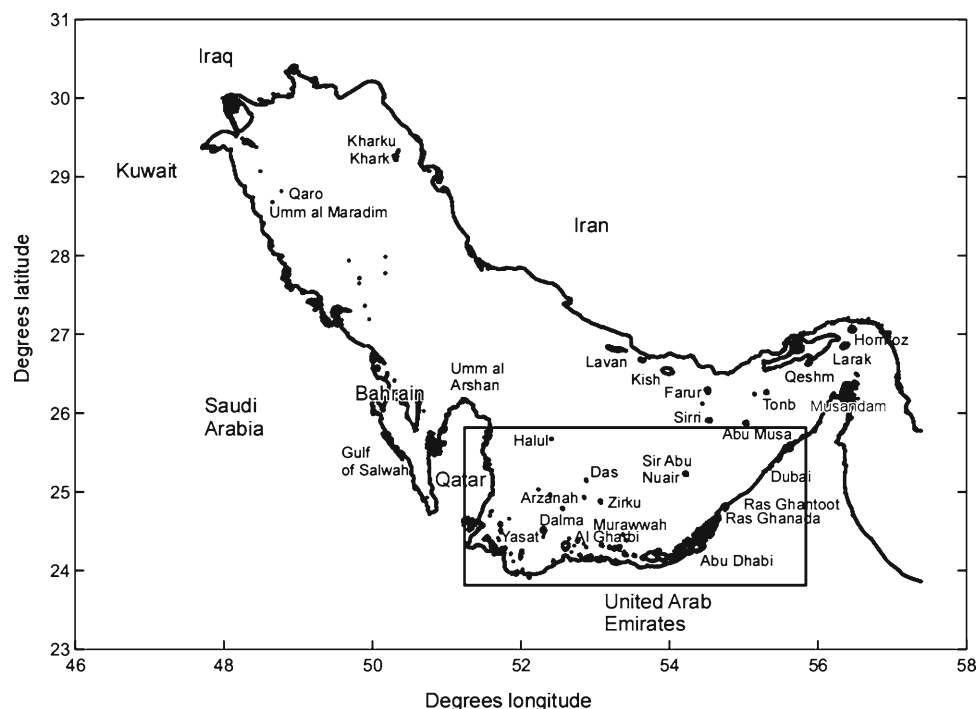


Fig. 5.1 Area in the Gulf from which most information for this article was derived. The boxed area has been subject to intensive monitoring by the authors since 1995. Sites mentioned in the text are shown

5.2.2 Ecological Background Data

Reefs used for this study were primarily situated in the UAE and Qatar and have been under close surveillance for over 15 years. Data regarding the biology of the system include series of 155×10 m and 50 m line transects taken in Abu Dhabi and Dubai in 1995, 1999, 2000, 2002, 2005, and 2006 and 360×5 m long belt (photo-)transects in Abu Dhabi from 2008 to 2011. One hundred eighty point observations for ground-truthing maps and satellite imagery, noting the species composition and taphonomic status of 1×1 m or 2×2 m sample areas were taken in 1995, 1996, 1998, 2000, 2002, 2003, 2005. Taphonomic status and breakdown sequence were evaluated by sampling corals and skeletons in 1995, 1996, 1999, 2000 and 2005 and point-observations at 90 sites from 2007 to 2011.

Transects were geo-referenced at the beginning point and placement was originally stratified random in a geographical grid before detailed habitat maps were available (prior to 2002). Later, additional phototransects were haphazardly placed within known sparse and dense coral areas for targeted sampling. Phototransects consisted of overlapping photographs along a 10-m-long, and later 5-m-long, measuring tape. After merging images and digitizing coral outlines, images were re-gridded to unit pixel-size to allow area and frequency calculations. Point observations are short (10 s), geo-referenced video-clips that allow qualitative and some quantitative observations of coral populations.

Although a coral area at Ras Hasyan that had been monitored since 1995 was mostly destroyed by the development of artificial islands and causeways in 2004/2005, community successional dynamics were still apparent, revisited and sampled in 2006/2007 and also described by Burt et al. (2008). During extensive surveys between Qatar and Dubai, noteworthy *Acropora* populations were found in Qatar only at Umm al Arshan and Halul, in Abu Dhabi between Ras Ghantoot and Ras Ghanada and at Al Hila, in Dubai at Ras Ghantoot and some survivors near Ras Hasyan, and in Sharjah at Sir Abu Nuair. These sites are also home to important communities of massive corals and connectivity can be assumed (own unpubl. data), which is important for the model.

Additional coral community and population status information was acquired from Bahrain, Kuwait, Saudi Arabia and Iran by data and images provided by colleagues (F. Benzoni, K. Samimi-Namin, C. Sheppard, personal communication).

5.3 Results

5.3.1 General Patterns of Community Structure in the Gulf

The analyses of coral community structure presented in this chapter are based on repetitive surveys in the area between Bahrain and the Straits of Hormuz, centered on Qatar and the

UAE, that we performed between 1995 and present. Further we review the literature and use observations by colleagues that allow us to include coral communities of Saudi Arabia, Kuwait and Iran. In Iran, some unique coral communities that are not found elsewhere in the Gulf exist on the islands close to the Straits of Hormuz (Samimi-Namin et al. 2009). Our observations and discussions are most pertinent to coral communities within the Gulf proper, in particular the southern Gulf from Kuwait to the UAE.

Community structure of corals inside the Gulf basin is rather uniform and corals occur in a gradation of dense to very sparse assemblages. Sparse assemblage here refers to a habitat that has between 1% and 25%, typically around 10%, space covered by living scleractinian corals. Visually, these areas appear as sandy stretches with well-defined clumps of coral. These clumps can be several meters across and can contain hundreds of colonies, or can just be isolated small groups of less than a dozen colonies. The visual impact of corals is much reduced in this habitat, partly also because the sparse corals are frequently surrounded by rubble and/or dead coral skeletons. This sparse assemblage occurs in a marginal habitat for coral growth which is characterized by hardground overlain by mobile sand sheets. If the sand is mobilized and impinges on the corals, their growth can be frequently interrupted. Nonetheless, sparse assemblages cover wide areas and are an important repository of coral biomass. The dominant corals tend to be either *Porites* or *Favia* species, in the most sandy areas, isolated colonies of *Siderastrea* occur (Fig. 5.2).

Throughout the Gulf, from northern Iran and Kuwait to Musandam, well-defined patches of very dense *Acropora* cover occurred prior to the local and regional mass mortality events. These dense patches disappeared in some areas while in others they persisted and/or regenerated (Benzoni et al. 2006; Burt et al. 2008; Riegl and Purkis 2009). Underneath the *Acropora* tables existed an understory of smaller massive colonies, a mixed assemblage of faviids, siderastreids and poritids. Sectioning massive corals and tagging of *Acropora* had yielded approximate growth rates of around 1–2 cm.year⁻¹ for massive corals and 5–10 cm.year⁻¹ for *Acropora* (Fadlallah 1996; Riegl and Purkis 2009). Thus, the coral assemblage was partitioned into a dominant guild made up by tabular *Acropora* species (primarily *A. downingi* and *A. clathrata*) and a subordinate guild made up by the massive coral genera (primarily *Favia*, *Favites*, *Porites*, *Anomastrea*). *Acropora* have a higher growth rate, a shape advantageous for overtopping other corals, and have more effective nematocysts than faviids and *Porites* which allows them to win in competitive interactions (Thomason and Brown 1986; Baird and Hughes 2000). Large massive colonies were able to persist despite being surrounded by a mostly closed canopy of *Acropora* if the massive colonies had grown to a size which made it impossible for the *Acropora* to overtop or kill them entirely when in physical contact. This usually required a

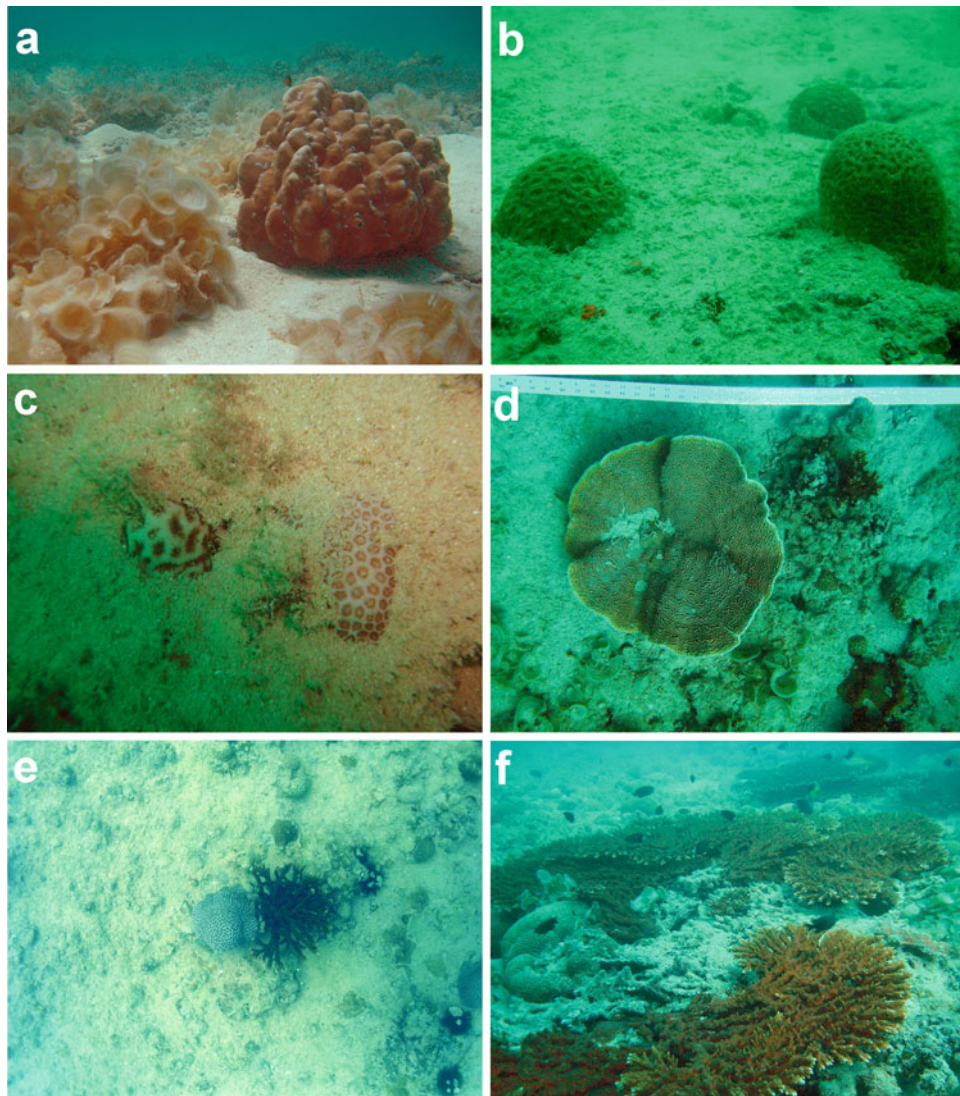


Fig. 5.2 Sparse coral assemblages of the Gulf: (a) *Porites lutea* dominated assemblage with seasonal bloom of the brown alga *Padina boergesenii*. (b) The faviid dominated sparse assemblage has the widest distribution in the Gulf. (c) In the sandiest areas, a sparse assemblage of

Siderastrea savignyana is found. (d) In deeper areas (15–20 m) *Turbinaria reniformis* becomes a characteristic species. (e, f) Shallow, sparsely covered hardgrounds serve as locus for the initiation of new *Acropora* thickets

size of at least 30–50 cm diameter in hemispherical colonies. In the studied systems and many other Gulf coral assemblages, topography plays no role since virtually all colonies grow on the same substratum at the same height. This is due to the strong bioerosion that removes colonies after mass mortality events (for detailed discussion of this phenomenon see Riegl 2001).

These dense assemblages dominated by *Acropora clathrata* or *A. downingi* have been described from Kharg Island, Iran, (Shinn 1976), Kuwait (Downing 1985; Fadlallah et al. 1993; Vogt 1996 and Lomando et al. 2003), Tarut Bay, Saudi Arabia, (Coles and Fadlallah 1991; Fadlallah et al. 1995),

Jana, Kurain, Karan and Abu Ali Islands, Saudi Arabia, (Basson et al. 1977; Fadlallah et al. 1993; Vogt 1996; Benzoni et al. 2006), Bahrain (Sheppard and Sheppard 1991), Qatar, Abu Dhabi and Dubai (Riegl 1999, 2001; Purkis and Riegl 2005; Riegl and Purkis 2009). They also occur on many islands in Iran (Samimi-Namin, pers. comm., Rezai et al. 2004).

Dense communities dominated by the nodular *Porites harrisoni* (previously often referred-to as *Porites compressa*) stands occur in Saudi Arabia (Vogt 1996), Dubai (Riegl 1999), Bahrain, Qatar (Sheppard and Sheppard 1991) and Abu Dhabi (Riegl and Purkis 2009, Chap. 4). In Dubai and Abu Dhabi, this assemblage occurs within the same habitat

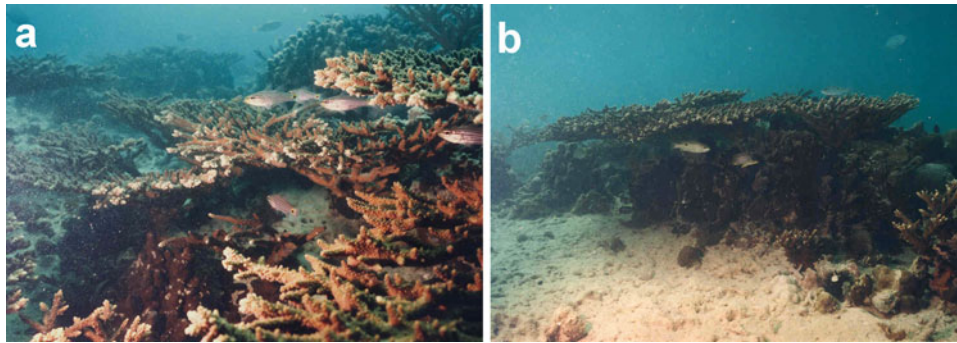


Fig. 5.3 Dense *Acropora* assemblage. The dominant species are *Acropora harrisoni* and *A. clathrata* (Dubai 1995, prior to mass mortality)

and often adjacent to massive *Porites* or tabular *Acropora* assemblages without any notable environmental gradient (i.e. different salinities as reported by Sheppard and Sheppard (1991) from Bahrain). During the 1996, 1998 and 2002 bleaching events, *P. harrisoni* and *P. nodifera* had markedly lower mortality than *Acropora*. In 2010, *Acropora* and *P. harrisoni* bleached to comparable levels and were both significantly affected by diseases (Chap. 6). Since mortality in *Acropora* was several-fold higher than in *Porites*, these dense *Porites* assemblages may be vestiges of previous mortality events that eradicated *Acropora* and subsequently *Porites* having taken over all available space. Such dynamics will be investigated in models (see below). In western Abu Dhabi, eastern Qatar and Bahrain, *P. harrisoni* tends to dominate clearly in the hottest and most saline regions with dense coral growth (43–45 ppt, Sheppard and Sheppard 1991; Chap. 4). In Saudi Arabia and Bahrain, *P. harrisoni* replaced *Acropora* dominance in deeper water (Sheppard and Sheppard 1991) (Figs. 5.3 and 5.4).

Depth zonation in Table 5.1 are based on descriptions by Basson et al. (1977) and Fadlallah et al. (1995) from Saudi Arabia, Sheppard and Sheppard (1991) from Bahrain, Lomando et al. (2003) and Benzoni et al. (2006) from Kuwait. Shallowest areas tend to be dominated by massive *Porites* with patchy *Stylophora* and *Acropora*. The adjacent slope has a shallow (*Cyphastrea*, *Platygyra* and *Porites*) and a deep mixed community (*Porites*, *Cyphastrea*, *Coscinarea*, *Favites*, *Acropora*). A “reef flat” community consisting of branching *Acropora* was observed in Qaro (Kuwait) and Sir Abu Nuair (Sharjah, UAE), with adjacent slopes up to 15 m depth with faviids and interspersed large *Porites lutea* (Fig. 5.5).

From these observations, the following dynamics within dense coral communities can be inferred.

- the dense coral assemblage can be divided into two major guilds: rapidly growing and aggressive (strong stinging cells) branching corals can dominate competitively over

slower-growing massive corals, within which faviids aggressively dominate poritids.

- within these two guilds, dynamics seem to be essentially neutral with no species capable of gaining a strong advantage over the others.
- large massive colonies can persist even in otherwise closed *Acropora* canopies, suggesting that the competitively inferior massive colonies grow into a size-refuge where displacement by others becomes impossible (Sebens 1982). The mechanism of persistence is taller size than neighbouring *Acropora*, thus eluding the fate of being overtopped, and having enough tissue area that losses due to direct competition (necroses caused by another colony’s stinging cells) cannot endanger the inferior competitor’s survival.
- while *Acropora* are considered competitively always superior over massive corals outside their size refuge, the *Acropora* suffer repeated catastrophic mortality at roughly decadal scales (Riegl 1999) as a true compensatory mortality (*sensu* Connell 1978) that only displaces the dominant competitor, providing members of the inferior guild an opportunity to reach their size refuge (Connell 1975) (Fig. 5.6).

5.3.2 Disturbance Dynamics

As outlined in other chapters of this book (Chaps. 2, 3, and 4) coral assemblages in the Gulf are strongly influenced by temperature-related mortality events (Sheppard et al. 1992; George and John 1999, 2000; Riegl 1999, 2001, 2002; Purkis and Riegl 2005) and potentially also disease epizootics (Chap. 7). Disturbances are repetitive and most likely cyclic in nature. Bleaching events with region-wide coral mortality were observed in 1996, 1998, 2002 and 2010 (George and John 1999, 2000; Riegl 1999, 2003; Sheppard and Loughland 2002; Purkis and Riegl 2005; Burt et al. 2008). Previous mortality events are known from Dubai in 1980 (Holt-Titgen

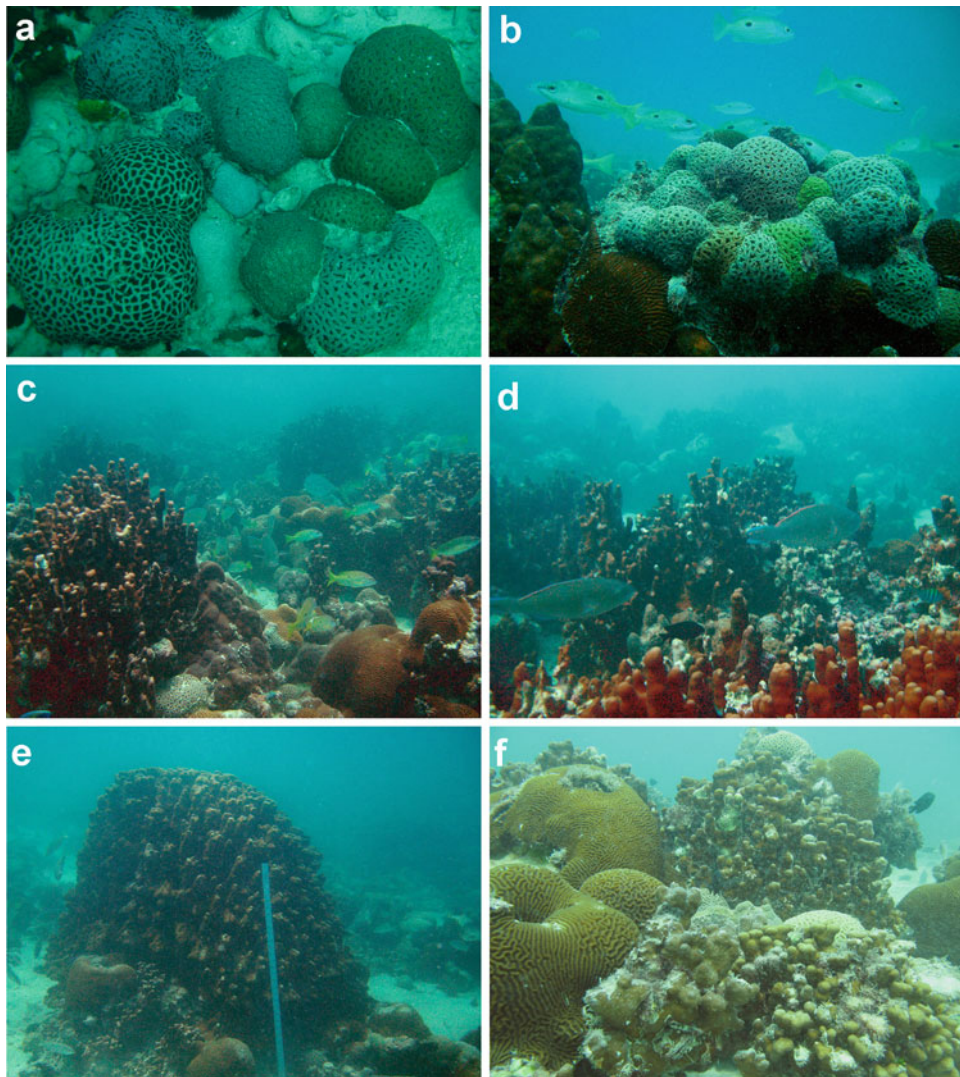


Fig. 5.4 Dense assemblages, not dominated by *Acropora*. (a, b) Dense assemblages consisting primarily of faviids. (c, d) Dense assemblages dominated by *Porites harrisoni*. (e) Some very large *Porites* (here

P. lobata) can be found in any assemblage. (f) Assemblages of mixed faviid and poritid dominance are frequent, and the two can interfinger (images from Abu Dhabi, 2008)

1982) and Qatar in 1964 (Shinn 1976). We used the HadISST dataset (Reynolds and Smith 1994) to identify peak highs and lows to verify the known mortalities and learn about others. During these anomalies, preferentially *Acropora* were killed (Shinn 1976; Riegl 1999; Purkis and Riegl 2005). In areas where *Acropora* was killed, massive corals (mainly faviidae and *Porites*) persisted and increased in size (Riegl 2003; Riegl and Purkis 2009).

The HadISST temperature data generally coincided with the mass mortality events that were known from literature records and own observations. In the 1×1 geographic degrees and monthly averaged dataset, the temperature spikes were generally not very obvious, with the exception of 1998, which clearly was an unusually hot year. The 1964 Qatar

mass mortality recorded by Shinn (1976) fell into a warmer-than-usual period, with 1964 being clearly a hot summer with a preceding warm and a following cold winter. Ruiz-Sebastian et al. (2009) suggest that the combination of cold winter/hot summer predisposes corals to bleaching. Therefore, it is possible that both a hot summer and then an unusual, but brief, cold spell in winter could have damaged the corals. Holt-Titgen (1982) suggests a mass mortality near Jebel Ali around 1980, and indeed 1980 had the highest positive seasonally adjusted summer temperature anomaly of the period 1969–1987, was followed by a cold winter, and then again by an even hotter summer in 1981. The years 1987/1988 both had hot summers and warm winters, but we are unaware of any mass mortality. The most important mass mortalities

Table 5.1 Depth distribution of coral assemblages in the Persian Gulf. Depths are idealized and should only be seen as rough guidelines condensed from the literature. Wide variability may occur

Depth zone	Dominant species	Described from	Author
0–1 m	<i>Stylophora pistillata</i>	Tarut Bay, Saudi Arabia, Umm al Maradem, Kuwait	Fadlallah et al. 1995 Lomando et al. (2003)
2–5 m	Massive <i>Porites</i>	Saudi Islands	Basson et al. 1977
2–5	Tabular <i>Acropora</i> , Small faviids	Umm al Maradem Sir Abu Nuair	Lomando et al. (2003), this study
5–10 m (or 2–10 m)	Tabular <i>Acropora</i> , mainly <i>A. clathrata</i> , <i>A. arabensis</i> and others with numerous faviids and <i>Porites</i> spp. also <i>Porites</i> <i>harrisoni</i>	Saudi Islands, Bahrain, Dubai Kuwaiti Islands, Sir Abu Nuair Dubai Karan	Basson et al. 1977 Sheppard and Sheppard 1991 Riegl 1999, 2001 Lomando et al. (2003) Riegl 1999, 2001 Vogt 1996 Benzoni et al. 2006
11–20 m	<i>Porites harrisoni</i>	Bahrain Saudi Arabia	Sheppard and Sheppard 1991 Coles and Fadlallah 1991 Fadlallah et al. 1995
11–20 m	<i>Montipora</i>	Saudi Islands	Basson et al. 1977
11–20 m	Bushy <i>Acropora</i> or <i>Pocillopora</i>	Saudi Islands	Basson et al. 1977
11–20 m	Massive Faviids and <i>Turbinaria</i>	Saudi Islands Dubai Sir Abu Nuair	Basson et al. 1977 Riegl 1999, 2001; 2003, this study

in the region were recorded in 1996, with a very hot summer and following cold winter, and 1998 with the hottest summer on record. Other bleaching events with less coral death were in 2002 (Riegl 2003; Purkis and Riegl 2005), and 2007, when only mild bleaching was observed in Qatar and parts of the UAE but corals in Iran suffered high mortality (Samimi-Namin, personal communication, in Baker et al. 2008). 2010 was a significant bleaching event in the UAE and Qatar, 2011 in the UAE. Details on the temperature regime between 2000 and 2010 can be found in Chap. 6. The sequence of major coral mortality events (1964–1981–1996–2010) suggests a roughly 15-year cycle of recurring mass mortality, predominantly in the genus *Acropora* (Riegl 1999). The three major *Acropora* mortality events (1981, 1996, 2010) were spaced by ~15 years. The mortality during these events was known from previous transect studies and was <25% for massive corals but at least 90% for *Acropora* (Riegl 2003, Riegl and Purkis 2009) (Fig. 5.7).

5.3.3 Successional and Taphonomic Dynamics

The described coral assemblages form part of a successional cycle, driven primarily by temperature-related coral death and probably also coral diseases (Riegl 1999, 2002; Purkis and Riegl 2005; Riegl and Purkis 2009; Chap. 7). Coral assemblages show a halo-like structure with patches of dense dead coral surrounded by sparse live coral and then by hard-

ground with only occasional corals (Fig. 5.8). Several positive temperature excursions killed wide areas of mostly *Acropora*. Once killed, the corals were soon settled by *Chama aspera* bivalves, and then by red algae *Lithophyton kotschyannum* (Fig. 5.8). A variety of green and brown algae also settled on the skeletons, the most conspicuous of them belonging to the genera *Cystoseira* and *Sargassum*. Increasing encrustation and concomitant boring by lithophagid bivalves and clionid sponges weakened the coral skeletons and after 6 years they began to break down (Fig. 5.8). Rubble dispersed quickly on the flat seafloor (Rasser and Riegl 2002). Where dense rubble beds were encountered, they tended to cement rapidly into hardground. Just as the changes in the coral community, the changes in the taphonomic sequence of coral breakdown followed a fairly predictable path. Observations over 12 years and evidence in the literature (Riegl 1999, 2002; Purkis and Riegl 2005) shows that these successions are recurrent and cyclical.

5.3.4 From Observation to Model

5.3.4.1 The ODE Model

We base our assumptions of ecosystem functioning on dynamics observed prior to, during and in the aftermath of coral mass mortality caused by temperature anomalies in 1981, 1996, 1998, 2002 and 2010. Based on observed coral population and community dynamics as well as growth rates,

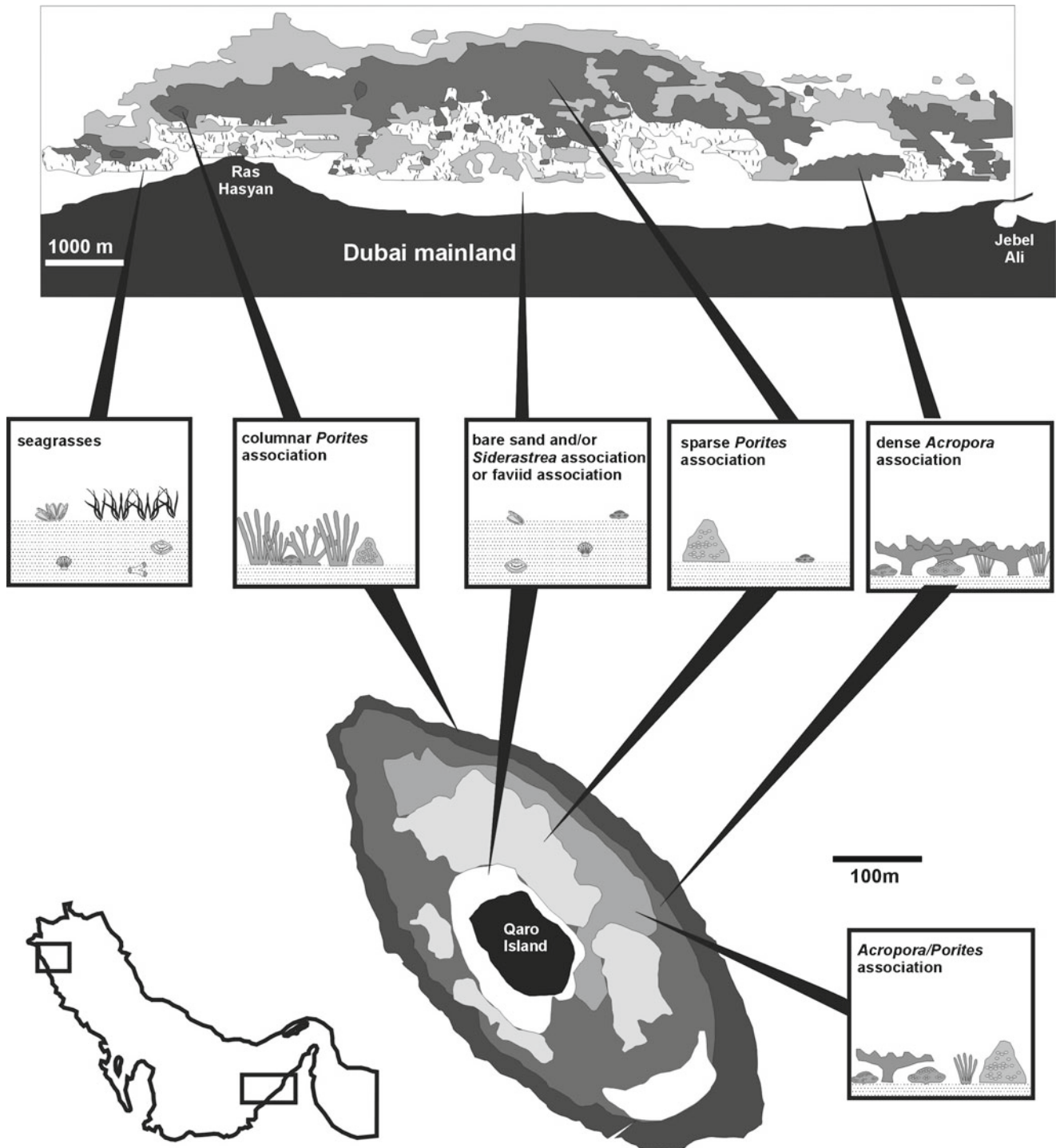


Fig. 5.5 Spatial patterns within coral assemblages in Dubai (UAE) and Qaro Island (Kuwait). Essentially the same coral assemblages occur throughout the Persian Gulf (Modified from Riegl et al. 2001; Lomando et al. 2003)

we assume that by 1996, some parts of the investigated coral communities had reached climax (Riegl 1999). The above described community dynamics (see previous chapters) clearly appear as a Lotka-Volterra-type competition between a dominant and a subordinate guild. A comparable system was developed by Sebens (1982) who modelled a competitively

inferior species suffering mortality from a dominant species only at the smallest colony stage but that could also attain a size refuge in which it was immune from competition. We extended this model to a three-species, two life-stages situation with more involved interactions. Only large specimens were considered fertile. Recruitment was allowed into any

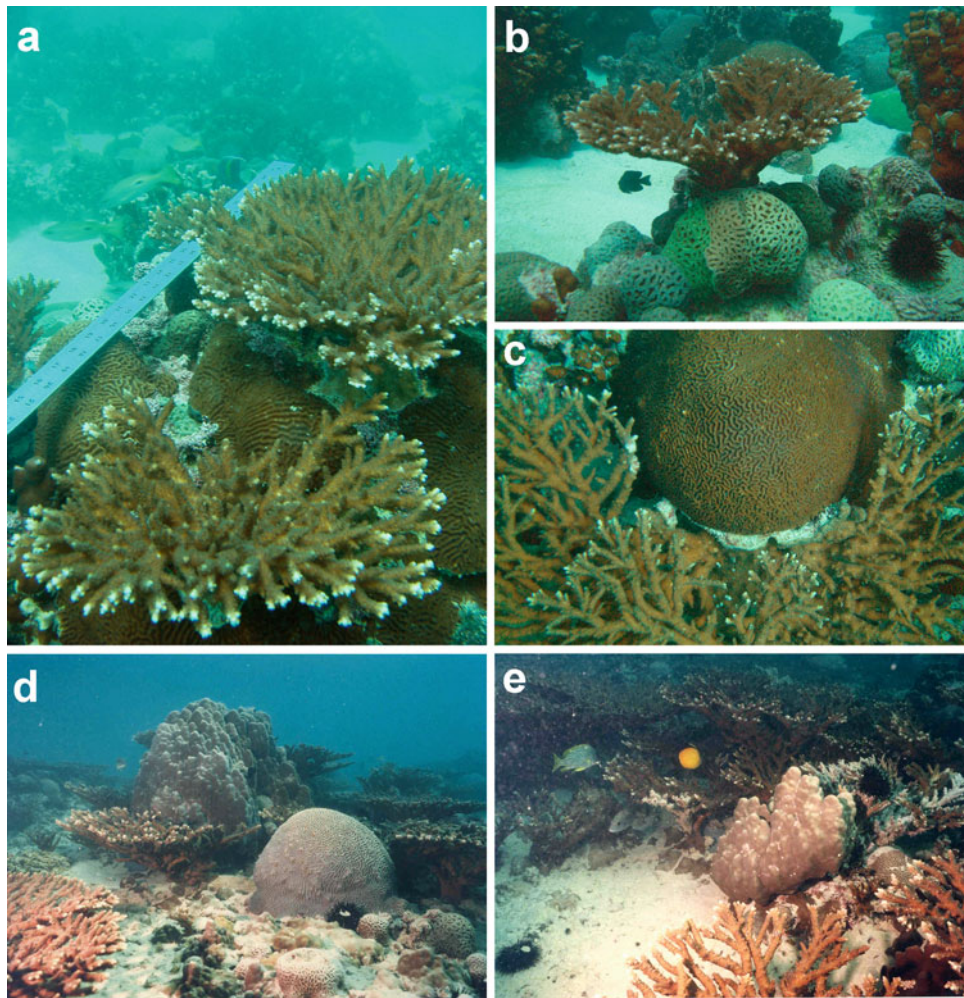


Fig. 5.6 Competitive interactions between *Acropora* and faviids. (a, b) *Acropora* can easily overshadow the smaller faviids and disadvantage them due to shading. (c, d, e) Once faviids and poritids have reached a certain size, they can no longer be overgrown, neither killed in direct confrontation. They have reached a size-refuge and persist

independently of *Acropora* dynamics. However, since they grow much slower than *Acropora*, disturbances in *Acropora* persistence (either by mass mortality or individual “wind-breaks”) help them and provide better opportunity to reach the size refuge (a, b, c from Abu Dhabi 2010, d, e, from Dubai 1995)

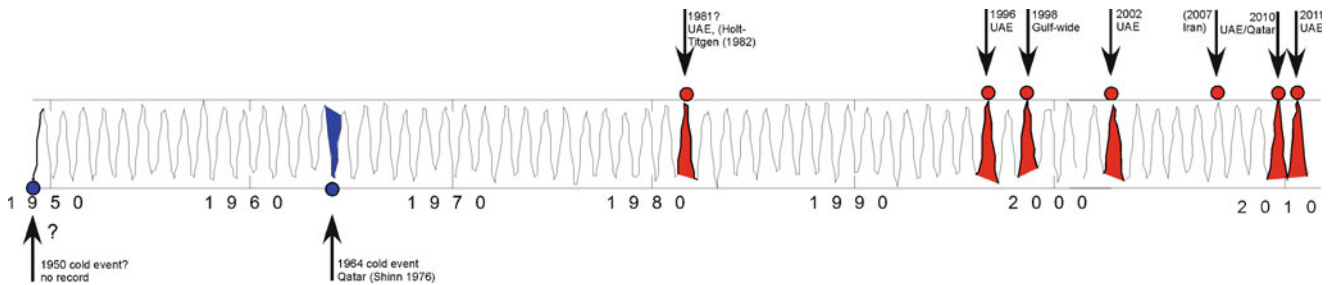


Fig. 5.7 Known (1964, 1981, 1996, 1998, 2002, 2010, 2011) and inferred (1949) bleaching and/or mass mortality events in the SE Arabian Gulf. HadISST1 temperature data, 1x1° grid for the tile

centered on the Ras Hasyan area in Dubai. Blue dot below the temperature curve infers mortality due to cold, red dot above the curve infers mortality due to heat

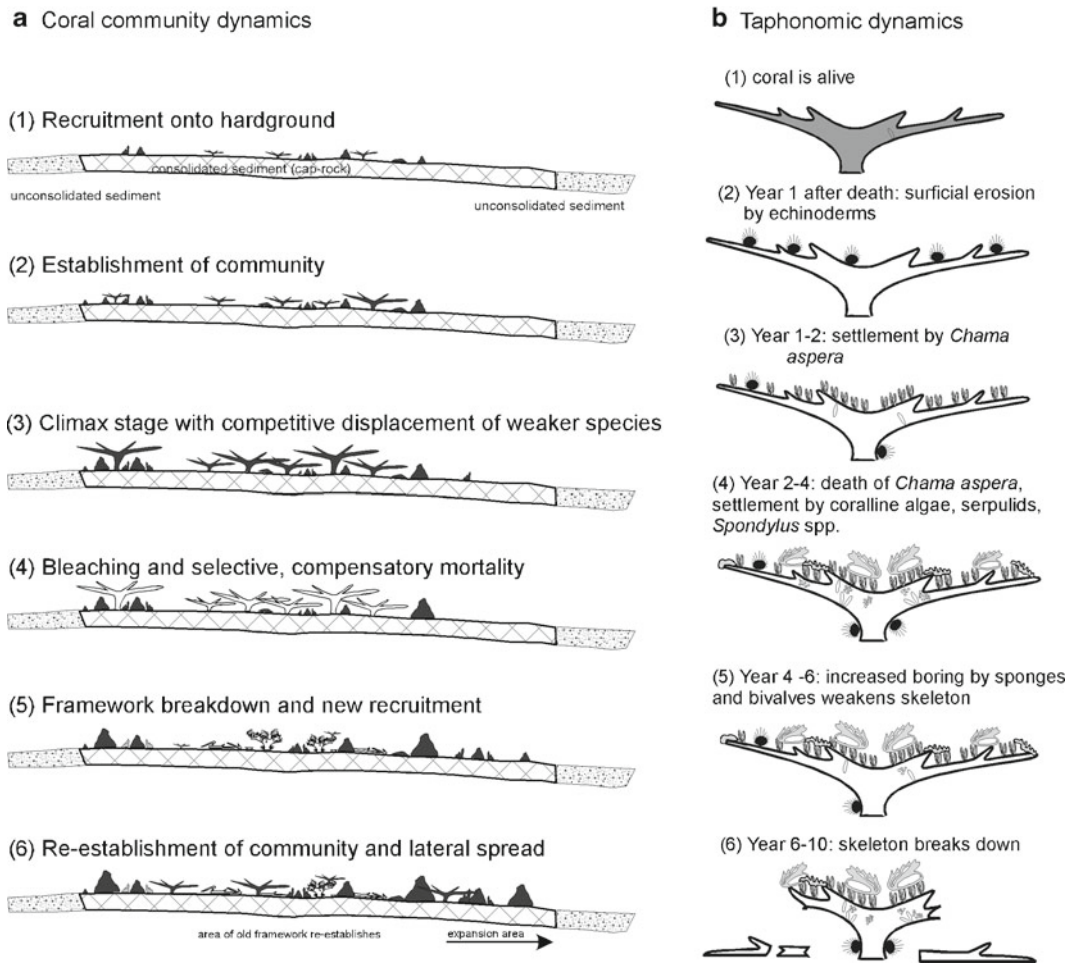


Fig. 5.8 Ecological (a) and taphonomic (b) dynamics within the coral communities that make up the patches of coral biostrome in the SE Gulf landscape (Modified from Purkis and Riegl (2005) where discussed in detail)

free cell, each cell could be settled only by one specimen, leading to a finite carrying capacity (K).

Small *Acropora* (aggressive, dominant guild) were modelled as:

$$\frac{dN_1}{dt} = \frac{R_1 N_2}{K} (K - N_1 - N_2 - N_4 - N_6) - N_1 (G_1 + D_1 + n) + mA \quad (5.1)$$

where $\frac{dN_1}{dt}$ is the rate of change in abundance of the small stage of the dominant guild as a function of fertility of the large specimens in the same guild ($R_1 N_2$) with recruits only allowed to settle into free space (thus subtraction of all large colony abundances from carrying capacity). Also, fragments of big *Acropora* can enter this size-class but fragment production rate is included in R_1 . Losses (subtractions in Eq. 5.1) occur by growth into the large size class (G_1) and mortality (D_1). Post-settlement mortality and death of early larval stages, which can be high (Mumby and Dytham 2006), is included in R_1 . D_i ($i=1,3,5$) occurs in Eqs. 5.1, 5.3, and 5.5

and refers to diseases or predation on young colonies, which can be important (Chap. 7). A distant but connected population (A) can add larvae to the focal population via a migra-

tion term m . Gulf *Acropora* are prone to local extinction during mass mortality, which requires another connected population for maintenance and regeneration of any local population. An emigration term (n) allows larvae to move from focal to connected population.

Acropora rapidly grow into large, aggressive colonies. Their rate of change $\frac{dN_2}{dt}$ depends primarily on availability of small colonies and their success to grow into the size refuge ($G_1 N_1$), mortality rate (D_2), and the ability to out-compete other species, which is implicit in other guild's carrying

capacity being influenced by the number of large *Acropora* (N_2 , see Eqs. 5.3 and 5.5).

$$\frac{dN_2}{dt} = G_1 N_1 \square D_2 N_2 \quad (5.2)$$

Faviids are massive corals with slower growth than *Acropora*, are competitively subordinate, but dominate *Porites* by causing them tissue mortality and overgrowing them. Rate of change of small colonies depends on adult fertility ($R_2 N_4$), recruitment density is self-limited (i.e. will not settle on congeners) as well as by large colonies of the subordinate guild. Losses occur due to growth ($N_3 G_2$), direct competition (i.e. overgrowth in same cell) by *Acropora* recruits (Baird and Hughes 2000 and pers. obs.) or other factors like diseases or predation (D_3). The likelihood follows Sebens (1982): Space covered by any species is N_j , rate of contact per unit space with propagules of other species i is $N_i R_i N_j / K$ (i and j denoting different species); hence, if faviids are agressed upon by *Acropora*, but not *Porites*, this is $N_3 R_1 N_2 / K$. Faviid recruits are also hindered by already settled *Acropora* of the small size-class (hence subtraction of N_1 from K). Again, immigration (m) and emigration (n) terms are added/subtracted in the end.

$$\frac{dN_3}{dt} = \frac{R_2 N_4}{K} (K \square N_3 \square N_1 \square N_2 \square N_4 \square N_6) \square N_3 \square G_2 + D_3 + n + \frac{R_1 N_2}{K} \square + mB \quad (5.3)$$

Large faviid colonies have equivalent dynamics to large *Acropora*. They have reached a size refuge and can no longer be killed by other species. They can lose tissue in competition, but won't die entirely. Such tissue loss is shrinkage, but it is assumed (personal observation and Foster 2011) to hardly ever be sufficient to shrink back into N_3 and size-variability within the big size-class is ignored. Hence no term for subtraction is necessary. A mortality term (D_4) allows for inclusion of diseases and other non-catastrophic mortality.

$$\frac{dN_4}{dt} = G_2 N_3 \square D_4 N_4 \quad (5.4)$$

Finally, small poritids are limited due to space pre-emption by all big and small colonies and loose in encounters with recruits of other species. A portion ($N_5 G_3$) grows up into adults and reaches a size-refuge, in which neither *Acropora*, nor faviids can kill them. Some (m) immigrate from outside populations, some emigrate (n).

$$\frac{dN_5}{dt} = \frac{R_3 N_6}{K_3} \square K \square \square_{i=1}^6 N_i \square N_5 \square G_3 + D_5 + n + \frac{R_1 N_2}{K} \square + mC \quad (5.5)$$

$$\frac{dN_6}{dt} = G_3 N_5 \square D_6 N_6 \quad (5.6)$$

In these six equations, the constants R_i (intrinsic rate of increase), K (carrying capacity), D_i (death rate), G_i (growth rate into adults) and m, n (migration rates) are equivalent in meaning and subscripts denote unique treatment for each species.

In the case of single, isolated populations, n (emigration) and m (immigration) could either be set to zero, fixed or random values between zero and unity could be assumed. Since we wished to consider more than one connected population (larvae import to the fringing systems from the offshore banks and islands, as well as among fringing systems), the dynamics of each population was encoded using the same set of 6 ODEs for the focal and the connected population, resulting in simultaneous solution of 12 ODEs, which then interacted dynamically via the n and m terms with A, B and C becoming the N of the appropriate connected population (for example $A = N_{i, \text{connected}}$ for $\frac{dN_{i, \text{focal}}}{dt}$ and vice versa, where $N_{i, \text{connected}}$ and $N_{i, \text{focal}}$ are solved simultaneously using

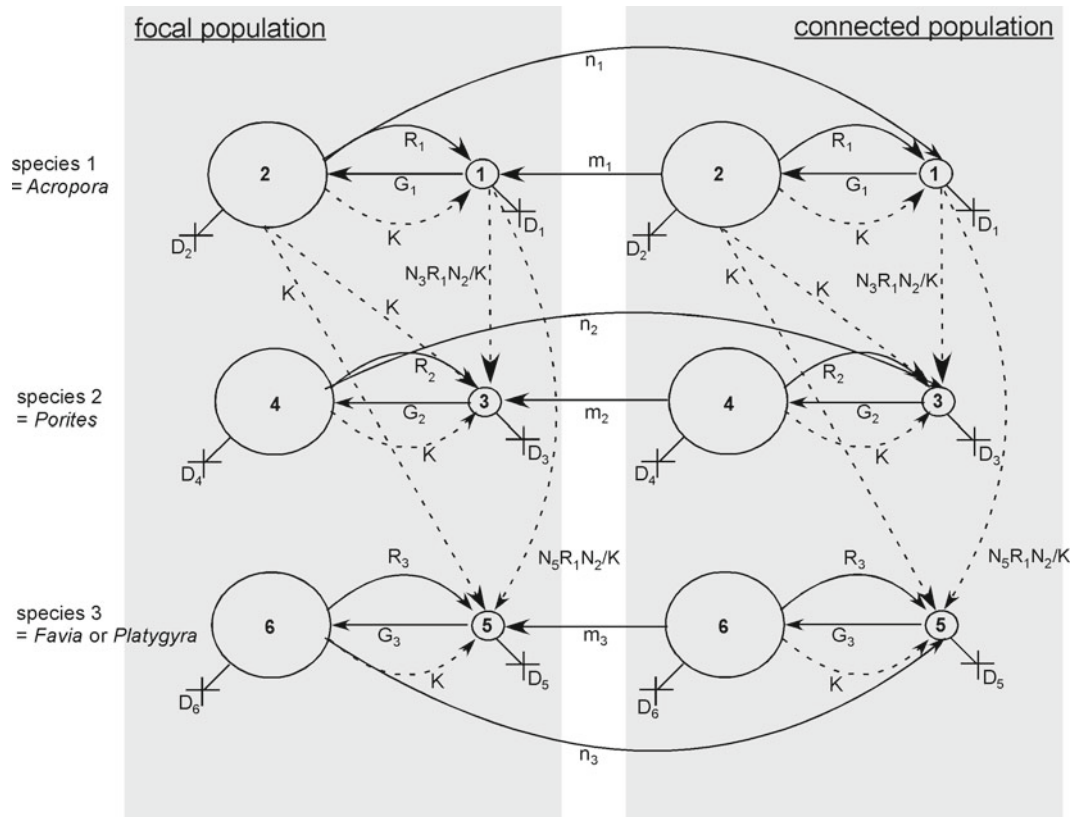


Fig. 5.9 Structure of the model. m migration term, D mortality term, R within-population recruitment term (ignoring immigration), G growth term, $N_j R_j N_k / K_j$ aggression term. K carrying capacity term indicating that presence of stage i in species i has a negative influence on another stage/species

at which the *arrow* is pointed. *Arrows* show the direction of an interaction. *Solid arrows* are growth-based interaction and point at the recipient of numerical increase, i.e. one stage grows or recruits into another. *Dotted arrows* are competitive interactions, the *arrow* points at the loser

1–10% survival of *Acropora* either in the form of adult colonies or offspring that survived the mortality event (Fig. 5.9).

5.4 Results

5.4.1 Assumption of Constant Rates – Model Runs for Ras Hasyan

We first tested whether the dynamics defined by the 6 ODEs had the capability of reproducing community dynamics as observed in the field. Parameters were needed that could fulfil the hypothesis that these coral assemblages had indeed been subjected to repetitive mass mortality but yet had persisted. We thus examined whether a set disturbance frequency and a set mortality rate would allow a perpetually regenerating population. We assumed the population levels of 1995 as the baseline since at this time the abundance of corals had been estimated and we could tune the model towards reaching comparable levels. We also had observed disturbances recurring twice at a 15-year interval and once at a 17-year interval. At first, we assumed a constant 15-year disturbance cycle

recurring 100 times and iteratively determined population parameters that allowed the populations to recover to levels comparable to 1995. Under assumption of constant reproductive rate (R) and no larval import from a connected population, it was possible to find parameters close to those derived by explicit solution that allowed a regularly recurring disturbance every 15 years for 1,500 years and full recovery to what we consider desirable pre-disturbance levels. Longer runs (>1,500 years) did not change the outcome. However, for *Acropora* not to go extinct, we had to increase its fertility from $R=0.4$ (Table 5.2) to $R=0.89$. None of the other parameters required adjustment. If we did not increase the R of *Acropora*, we required larval import from a connected population (parameter m set as non-zero) to support regeneration of the decimated *Acropora* population. This is not an unreasonable assumption, since reefs in the Gulf are likely highly connected (see below). Suitable values were a stable outside population of $A=N_2$ (the start and 1995 values) with $m=0.12$. In the same scenario ($m=0.12$, $R=0.4$) the population also regenerated between disturbances if the disturbance recurrence interval was randomly chosen from a normal distribution with a mean of 15 and a standard deviation of 5. This

Table 5.2 Population parameters used to model coral assemblages. They were derived and their usefulness was demonstrated by Riegl and Purkis (2009). The disturbance sequence mirrors observed events

	<i>Acropora</i>	faviids	Porites	Carrying capacity 8066812	Disturbance sequence 100*15 years, or 15-17-15-2-4-8-1
Fertility per colony	Basic: 0.4 disturbed: 0.89	1	0.6		
N _{small}	645295	1758421	1930192		
N _{big}	586632	525242	750630		
Big colony mortality	0.27	0.37	0.28		
Growth to bigger size	0.4	0.11	0.07		
Neighboring population size	0 or 586632 or random	0 or 1758421 or random	0 or 1930192 or random		
Migration rate	0, 0.1, 0.01, random	0, 0.1, 0.01, random	0, 0.1, 0.01, random		
Mortality at disturbance	90% or 99%	25%	25%		

provides evidence that, under the chosen parameters, Gulf coral populations should be able to persist under repetitive mass mortality almost indefinitely (Fig. 5.10).

Next, we tested these assumptions in a more realistic disturbance scenario. We assumed for want of better data, that the same number of corals as in 1995 had existed in 1949 at the start of the model runs. Thermal anomalies were detected in 1949, 1964, 1981, 1996, 1998, 2002, 2010, and 2011. The mortality incidences were kept constant: small and large *Acropora* were reduced by 90%, while small and large faviids were reduced by 25%, as suggested by field-data. In order to maintain the *Acropora* population, its R value had to be raised from 0.4 to 0.87. When this was done, *Acropora* populations were found to strongly rebound without outside larval input, as did faviids and *Porites*, until the closely spaced 1996-8-2002 disturbance triplet did not allow sufficient time for population recovery, pushing all populations to very low levels, and *Acropora* to near-extinction. Although faviids and *Porites* showed strong signs of recovery from 2002 to 2010 and had almost attained full population level again, *Acropora* remained at very low population levels (7,870 small, 4,495 big colonies, Fig. 5.11a). If, however, mortality was assumed to be local only and connectivity to an outside population of constant size was allowed, then *Acropora* populations regenerated even after the three closely-spaced mortality events (Fig. 5.11b). The 2010/11 events, however, greatly reduced all populations.

The next model runs addressed the question whether the *Acropora* population, with unaltered recruitment or mortality rates, could sustain itself if 99% mortalities, as observed in 1996, were the recurrent norm. We used the same realistic disturbance frequency (15-17-15-2-4-8-1 years) as above. While faviids and *Porites* persisted through the disturbances with 25% mortality, and showed strong recovery

after the three short-interval disturbances (2-4-8-1 years), *Acropora* went extinct latest after the second of the three closely-spaced disturbances (which would have corresponded to the 1998 disturbance; Fig. 5.12b). This suggested that the 1996 mortality was unusual in its severity, that the spacing between the 1996 and 1998 events was unusually close, and that the corals could not persist without significantly altered community structure if such disturbances became the norm.

However, we observed in the field that *Acropora* persisted through these three disturbances and had staged a moderate come-back by 2008 (see also Burt et al. 2008). Therefore, we had to assume that we either overestimated the mortality, which was unlikely given the extensive research effort during and after the events, underestimated coral fecundity, which was also unlikely given the high estimated value ($R > 0.8$), or that outside populations replenished the locally depleted populations. Indeed, we are aware of areas having escaped both the 1996 and 1998 mortalities that could have served as larval sources for the investigated populations (Riegl 1999, 2002). For example, only some reefs in Iran were depleted of their *Acropora* in 2007, those in Kuwait in 2010, and offshore islands in the UAE (p.ex. Sir Abu Nuair) and Iran (p.ex. Greater and Lesser Tonb; Samimi-Namin personal observation) retained good *Acropora* populations throughout.

We therefore modified the model to allow connectivity via larval import. We considered two fully connected populations and therefore allowed continuous larval import of 1% of the outside population of recruits in each species group, assuming that this population had the same vital rates and population parameters as the one in the core area under investigation. This is likely a conservative underestimation of the realistically available pool of corals. However,

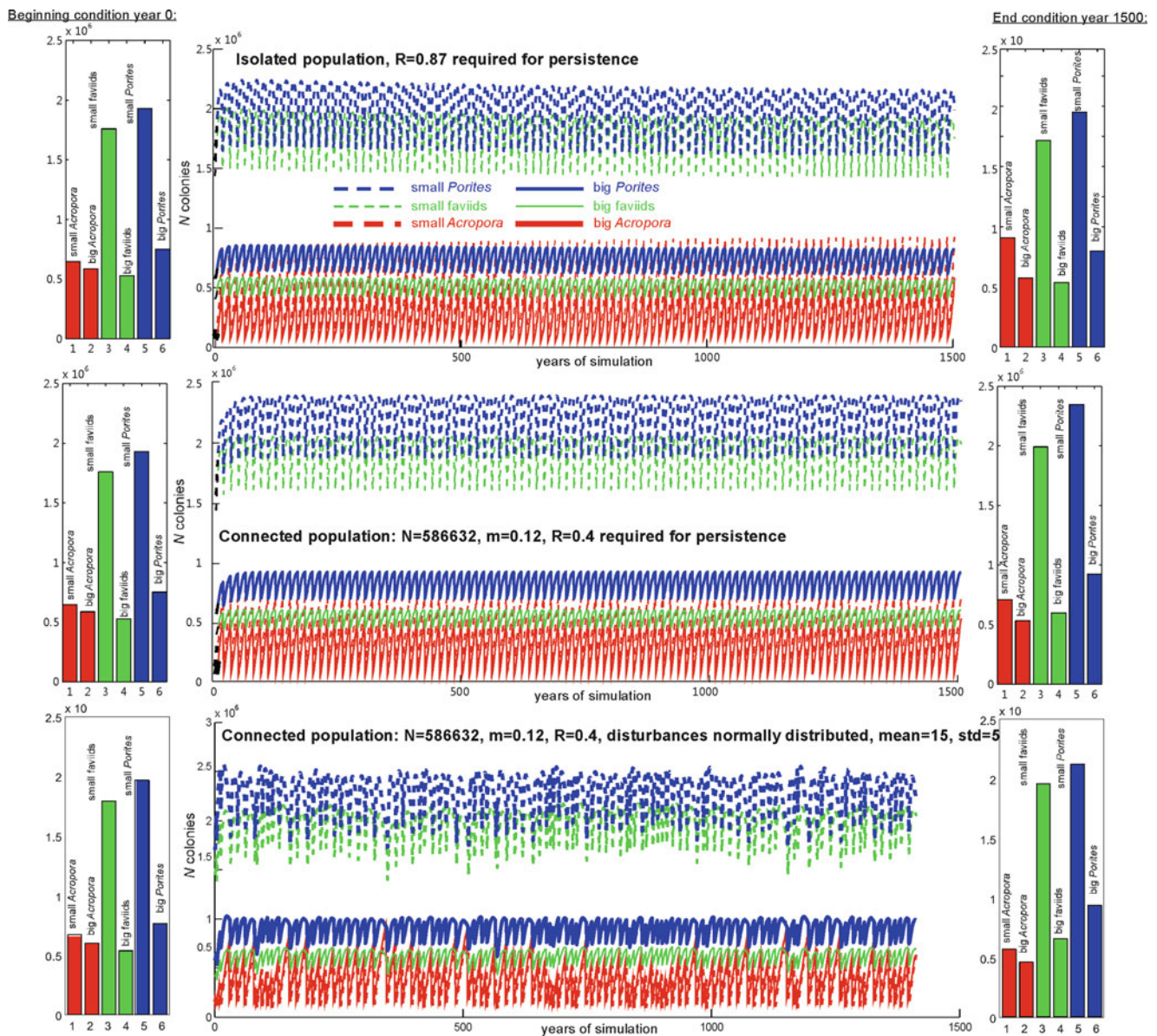


Fig. 5.10 Model of 100 recurring disturbances at 15-year intervals, no population connectivity in the *upper* panel, annual fixed larval import from a connected population in the *lower* panel. R constant throughout (*Acropora* $R=0.89$ in *upper* panel, 0.4 in *lower* panel). Each disturbance causes 90% *Acropora*, 25% faviid and *Porites* mortality. Mortality

uniform across stages. In the *upper* two panels, mortalities recur regularly at 15 year intervals, in the lowermost panel, disturbance frequency is normally distributed with a mean of 15, and a standard deviation of 5. Model parameters are shown in Table 5.2. Bar charts to the *left* and *right* show the beginning and end conditions

these outside populations should also be subject to similar population fluctuations. Therefore three scenarios could be tested in a short-term (disturbance cycle 15-17-15-2-4-8-1) experiment:

- outside larvae pool remains constant, since it is spread over several areas and the fluctuations within these even out
- connectivity is either symmetric (larvae export=larvae import, so each reef sends as much to the connected reef as it receives) or asymmetric (export 10, import 1; one reef is primarily donor, the other primarily recipient)
- both populations fluctuate synchronously (i.e. region-wide, uniform impact of mortality event)

- outside larvae pool fluctuates randomly between 10^5 and 10^6 individuals

In the scenario of two similar-sized populations with synchronized disturbances, *Acropora* went extinct soon after the 1998 disturbance, while faviids and *Porites* expanded due to the absence of competition (Fig. 5.13). In the scenarios that held either a constant outside larval pool or a fluctuating outside larval pool, *Acropora* persisted at low(er) levels, but the other species groups increased in frequency at its costs. This was not the situation observed in nature prior to the 1996 mass mortality (year 47 being the baseline), so we deduce that populations as observed in

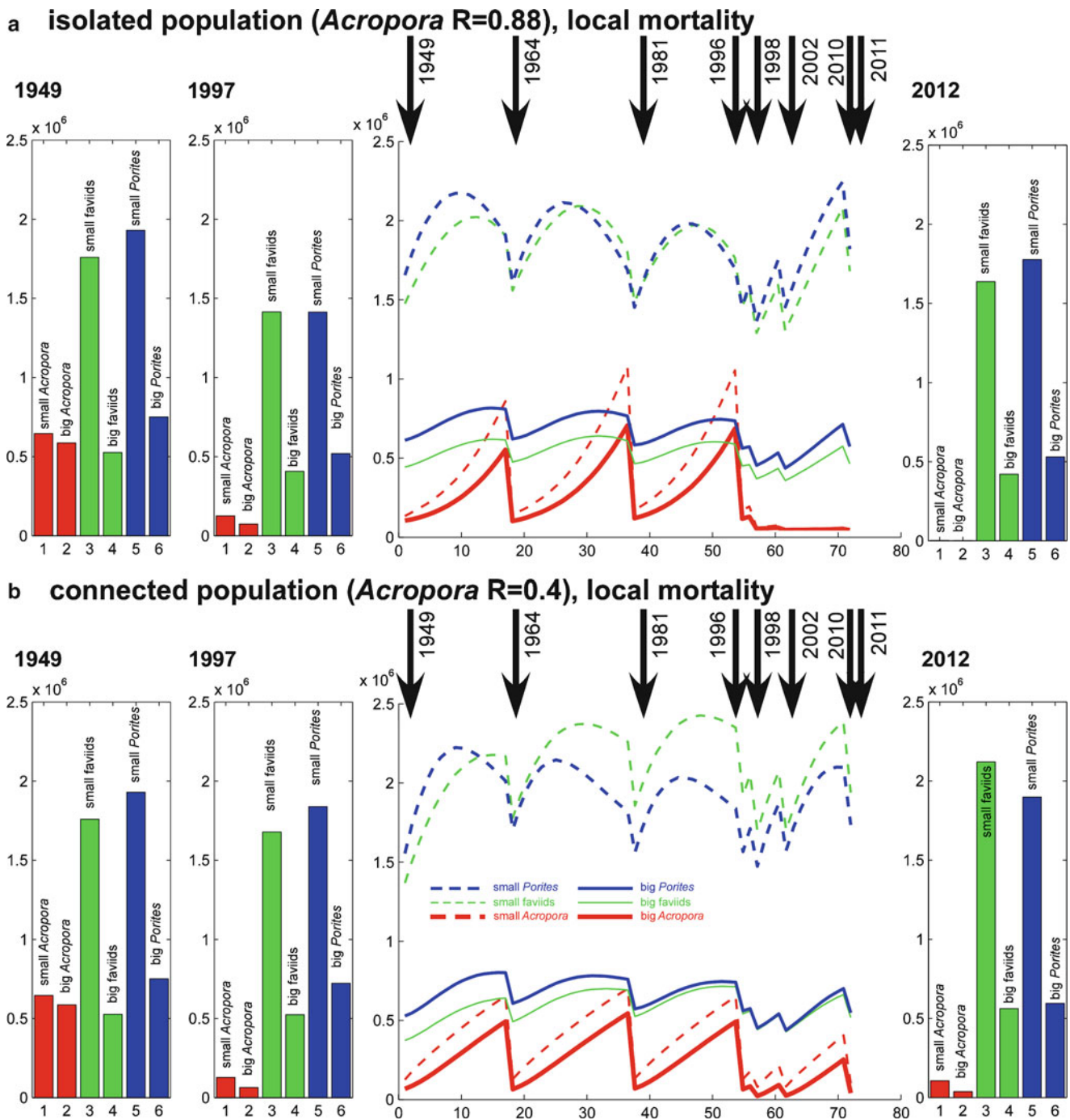


Fig. 5.11 Model of seven disturbance cycles that suggests that parameters can be found to allow persistence of the coral assemblage in the postulated disturbance regime. *Acropora* fertility had to be more than doubled from original assumptions to allow persistence ($R=0.87$) if the population was isolated. (a) Beginning and ending conditions after three disturbances (15-17-15 years) do not differ significantly (Chi-square test, $p < 0.001$), the following closely-spaced three disturbances

(2-4-6 years) significantly change the community composition by eliminating *Acropora*. (b) The case of two connected populations in which only the focal population suffers mass mortality, the connected population does not. This could be the case if mortalities are local, or if a sufficiently large larval pool is available. In this case, the *Acropora* populations rebound – a situation observed in the field

1996 could only have existed if recurrent mass mortality did not exceed 90% on a regular basis, again confirming the 1996 mortality event as unusually severe. However, connectivity is required to maintain *Acropora* populations. It is also

important that a sufficiently-sized larval pool stays available and region-wide declines that would uniformly suppress larval availability from connected populations would lead to extinction (Fig. 5.13).

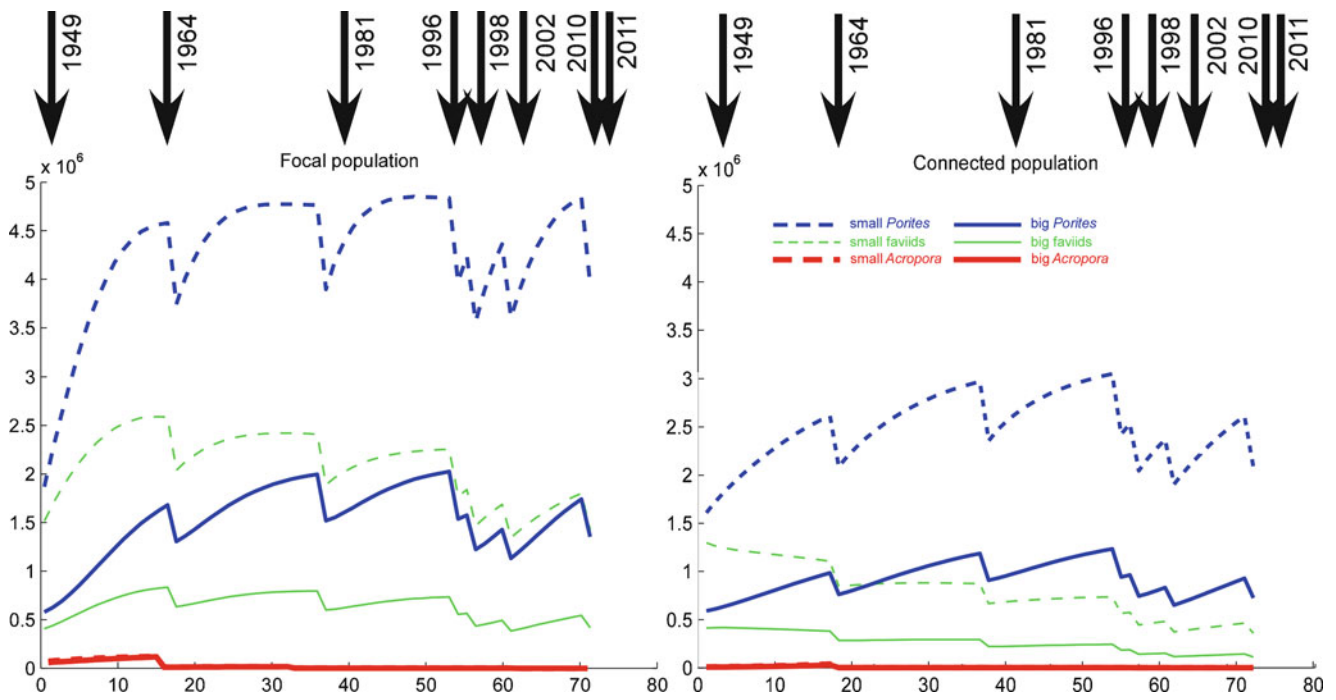


Fig. 5.12 Trajectories of dynamically linked populations with asymmetrical movement of propagules among populations ($m=0.12$, $n=0.01$ in receiving population, $n=0.12$, $m=0.01$ in donor population; $R1=0.4$, 90% mortality in *Acropora*, 25% in faviids and *Porites*, D1, D2 and D3

as in Table 5.2). Low *Acropora* values are due to simultaneous depression in focal and connected population. This was not observed in the field, suggesting that a larger larvae pool exist and dynamics will be more akin to Fig. 5.11

5.4.2 Assumption of Stochastic Rates

While we were able to recreate a stable dynamics under assumptions of constant recruitment and larval import, we nonetheless have to acknowledge that the world is not constant. Thus, the model would be even more plausible if expectations of constant recruitment could be relaxed and a comparable outcome was achieved. We therefore changed to stochastic variability of recruitment and larval export/import. R , m and n were assigned Gaussian random numbers and we used the realistic disturbance scenario (15-17-15-2-4-8). We simultaneously solved for two connected populations that varied independently with regards to R , m and n , but always could exchange propagules. Despite the stochastic variability in key population parameters, the model, averaged over 500 simulations, recreated dynamics comparable to those observed in the field. Despite 90% mortality, *Acropora* populations were able to rebound. The dynamics were similar to the model-runs with fixed parameters, but with stronger *Acropora* dominance. Also in the stochastic simulations it was clearly shown that the *Acropora* population was not able to withstand the high disturbance frequency from 1996 to 2002. In the 99% mortality scenario, *Acropora* became increasingly rare with each disturbance and became extinct in both populations (focal and connected) after the 1996/1998 disturbances. This again suggests that 99% mortality is not

sustainable by the *Acropora* population, even in a connected population if the disturbances are synchronized.

We next investigated whether populations could be maintained over a 1,500 year period with random recruitment. When trajectories were simulated for isolated populations with a constant 15-year cycle of 90% *Acropora* and 25% faviid and *Porites* mortality, violent swings within and among the populations were observed. Since reproductive rates were determined by Gaussian random numbers, trials differed in outcomes, but a representative sample of a single run and an average over 500 trials are shown in Fig. 5.14. The models show alternations of abundance with either faviids, *Porites* or *Acropora* dominating. Due to the irregular reproduction, *Acropora* could not maintain high enough numbers in the long run to outcompete the other groups. All groups persist in the system, albeit *Acropora* became increasingly rare (Fig. 5.14).

We then considered two populations and R was varied randomly and independently in each population, but we held import and export rates of larva constant at 1% or 10% of all viable recruits being exchanged among the connected populations. Both populations were synchronously affected by mortality, 25% in faviids and *Porites*, 90% in *Acropora*. In such a scenario, *Acropora* maintained its presence in the system, however, it went temporarily extinct in the focal population in individual simulations (single run, cf. Fig. 5.14). In some simulations, all corals went temporarily extinct.

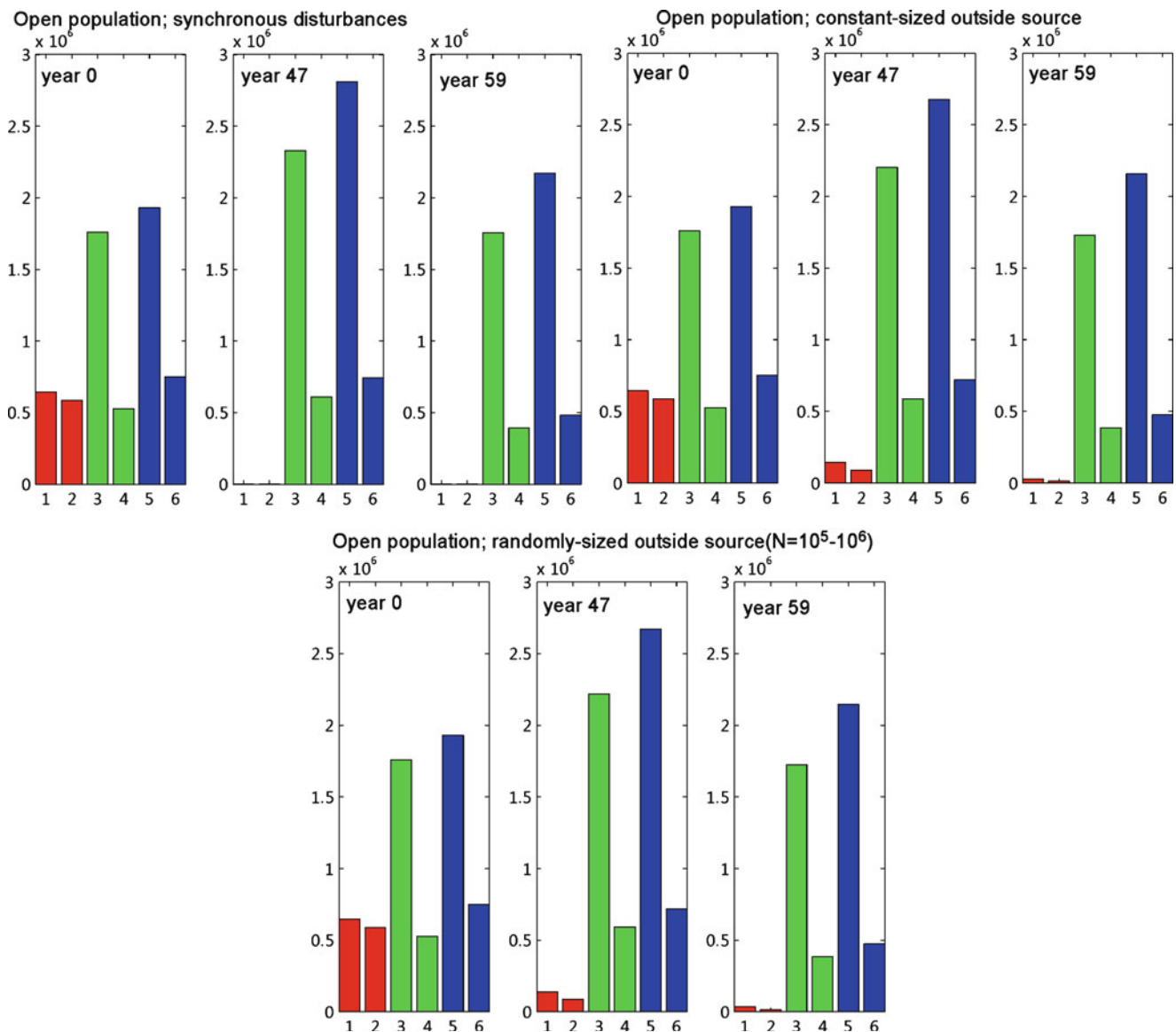


Fig. 5.13 Outcomes of connected model runs. *Acropora* can persist in a scenario of 99% recurrent mortality only if a connected population of constant size, or variable between 1 and 100% of individuals in the core

area, exists. All scenarios suggest significant changes in community structure. 1=small *Acropora*, 2=big *Acropora*, 3=small faviids, 4=big faviids, 5=small *Porites*, 6=big *Porites*

Averaged over 500 repeats, the situation shows all coral populations surviving, however *Acropora* becoming increasingly rare and *Porites* being increasingly dominant.

5.5 Discussion

Coral communities are fairly uniform throughout the Gulf and patterns and assemblage composition is repeated throughout the region. A host of studies has over the years contributed to our knowledge and has allowed to understand typical communities on a Gulf-wide base (Table 5.1; Fig. 5.5). Gulf coral assemblages are different from typical

reef communities in that many, in particular in the southern Gulf, exist in areas on low topography in a typical carbonate ramp setting (Purkis et al. 2005; Purkis and Riegl 2005). Thus, spatial and ecological patterns within many Gulf coral communities are not primarily driven by bathymetry and exposure, but by other processes linked to settlement and habitat availability. Bathymetric differentiation exists where true frameworks are present and/or where corals have settled on an underlying topography that provides a reef-like habitat. Such bathymetric zonation has been described primarily from the offshore islands but also from some nearshore reefs (Basson et al. 1977; Fadlallah et al. 1993, see Table 5.1).

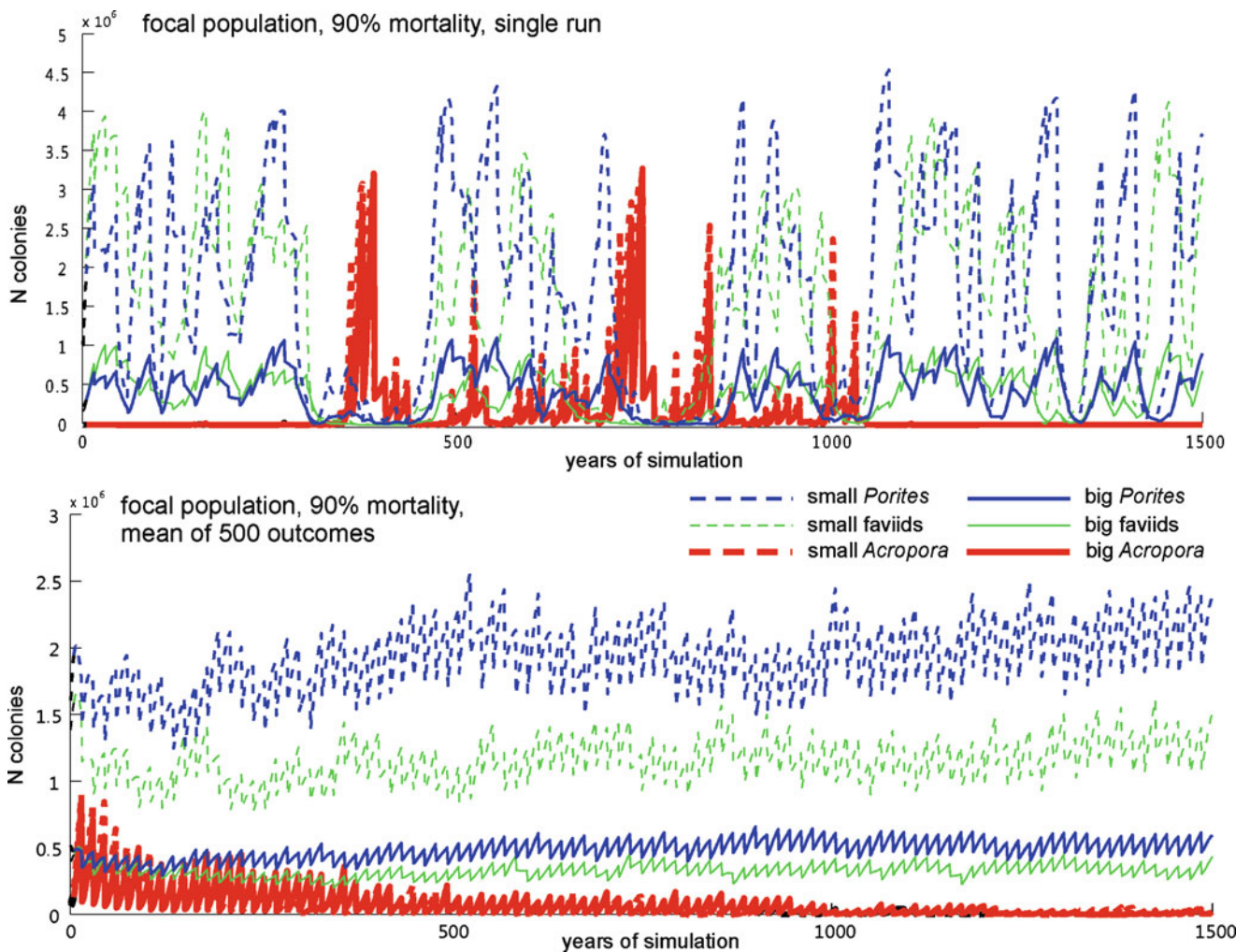


Fig. 5.14 Effects of random recruitment. Simulation of 100 recurring disturbances at 15-year intervals, no metapopulation, the populations rely entirely on their own larval supply, R is a Gaussian random number with mean zero. Each disturbance causes 90% *Acropora*, 25% faviid

and *Porites* mortality. Mortality uniform across stages. Variables (except R) are shown in Table 5.2. The outcomes vary – in single runs it is visible that corals undergo boom-and-bust cycles, however, this averages out over many simulations. All corals persist in the system

A striking feature of Gulf coral assemblages is that, despite having dense coral growth, many (or most) do not appear to form proper reefal frameworks and those that have been reported or measured are only less than a few meters in thickness. In the Indian Ocean, as a contrast, Holocene reef thicknesses are at the order of 5–10 m (Montaggioni 2005). This lack of carbonate accretion and the observed repeated mass mortalities have led to the notion that Gulf coral assemblages are, geologically speaking, ephemeral (Riegl 1999, 2001). Environmental conditions in the Gulf's high-latitude setting allow the recurrence of extremes that exceed the physiological tolerances of at least some reef coral species (mainly *Acropora*, which are among the most important framework builders in the Indo-Pacific Holocene; Montaggioni 2005). This leads to mass mortality, subsequent bioerosion of skeletons and framework switch-off (Riegl 1999, 2001).

The models presented in this chapter support the postulate that coral communities can indeed persist under a repetitive disturbance regime. Not surprisingly, dependent on the parameterization of the model, in particular dependent on assumptions of constant or variable fertility, overall dynamics and ecological implications vary dramatically. The models demonstrate that connectivity among sites plays an important role in regeneration dynamics, since connected populations can survive with lower per-capita fertility. Connectivity, however, also depends on the amount of larvae available that can travel among patches. Thus the scale of each mass mortality event, whether local, regional, or Gulf-wide, becomes an important determinant of species persistence. Since these scales of impact are likely to change as world climate warms (Alexander et al. 2006), important lessons for worldwide reef survival can be derived from dynamics observed in the Gulf.

Models demonstrate that the 99% mortality suffered by *Acropora* along the UAE coast in 1996 must have been unusual in its severity, since no realistic parameters could be found that would allow survival under repeated such mortalities. The greatest mortality rate that a model *Acropora* population could sustain repeatedly was 90%, provided enough recruitment was provided for regeneration ($R=0.4$ in the connected model, $R=0.8$ in the isolated population). According to the models, repetitive 25% population reductions do not appear problematic for faviid and *Porites* populations. This is verified by field observations that faviids as well as *Porites* sustained far higher levels of populations than more susceptible corals (*Acropora*, *Stylophora*) through the 1996/1998 and 2002/2010 bleaching events.

Not only was 1996 an unusually severe disturbance, the close spacing of the 1996, 1998 and 2002 crises had a significant effect in the models by causing a shift in many populations towards functional (very low abundance), or complete *Acropora* extinction. This was also observed in the field in the UAE and Qatar. After 1996/1998, *Acropora* had become very rare in the previously dominated assemblages and some areas moved towards dominance by other species. For regeneration, the levels of within-population fertility (for *Acropora*, whether an R of 0.8 or 0.4 was assumed) and connectivity were very important. Unless *Acropora* was well-connected to another large population, probably unrealistically high fertility assumptions (according to the explicit solutions obtained from the model equations if size-distributions and growth-rates observed in the field were used) had to be used to maintain its dominance, or even to avoid its local extinction. The fact that synchronous depression of connected populations (Figs. 5.13 and 5.14) also leads to extinction suggests that region wide mortality events should have more impact on assemblage structure than more localized events even if the latter were characterized by much higher mortality. Support for this hypothesis can be found in the patterns of coral assemblages of the SE Gulf observed between 2005 and 2011. Well-developed *Acropora* populations have been found primarily on the offshore islands, where they appear well-connected since situated directly within the major current system of the Gulf (Fig. 5.15). Severe *Acropora* mortality in the northern Gulf (Iran) was observed only in 2007/2008 (Samimi-Namin, pers comm. in Baker et al. 2008), thus the populations in the SE Gulf could have been replenished from there after 1996 and prior to 2007. Indeed, the areas where regeneration had been observed (Dubai: Burt et al. 2008; Abu Dhabi and Dubai, Halul in Qatar: Riegl and Purkis 2009) are situated downstream from rich Iranian reefs (Fig. 5.15).

In eastern Abu Dhabi and Dubai the coastline is oriented perpendicular to dominant wind drift and current direction and is directly downstream from many offshore islands (Halul, Sir Abu Nuair, Greater and Lesser Tonb). While also affected by mortality, these localities are situated directly within the gen-

eral flow of the large scale current pattern, and are also probably connected by wind-driven surface drift. The Abu Dhabi and Dubai coasts where strong regeneration was found (Burt et al. 2008; Riegl and Purkis 2009) are directly downwind from Halul and Sir Abu Nuair where *Acropora* had survived or strongly regenerated. Halul is situated in the path of a current filament that frequently creates a direct connection to Iranian reefs (Fig. 5.15; Chap. 2). Since Iran did not lose its *Acropora* until 2007, there was ample time for recruits to reach the offshore islands (Halul and Sir Abu Nuair) and from there the eastern Abu Dhabi and Dubai coasts. Iran still contained many healthy *Acropora* populations at the time of print.

Field observations and models thus agree that Gulf coral assemblages are adapted to disturbances. However, the regeneration trajectory taken by any given community depends on the frequency, severity and geographic extent of the disturbance. In the SE Gulf and around Qatar, the disturbances of the 1980s through the first decade of the 2000s has led locally to significant changes in assemblage composition. Most of the offshore banks and islands, as well as the mainland coast where corals occurred, were characterized by more or less well-developed windward *Acropora* fringes (Shinn 1976; Purser 1973; Holt-Titgen 1982). The extensive mortality over 1996/1998 caused the near-total disappearance of *Acropora* in most of this area. Mortality appears to have been most dramatic in the lee of the Qatar Peninsula with respect to the dominant wind direction, where coral mortality was almost complete. In this area (pink in Fig. 5.16), temperature excursions are more extreme and overall temperatures are somewhat higher than in the eastern region which is more exposed to winds and swells (Sheppard and Loughland 2002; Riegl 2003, Chap. 4; Fig. 5.16). In the sheltered, hotter, area coral assemblages are mostly dominated by nodular *Porites* (mainly *P. harrisoni*) and faviids with *Acropora* rare or completely absent. This situation compares well to model results in Figs. 5.12 and 5.14 in which *Acropora* disappears from the community if all connected populations are depleted simultaneously. Also, the Qatar peninsula forms a break between the upwind (and upstream) Saudi islands from where recruits could be obtained.

In many areas of the Gulf, *Porites* is the dominant genus and *Acropora* rare, although enough apparently suitable habitat is available. This is usually the case in regions with a harsher environment (like the Gulf of Salwah, the Yasat Islands and the Khor Odaid area; Sheppard and Loughland 2002; Chap. 4) where temperature excursions are higher and presumably less predictable. Thus the community pattern can be explained as a result of long-term *Acropora* decline, as predicted in our model with stochastic fertility rates and connectivity. With disturbances potentially becoming more severe and more frequent (Sheppard 2003) due to higher temperature extremes (Nasrallah et al. 2004; Alexander et al. 2006), the entire Gulf may be moving towards a similar trajectory, casting shadows over the

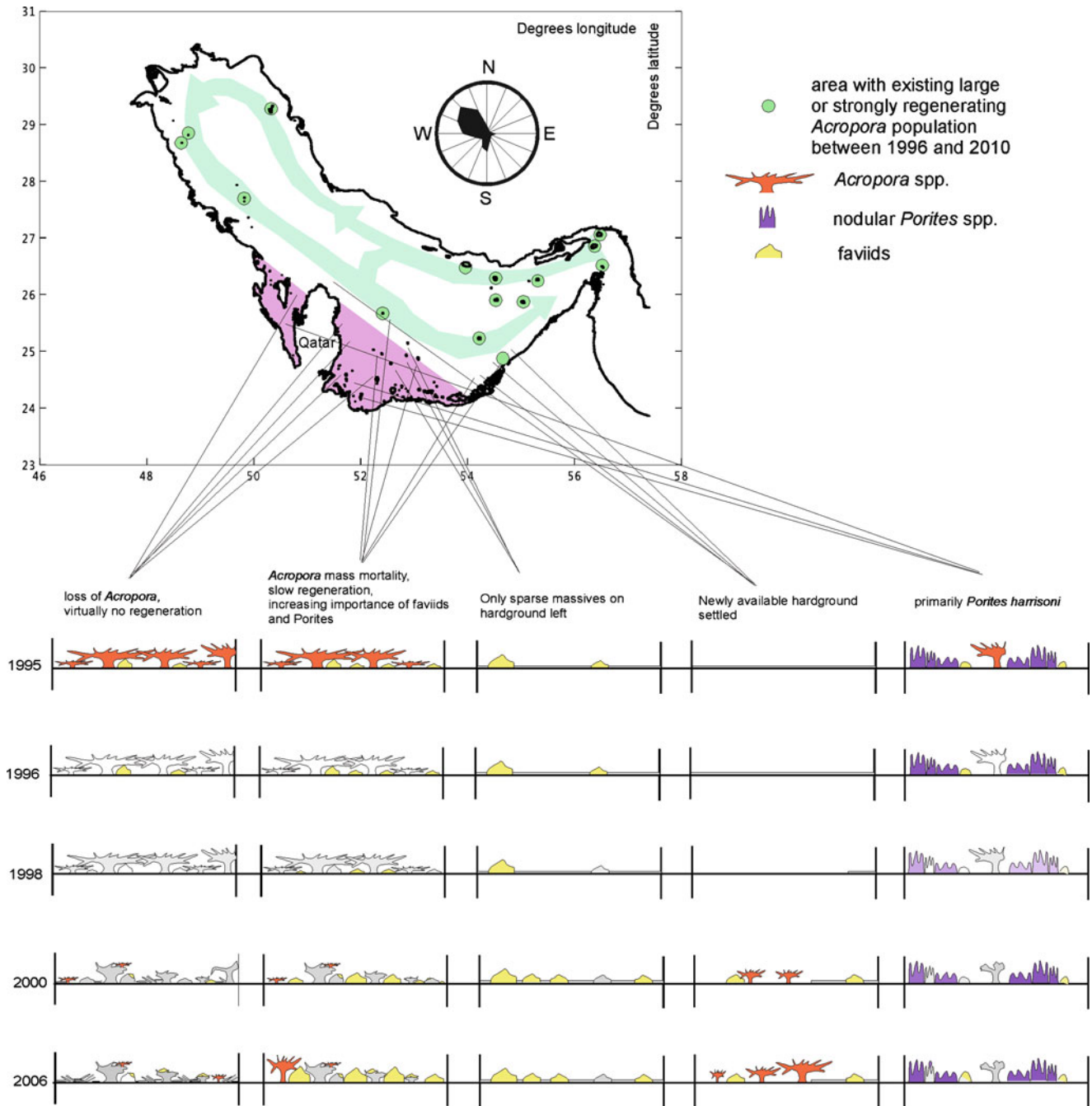


Fig. 5.15 Biogeography and dynamics of coral regeneration (or absence thereof) in the southern Gulf. Several well-defined assemblage types exist. By 2010, well-developed *Acropora* dominance was primarily maintained on offshore islands or nearshore settings situated within the major currents or the dominant surface wind-drift (indicated by

windrose). Areas in the lee of major headlands (Gulf of Salwah, area in the lee of Qatar, shaded pink) showed less *Acropora* regeneration and coral assemblages more typical of higher temperature and salinity extremes. The regeneration patterns are compatible with community dynamics as suggested by the models

future of *Acropora* as a dominant species. The implications for coral community structure in other oceans are also very clear. *Acropora* are always among the species suffering first and most from bleaching (Loya et al. 2001).

If we accept as premise that either unusual cold (Coles and Fadlallah 1991) or hot events (George and John 1999;

Riegl 1999; Purkis and Riegl 2005) cause mass mortality, then no direction for evolutionary change towards either hot- or cold-adaptation would be expected, but selection would favour alleles with a generally wide temperature tolerance. Unidirectional stresses (i.e. only heat or only cold) would lead to more predictable population genetic outcomes,

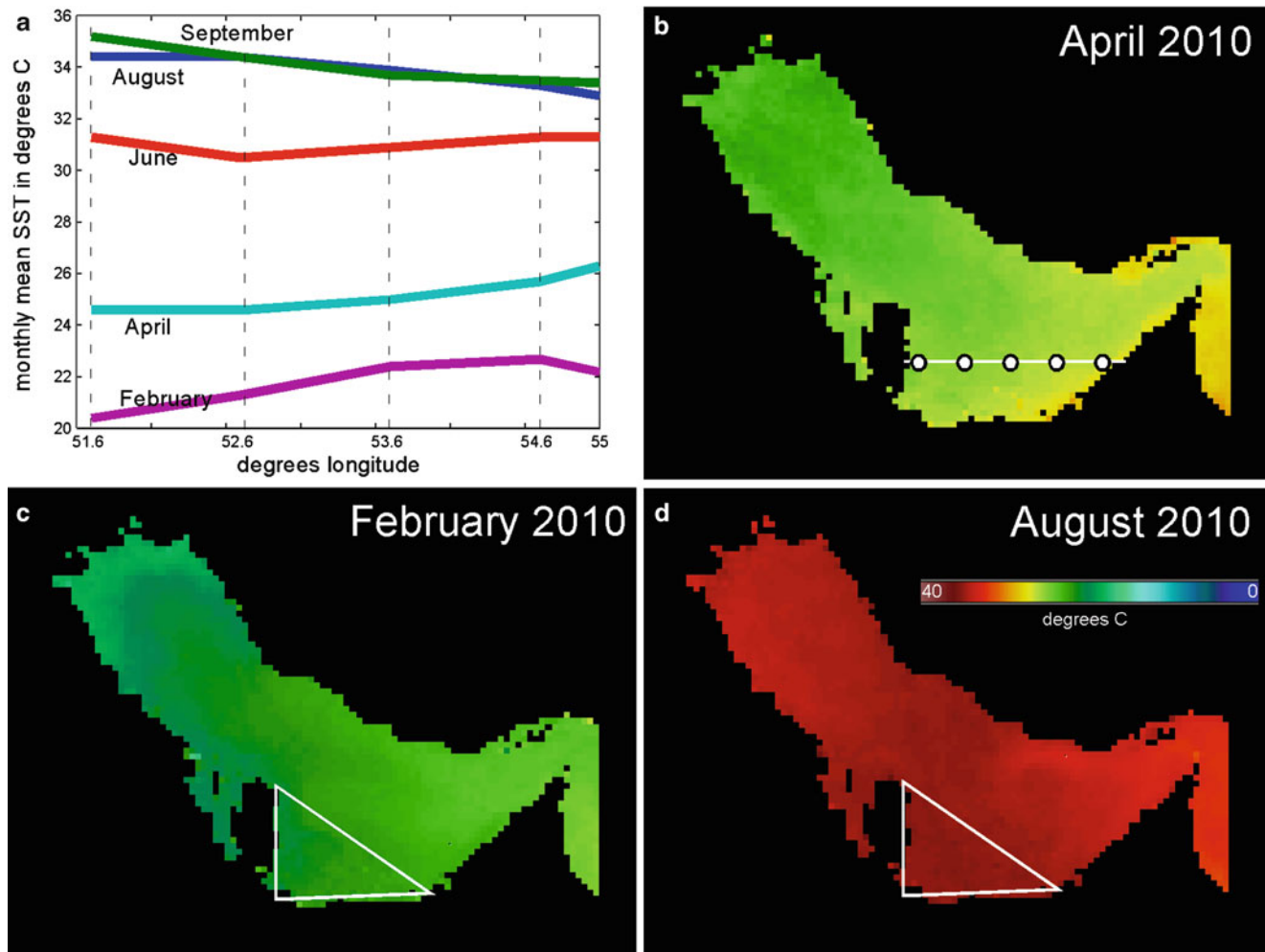


Fig. 5.16 The area in the lee of Qatar, with respect to the dominant wind direction (see windrose in Fig. 5.16) is indeed characterized by higher temperatures in summer and lower temperatures in winter: (a) shows transects from 2010 of mean monthly SST derived from the

MODIS sensor, (b) shows the transect and sampling locations, (c, d) show the approximate area that is hotter/colder, which is reflected in coral assemblages and dynamics

namely dominance of the allele with the tolerance for the highest (or lowest) temperature, since the high mortality (90 or >90%) certainly would rapidly depress the evolutionary fitness of the worse adapted allele. In the present case, the alleles of the zooxanthellae are as important as those of the coral, since coral death is mostly due to heat or cold induced bleaching. Our models support that notion as do data in Baker et al. (2004) and Ghavam Mostafavi et al. (2007), who found most Arabian Gulf *Acropora* to contain the temperature-tolerant zooxanthellae clade D, and to a lesser extent C.

Our direct observations can only confirm hot-kills but the literature (Shinn 1976; Coles and Fadlallah 1991) clearly implicates cold-kills as well, which would suggest no clear direction for evolution towards either hot- or cold-adaptation in the long run. Since we have no quantitative information regarding the proportion of hot- to cold-kills, we cannot offer

a more quantitative analysis. Certainly the rapidly-spaced hot-kills of the late 1990s and early 2000s may have led to a phenotypic shift towards more hot-adapted corals, in particular *Acropora* (Riegl 2003 illustrates bleached faviids and unbleached *Acropora* – a clear reversal of the situation in 1996, where the mortality pattern was exactly the opposite). Also climate models and observations (Sheppard 2003; Nasrallah et al. 2004; Alexander et al. 2006) suggest an increasing incidence of hot over cold extremes. Such extremes may lead to region-wide synchronous coral mass mortality. This would, as we have demonstrated above, lead to potentially irreversible shifts in community structure due to the region-wide depletion of all connected populations. *Acropora* could then be lost from the Gulf to leave it dominated by the more resistant and resilient *Porites* and faviids. As the models and monitoring observations clearly show, these changes in

dominance will depend on the frequency and severity of the disturbances. One could surmise that more rapidly repeated and severe bleaching events will leave a depauperate community of few very robust species worldwide.

The patterns of population crash and recovery, especially in *Acropora*, is still in contrast to the situation in other seas, but bears some resemblances to the situation in the Caribbean. Also a peripheral, northern subtropical sea, the Caribbean has been dominated by *Acropora* throughout the Pleistocene and early Holocene (Pandolfi and Jackson 2006). A population crash of *Acropora* occurred in the 1970s–1990s and the next-dominant coral (*Montastraea annularis* group) has been suffering since the 1990s a similar decline. This has been largely blamed on hurricanes, bleaching, coral diseases, and ecological shifts towards macroalgae dominance due to mass mortality of the dominant grazers (sea urchins) and overfishing (Hughes 1994). The coral decline has, to this day, not been reversed. In the Gulf, *Acropora* has also dominated throughout at least the late Pleistocene (Chap. 2), but local crashes have so far regenerated. However, regeneration is becoming more difficult due to increasing pollution and environmental degradation (Chap. 16). In all areas of the Gulf where good reef regeneration in general and *Acropora* regeneration in particular was observed, sea urchins are abundant (~5 m⁻² in Riegl and Purkis 2009; Chap. 4) and good fish populations remained. Thus, free substratum remains available for settlement and macroalgal competition is controlled. However, this advantageous situation for corals is changing fast, since fish populations are becoming more and more depleted (Chaps. 8 and 16) and increasing coastal eutrophication favors algae (Chap. 16). It is therefore possible that Gulf coral populations might be heading towards similarly precipitous declines as in the Caribbean. Close attention should be paid to the careful and responsible management of the Gulf's coral resources.

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Coral Bleaching and Mortality Thresholds in the SE Gulf: Highest in the World

Bernhard M. Riegl, Sam J. Purkis, Ashraf S. Al-Cibahy,
Suaad Al-Harathi, Edwin Grandcourt, Khalifa Al-Sulaiti,
James Baldwin, and Alaa M. Abdel-Moati

6.1 Introduction

Bleaching is a stress reaction in corals, during which the symbiosis between corals and the algae (zooxanthellae) living in the coral cells breaks down. As a result, zooxanthellae are expelled, and the coral appears pale or even white (Fig. 6.1; Baker et al. 2008). The link between environmental variables and coral bleaching has been well-established in a variety of studies and synthesized in several places (Phinney et al. 2006; Baker et al. 2008; van Oppen and Lough 2009). Large-scale and region-wide bleaching events, such as occur in the Gulf, have been clearly linked to unusually high temperatures and the accumulation of heat stress in corals. Other drivers, such as UV and water acidity can have compounding effects (Baker et al. 2008) and bleaching can also be caused by these factors alone, or other local drivers such as unusually cold temperatures (Saxby et al. 2003; Lajeunesse et al. 2007). However, it is heat stress that has been demonstrated as the most reliable predictor and defined time-integrated bleaching thresholds exist for various regions of the Indo-Pacific and the Caribbean (Berkelmans 2002b; Manzello et al. 2007; Berkelmans 2009).

Since corals adapt to their local environment, bleaching thresholds vary within and among regions (Berkelmans

2002a, 2009; Manzello et al. 2007; Baker et al. 2008). As previous chapters in this book have demonstrated, Gulf corals exist in a uniquely extreme environment both with regards to extreme highs and lows, the regularly recurring long-time summertime highs (Chap. 4), however, unsurpassed among any region in the world. Corals do exist in other areas of the world in very hot environments, for example in the well-demonstrated case of tide-pools in Samoa (Birkeland et al. 2009) where temperatures can also reach 34.5°C but only for few hours. Gulf corals are unique in being able to survive daily mean summertime temperatures in excess of 34 or even 35°C for months (Chap. 4). Thus the question becomes just how much heat is necessary to bleach, or even kill these apparently uniquely adapted corals. Such information has much practical value, since it demonstrates just how much corals can acclimatize in a heating world (Sheppard 2003).

During 2010, a major, region wide bleaching event occurred in the SE Gulf. While some previous region-wide bleaching and mass mortality events (1996, 1998, 2002) are well-documented with regards to their effects on coral populations and communities (George and John 1999, 2000; Riegl 1999, 2001, 2002, 2003; Sheppard and Loughland 2002; Purkis and Riegl 2005; Burt et al. 2008; Riegl and Purkis 2009; Chap. 5), associated temperature data have been sporadic and coarse in resolution (Riegl 2002; Sheppard and Loughland 2002). During 2010, we had available both locally continuous temperature and coral monitoring data throughout the bleaching event which now allows the construction of bleaching threshold curves and estimates of differential impacts on all involved coral taxa.

6.2 Study Area and Methods

Study locations were situated in the SE Gulf, in the UAE and Qatar and are part of a routine monitoring program established over 2006/2007. Some of the sites are described in Chap. 4. For the present contribution, local bleaching thresholds were derived at Bu Tinah in the UAE from where an

B.M. Riegl (✉) • S.J. Purkis
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu; purkis@nova.edu

A.S. Al-Cibahy • S. Al-Harathi • E. Grandcourt
Environment Agency-Abu Dhabi, Abu Dhabi,
United Arab Emirates
e-mail: aalcibahy@ead.ae; salharathi@ead.ae; egrandcourt@ead.ae

K. Al-Sulaiti • J. Baldwin
Qatar Gas, Ras Laffan Industrial City, Qatar
e-mail: KAAlsulaiti@qatargas.com.qa;
James.baldwin@qatargas.com.qa

A.M. Abdel-Moati
Ministry of Environment, Doha, Qatar
e-mail: mamoti@moe.gov.qa

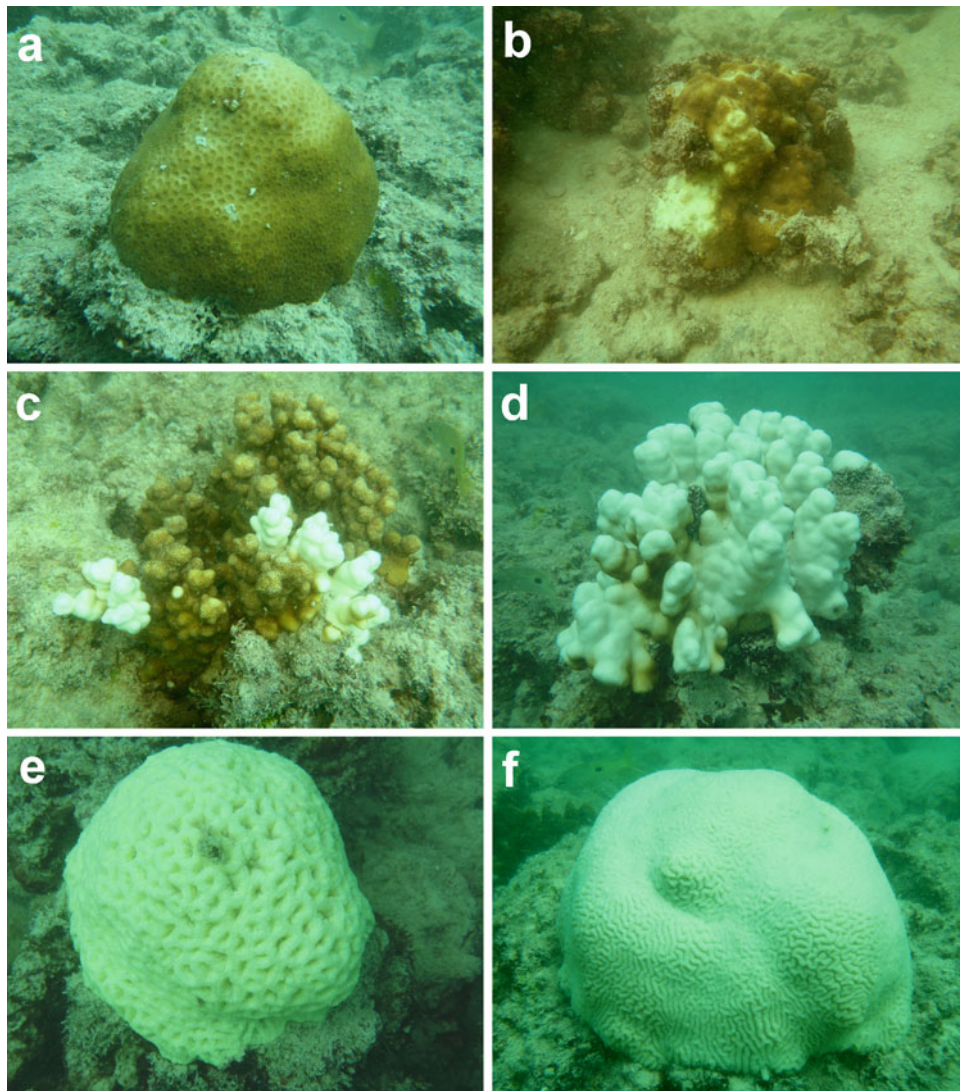


Fig. 6.1 Bleached corals in Qatar, October 2010. (a) A bleached *Plesiastrea versipora*. Blanching is a stress state that occurs prior to bleaching and is detected by an overall paling of the coral's color. (b) A partially bleached *Cyphastrea microphthalmma* at the height of the 2010 bleaching event. Only a part of the coral is visibly bleached. (c) A partially bleached *Porites harrisoni*, (d) a completely bleached

Porites harrisoni not far from the specimen shown in (c) at the same time. Differences in clades of zooxanthellae, resulting in differential heat-susceptibility of the algae seem to be responsible (Baker et al. 2004). (e) A completely bleached *Coscinarea columna*. (f) A completely bleached *Platygyra daedalea*. All photographs from the same area and same time

almost complete temperature timeseries exists from 2007 through the end of 2010 (HoboTemp loggers recording hourly temperatures at 4 m depth) and at Fasht el Hurabi in Qatar from where a continuous temperature time series exists also from 2007 to 2010 (HoboTemp loggers recording at hourly intervals in 2007 and 2008, VEMCO Miniloggers recording at half hourly or hourly intervals in 2009 and 2010 at 5 m depth). Large-scale temperature records for the entire Gulf and world-wide, in order to evaluate the severity and extent of the thermal anomaly, were obtained from the Met Office, UK. For Gulf-wide analysis we employed the HadISST 1×1° gridded dataset, and for worldwide analysis

the HadISST and HadISST2 5×5° gridded products offered at www.hadobs.org (Rayner et al. 2003, 2006). Graphs were produced using the Erddap mapping facility (<http://coast-watch.pfeg.noaa.gov/erddap/>). Air temperature data for Sharjah airport were obtained from <http://climexp.knmi.nl/>. MODIS global SST data were obtained from <http://neo.sci.gsfc.nasa.gov>.

Additionally, detailed information about coral mortality existed at both sites and in the general region from monitoring programs maintained in Qatar and the UAE. While obviously local variability exists in temperature among sites within the SE Gulf, the overall pattern is very similar (Chap. 4).

We therefore investigated coral bleaching and mortality at several sites in order to detect any commonalities or differences in local population responses. Sites were at Ras Ghanada, Al Heel, Dalma and Bu Tina in Abu Dhabi and Fasht el Hurabi in Qatar. At these sites, phototransects were taken during and after the bleaching event and compared to similar transects taken earlier (Ras Ghanada; transect time series dating back to 2000, regular annual data since 2007). At Al Heel, and Dalma, phototransects exist dating back to 2007. Also at Fasht el Hurabi in Qatar, phototransects, as well as tagged coral colonies existed for the evaluation of bleaching. All coral monitoring took place at the end of the bleaching event, in the last week of September or the first 2 weeks in October 2010.

Thermal bleaching and mortality thresholds were derived according to Berkelmans (2002a, b, 2009) and Dunne (2002). At each location, the cumulative time (in days) at each temperature between 30°C and 36°C (average daily temperature, since either 24 or 48 daily readings were available) was calculated. It is known from previous bleaching events in the Gulf that temperatures need to exceed 35.5°C for significant mortality to occur (Riegl 2002). Bleaching thresholds were derived using Berkelman's corrected (2002b) equation:

$$b_c = T_n + [s/5](T_b - T_n), \text{ for } T_b > T_t \quad (6.1)$$

Where b_c is the predicted temperature value for the bleaching curve, s is a non-dimensional weighting factor that scales bleaching severity on a scale from 1 to 4 (we used 4 in this paper; 1 is mild bleaching, 4 the most severe), T_b is the temperature distribution in the coolest bleaching year (in our case, since only one bleaching event was captured, the temperature curve for 2010), and T_n is the temperature distribution in the warmest non-bleaching year. T_b and T_n are obtained by comparing graphed or tabulated values of the cumulative times spent at 30°C or higher (see above). T_t is the threshold temperature, i.e. the highest temperature at which no bleaching occurs.

Mortality curves were derived using Berkelmans' (2009) method. These mortality curves are specific to the most susceptible genus, *Acropora*, which suffered almost 100% mortality (see below) in western Abu Dhabi (Dalma, Bu Tina, Al Heel), and overall 60–80% mortality in eastern Abu Dhabi (Ras Ghanada). We therefore followed Berkelmans (2009) in the assumption that T_{L50} , the temperature value at which 50% mortality occurs in the indicator corals, is situated halfway between the bleaching threshold and the value causing 100% mortality.

We also calculated degree heating days (DHD) and heating rate (HR), which Maynard et al. (2008a) have shown to be a useful stress indicators.

$$DHD = \sum (T_{\text{heating}} - LMST) \quad (6.2)$$

where LMST is long-term mean summer temperature (July, August, September) and T_{heating} is the daily average temperature during bleaching. We did not have a long-term record available, since comparison of in-situ temperature records with remotely-sensed records did not coincide (see results). As closest proxy to a long-term record, we used the mean daily temperatures from 1 July to 30 September over the three non-bleaching years (2007, 2008, 2009) compared with the bleaching year (2010). The period 1 July–30 September encompasses peak temperatures (Fig. 6.9). Heating rate was calculated as

$$HR = DHD / \sum_{\text{days}} (T_{\text{heating}} > LMST) \quad (6.3)$$

6.3 The 2010 Bleaching Event in the SE Gulf

Coral bleaching was observed, depending on locality from August through October 2010. The event was comparable in severity with the 2002 bleaching event, when almost all corals bleached at least to some extent, but no wide-spread mass mortality was observed (Riegl 2003). Comparable data for Qatar are missing, since the 2002 event was not witnessed there, but presumably similar dynamics occurred.

Depending on locality, the onset of bleaching occurred in the early to latter half of August and abated by mid September in eastern Abu Dhabi and in October in Qatar and western Abu Dhabi with colonies regaining color and no new bleaching observed. At all sites, at least some bleached corals persisted into October 2010. At Fasht el Hurabi, Qatar, most corals remained bleached until the third week of October (Figs. 6.1 and 6.2). At Ras Ghanada, most corals had regained color by the last week of September 2010. At all sites in Abu Dhabi, significant mortality in *Acropora* was observed. At least at Ras Ghanada, this mortality was not uniquely due to bleaching but to a large extent, if not predominantly, to an outbreak of diseases, so-called white syndromes (Chap. 7) in the immediate aftermath of the bleaching. Many *Acropora* were able to recuperate from bleaching and coral diseases did not kill the entire local population. While some patches of *Acropora* escaped unscathed, much of the area suffered ~90% loss of *Acropora* tables of all sizes (recruits similarly affected as large colonies) (Fig. 6.2). At Ras Ghanada, an estimated 60% of the overall *Acropora* population was lost. Also at Al Heel and Dalma, *Acropora* was the worst-affected genus, with all colonies in the sampling sites suffering mortality (Fig. 6.2). At Bu Tina and Fasht el Hurabi *Acropora* does not occur. *Porites harrisoni*, a dominant coral throughout the area, bleached heavily. At Ras Ghanada most colonies had regained most of their color by late September, with

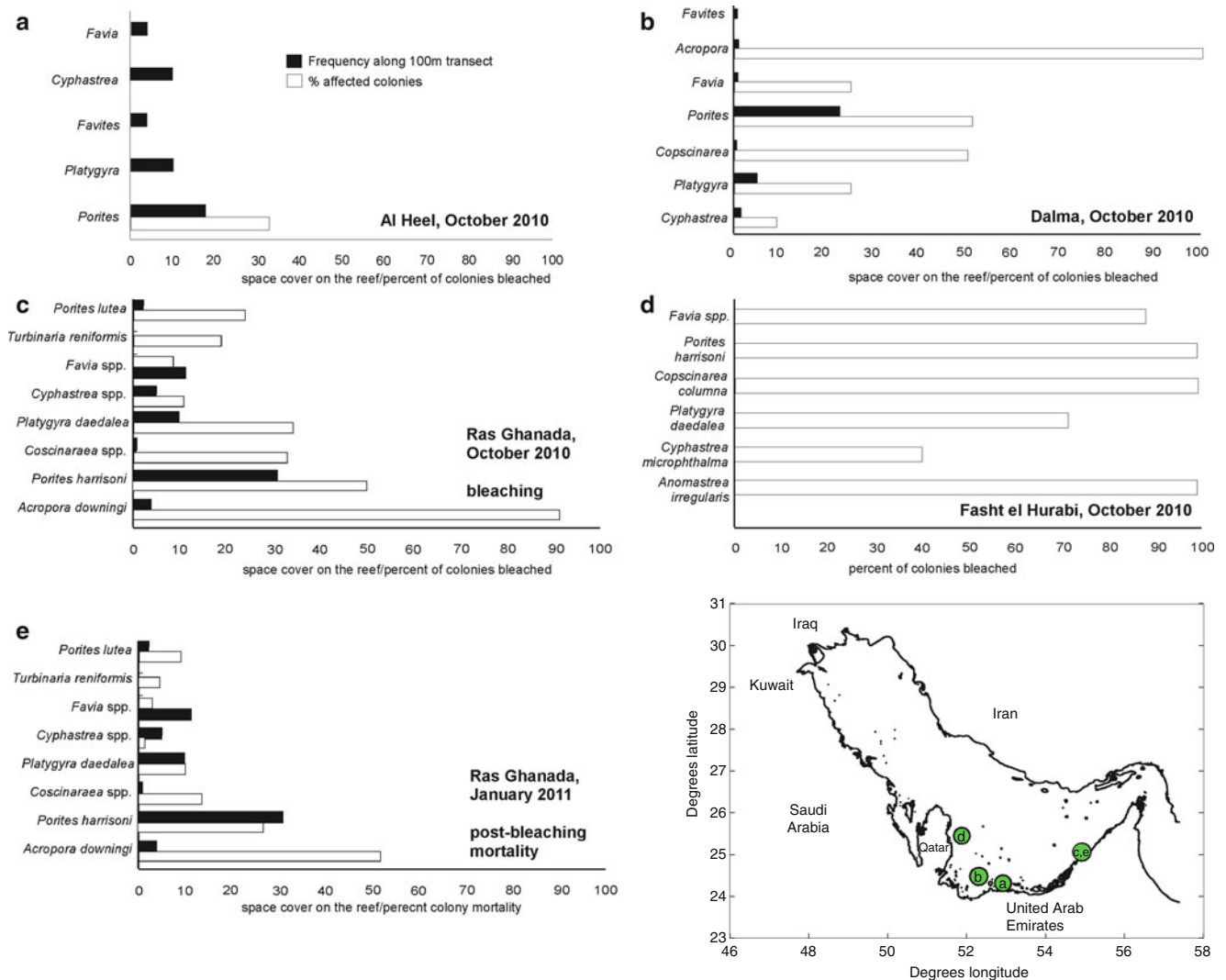


Fig. 6.2 Taxon-specific bleaching levels during the 2010 event at selected sites in Abu Dhabi and Qatar, SE Gulf (locations detailed in inset map). (a, b) Relative frequency of taxa along point-intercept transects in Abu Dhabi and the bleached proportion. (c) Space cover in phototransects in Abu Dhabi and the bleached proportion. (d) Bleached

proportion of tagged experimental colonies in Qatar. (e) Space cover in phototransects and proportion of colonies that died in the period from the onset of bleaching to the monitoring period. The mortality value thus includes bleaching mortality and subsequent disease attacks (Chap. 7)

about 50% remaining blanched (i.e. somewhat paler than usual), at Al Heel and Dalma about half of the colonies remained bleached to various extents and at Fasht el Hurabi, Qatar, most colonies remained bleached white into the second week of October. Among the faviids, the genera *Favia* and *Favites* bleached less than *Platygyra*. Most *Platygyra* colonies still showed signs of bleaching (white, whitish or pale tissue patches as well as increased signs of recent mortality) and subsequent partial mortality.

A clear gradation of bleaching recovery was observed from W to E, with the least impact and the most rapid regeneration at Ras Ghanada in the E, and the longest duration of the event at Fasht el Hurabi in Qatar, at the western extreme of the study area.

6.4 Temperature Regime During the 2010 Bleaching

6.4.1 Gulf-Wide Pattern

2010 was an overall hot year in the Gulf region. In September 2010, the Gulf was one of the warmest places in the world's ocean (Fig. 6.3). A significant positive temperature anomaly existed over most of the NW Indian Ocean, Red Sea and Gulf region that persisted throughout the bleaching months of September and October well into December 2010 (Fig. 6.4). The Gulf showed a positive anomaly between 1 and 3°C over this period. The warm temperatures extended both over land and sea (HadISST and HadISST2 data; Rayner

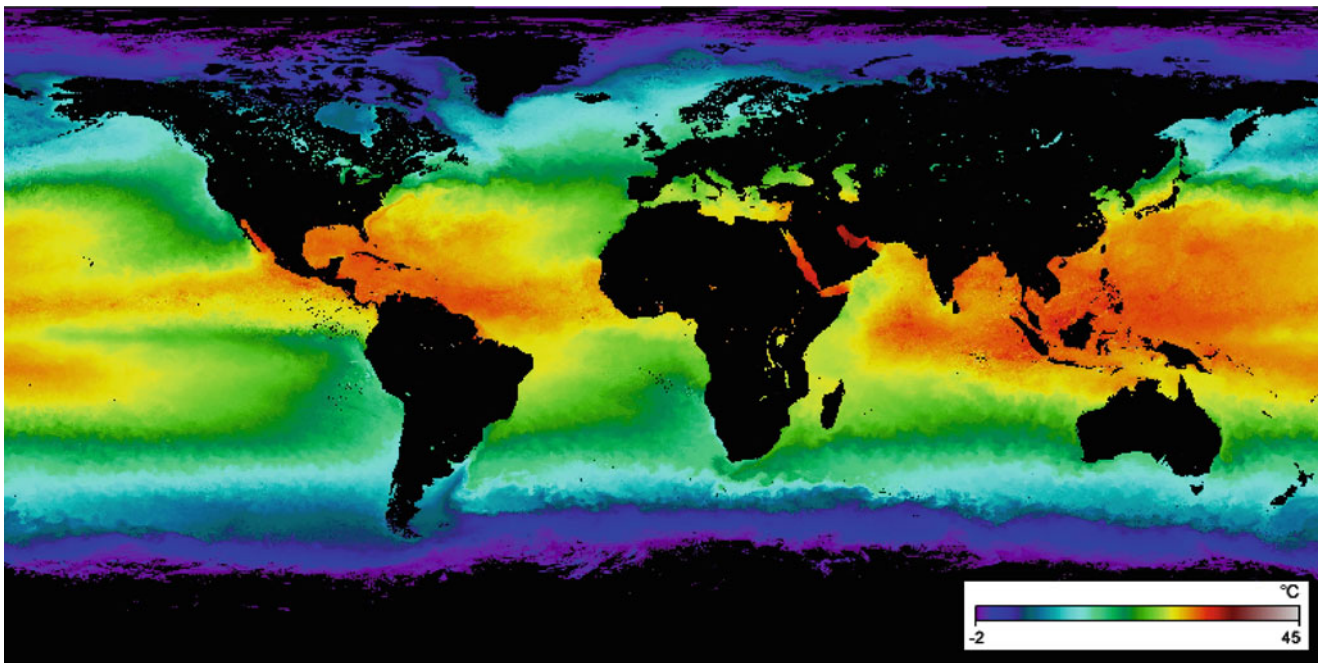


Fig. 6.3 Composite image of mean MODIS SST between Sep. 1 and Sep. 30, 2010. During this month and during the bleaching event, the Gulf was the warmest sea worldwide

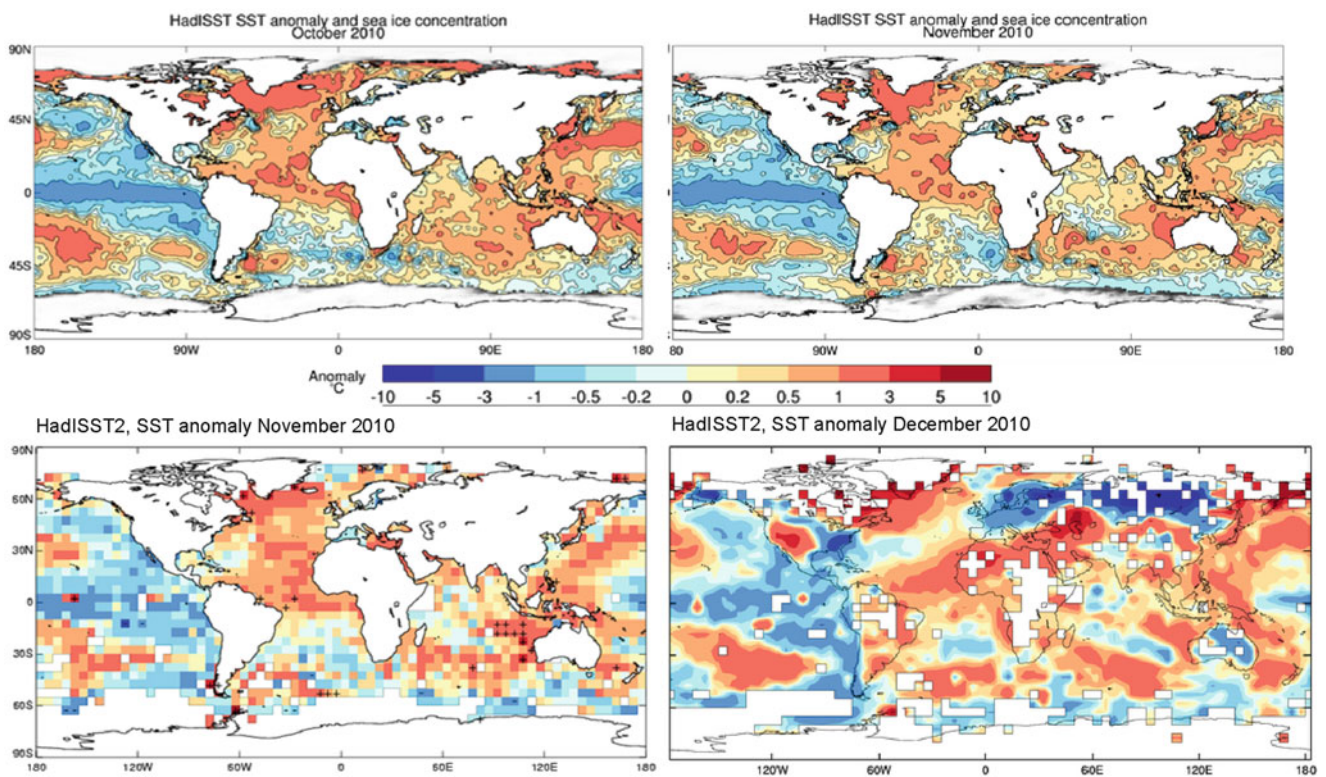


Fig. 6.4 World-wide sea surface temperature anomalies during the 2010 Gulf bleaching (October, November $1 \times 1^\circ$ HadISST data) and shortly thereafter (November, December $5 \times 5^\circ$ HadISST2 data). Composite images courtesy The MetOffice (<http://www.hadobs.org>,

copyright). The anomalously warm temperatures in the Gulf region are clearly visible. The anomaly is defined as deviance from the monthly means in the period 1961–1990

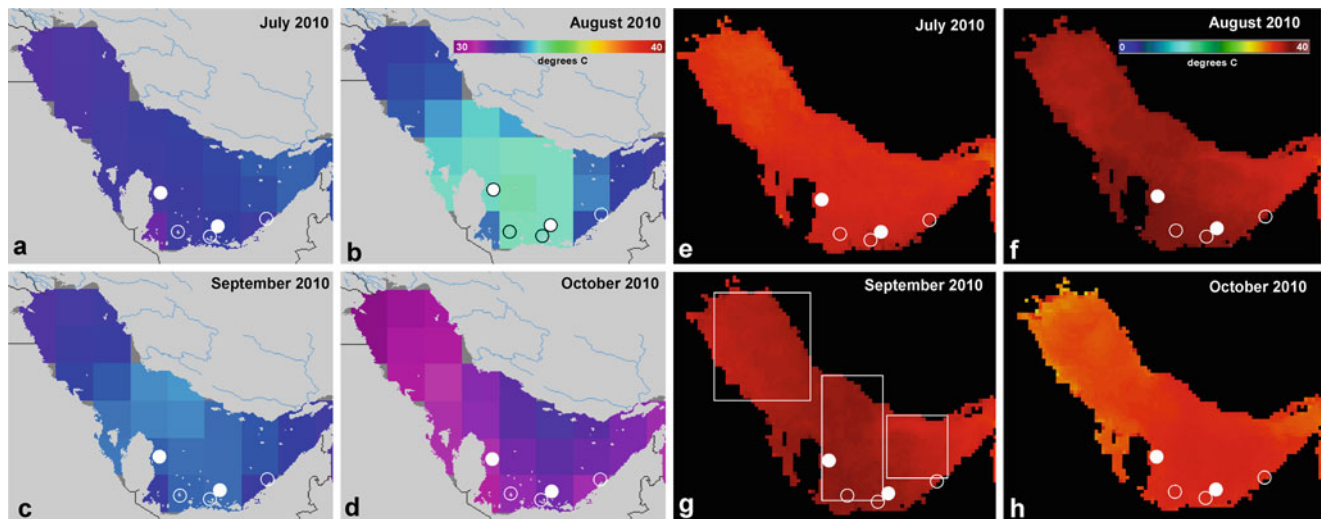


Fig. 6.5 Gulf-wide remotely-sensed sea surface temperature through the 2010 bleaching event (a–d HadISST, e–h MODIS). Coral monitoring sites for this study are indicated by *white circles* and correspond to those of Fig. 6.2. Sites where temperature was monitored as well are indicated by a filled *white circle*. Both HadISST and MODIS data suggest August as the hottest month and that bleaching was concentrated in

the central and SE Gulf. The Ras Ghanada study site experienced the lowest temperatures, which explains the observed lower bleaching impacts. The monthly averaged HadISST and the MODIS data underestimate peak local temperatures by about 1°C. (HadISST data courtesy The Met Office, Crown copyright)

et al. (2003), obtained from the MetOffice website; <http://badc.nerc.ac.uk>; crown copyright is acknowledged). Gulf-wide, the strongest heating was restricted to its central and SE parts, as suggested by the HadISST and the MODIS datasets (Fig. 6.5). Highest 1×1° gridded temperatures were observed in August, with maximum heat in the area of the Abu Dhabi and Qatar offshore islands and banks. Average monthly SST (MODIS) in August/September was 33.5°C in the northern Gulf, 32.78°C in the eastern Gulf, but 34.45°C in the central bleaching region. The eastern Abu Dhabi region (Ras Ghanada study site) received less heat. The HadISST dataset suggest that heat abated through September.

6.4.2 Local Temperature Observations

2010 was overall a hot year with a long summer. Maximum locally-recorded hourly temperatures at BuTinah (Abu Dhabi) reached 36.4°C and Fasht el Hurabi (Qatar) 36.1°C. At Bu Tinah, these temperatures were recorded on 9th and 10th September, at Fasht el Hurabi daily from 12th to 15th August 2010 (Fig. 6.6). Average daily temperatures reached 35.48°C at Bu Tinah on 3 September and 35.72°C at Fasht el Hurabi on 15 August, which significantly exceeded the long-term mean daily summer temperatures (Fasht el Hurabi 33.21°C, Bu Tinah 33.78°C). DHD and DR values were higher in August than either in July or September, suggesting the onset of bleaching in August (Table 6.1). At Bu Tinah, short-term maximum temperatures were higher (36.6°C) in 2007 but no bleaching was recorded. This was

not the case at Fasht el Hurabi, where hourly maxima were lower in 2007 (35.8°C).

6.5 Bleaching Threshold in the Gulf

Corals at Bu Tinah are exposed to higher temperature variability than corals at Fasht el Hurabi, as can also be seen from the summertime temperatures in Fig. 6.6. The shallow water body over the large Bu Tinah bank rapidly absorbs and loses more heat than the much smaller Fasht el Hurabi. As the cumulative temperature curves show, Gulf corals spend between 4 and 5 months every year at daily mean temperatures above 30°C, about 2 months above 33°C. These are the highest recorded temperature tolerances of corals anywhere. It is interesting to note that 2007 was almost as hot as 2010, yet no unequivocal bleaching records exist for the SE Gulf (but see ch. 4). However, coral reefs in Iran were subjected to significant bleaching and subsequent mortality that year.

The bleaching threshold curves for Bu Tinah and Fasht el Hurabi are similar (Fig. 6.7) and suggest that the maximum temperatures supported by Gulf corals are between 35.7 and 36.0°C, above which bleaching is triggered. The annual cumulative temperature curves suggest that corals were subjected in 2010 to longer exposure to temperatures between 33 and 35°C than in the other years (Table 6.2). The difference is much higher at Bu Tinah than at Fasht el Hurabi. Maximum temperatures in 2010 were similar to, or lower than, in 2007. This suggests that the total time exposure to sublethal temperatures in the range 33–35°C is the

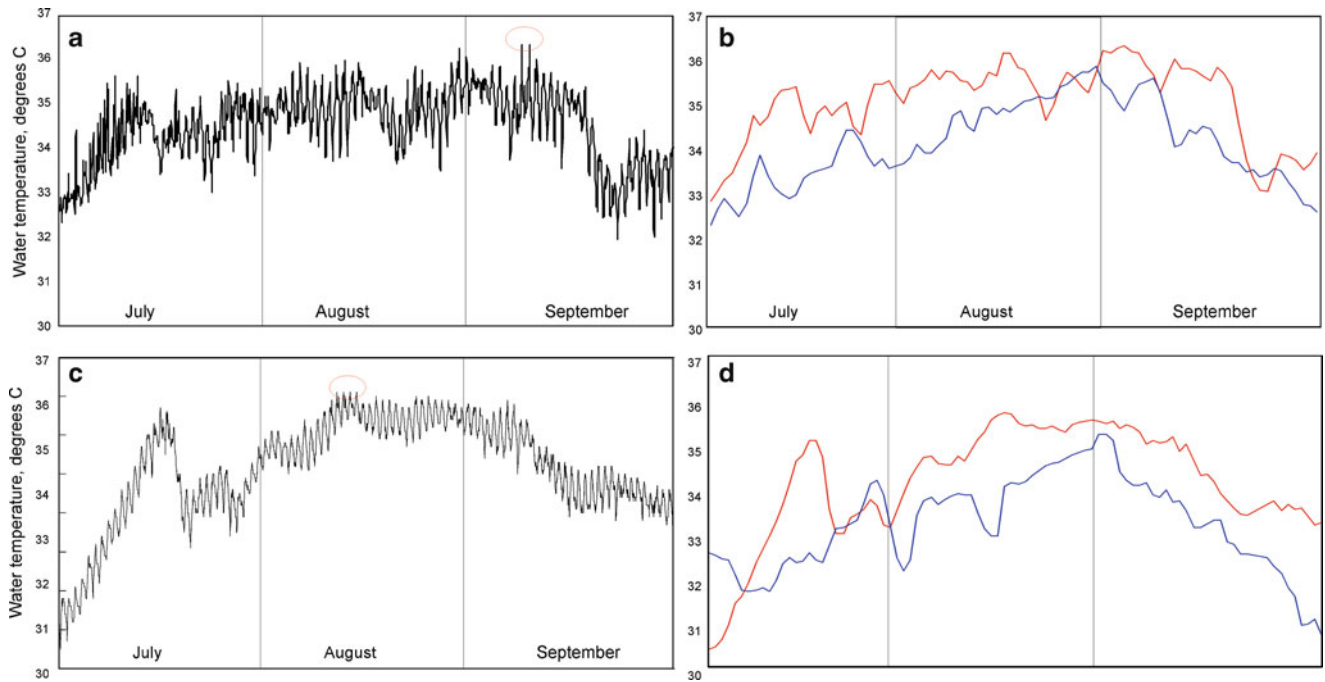


Fig. 6.6 Peak hourly temperatures observed in situ at temperature monitoring sites at (a) Bu Tinah (c) Fasht el Hurabi. Peak temperatures are circled red. (b, d) Deviation of mean daily temperatures in 2010 (red) from the mean daily temperatures 2007–2009 (blue). The in situ

temperature record shows more detail than the 1×1° gridded HadISST data (Fig. 6.4). Local temperatures are higher than in the 1×1 cell and the cooling trend observed in September in Fig. 6.4 did not correspond to all local data

Table 6.1 Degree heating days (DHD) and heating rate (HR) at sites in Abu Dhabi and Qatar. The peak in DHD in August suggests onset of bleaching in that month

	DHD July	HR July	DHD August	HR August	DHD September	HR September
Fasht el Hurabi	21.4	0.9	74.3	2.4	40.7	1.35
Bu Tinah	12.8	0.6	36.1	1.2	25.6	1.34

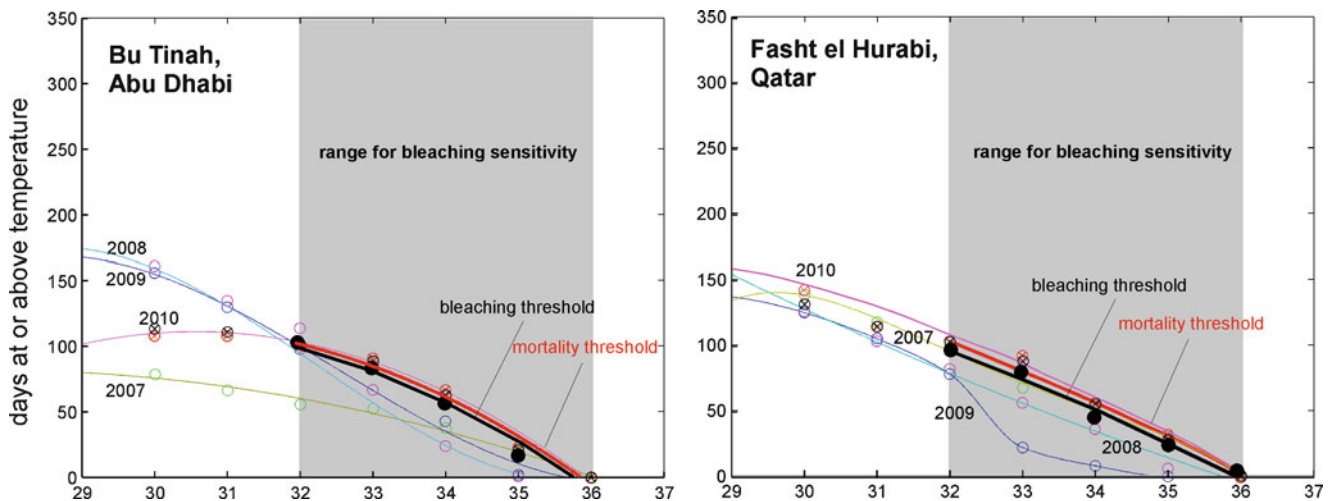


Fig. 6.7 Bleaching and mortality thresholds from Abu Dhabi and Qatar. Each datapoint represents the number of days spent at or above the temperature on the x-axis

Table 6.2 Bleaching table and bleaching thresholds. Values in columns refer to the numbers of days spent at, or above the indicated temperature. Thus, the values of each higher temperature are included in those of the lower temperature. To obtain time spent at each temperature, the sum of all values of time spent at higher temperatures in the same line must be subtracted. Temperature data exist from 7 July 2010 to 31 December 2010, thus the time spent at temperatures <32°C is under-represented. Bleaching thresholds were calculated using the method of Berkelmans (2002a, b). The values in columns are the cumulative days spent at or above the indicated temperature. Any time spent longer at these temperatures will lead to bleaching. Mortality thresholds (T_{L50}) were calculated using the method of Berkelmans (2009). The T_{L50} is assumed to lie halfway between the bleaching threshold and the curve that produced 100% mortality. * = incomplete data record.

Year	>30°C	>31°C	>32°C	>33°C	>34°C	>35°C	>36°C
Bu Tinah							
2007	79*	67*	56*	53*	38*	20*	0
2008	156	130	98	67	43	2	0
2009	161	135	114	67	24	1	0
2010	108	108	100	91	67	23	0
Fasht el Hurabi							
2007	136	119	101	76	53	27	0
2008	121	105	78	57	38	4	0
2009	125	105	78	22	8	0	0
2010	136	115	104	93	57	33	0
Bleaching Thresholds							
Fasht el Hurabi	134	113	99	79	47	26	0
BuTinah	113	110	101	86	58	18	0
Mean	124	112	100	83	53	22	0
Mortality Thresholds							
Fasht el Hurabi	136	115	104	93	57	33	0
BuTinah	119	113	102	89	62	21	0
Mean	127	114	103	91	60	27	0

determinant whether bleaching occurs or not, rather than the maximum temperatures.

Although local variability is obvious in our dataset and has been demonstrated from many regions (Berkelmans 2002a, 2009; Manzello et al. 2007), we also evaluated a mean bleaching curve, which takes the average of the observations at Bu Tinah and Fasht el Hurabi. These mean values would suggest that, as a rule of thumb, Gulf corals are likely to bleach if they are exposed to more than 3 weeks at daily mean temperatures at or above 35°C and between 8 and 9 weeks at or above 34°C. Such a situation is only likely to occur in hot summers with heat wave conditions.

6.6 Discussion

Bleaching thresholds in the Gulf are the highest recorded in the world, and far exceed those recorded from the Great Barrier Reef (Berkelmans 2002a, 2009), Galapagos (Podesta and Glynn 1997, 2001) and Caribbean (Manzello et al. 2007; Baker et al. 2008). This is clearly selected by the Gulf being in summer maybe the hottest place on earth supporting significant coral growth (Fig. 6.3) forcing Gulf corals to have higher absolute temperature tolerance than anywhere else. Daily maximum temperatures survived by corals in lagoons in American Samoa can exceed 34°C (Birkeland et al. 2009), however, only on an hourly basis, while in the

Gulf daily mean temperatures, peaking sometimes above 36°C, can be above 34°C for over a month. From nowhere else have similar long-term warm temperature extremes been recorded. On Australia's Great Barrier Reef and in the Caribbean, bleaching thresholds are mostly anchored around maximum temperatures ~30°C.

While we fully appreciate that much local variability exists with regard to the onset of bleaching, and this is also shown in our dataset (Figs. 6.5 and 6.6), we nonetheless find a mean bleaching curve, as we show in Fig. 6.8, very instructive. It suggests that a severe Gulf bleaching event of the type that causes severe *Acropora* die back, as treated in Chap. 5, requires about 3 weeks of exposure to >35°C average daily temperatures. This agrees with findings of Riegl (2002) for the 1996 and 1998 *Acropora* mass mortalities. Our findings also correspond well with those of Manzello et al. (2007) who found that a combination of maximum SST, and the number of days spent above a certain threshold (30.5°C in the Caribbean, 35°C in the Gulf) are the most significant determinants for the onset of a bleaching event.

By varying parameter s in Eq. 6.1 (methods section), we can obtain some insight into the temperature loading required for milder bleaching to develop (Fig. 6.9). These results would suggest that, given previous heat-stress accumulation, about 1 week of average daily temperature means above 35°C will cause mild symptoms of bleaching, while about 3 weeks of exposure will cause a severe bleaching event.

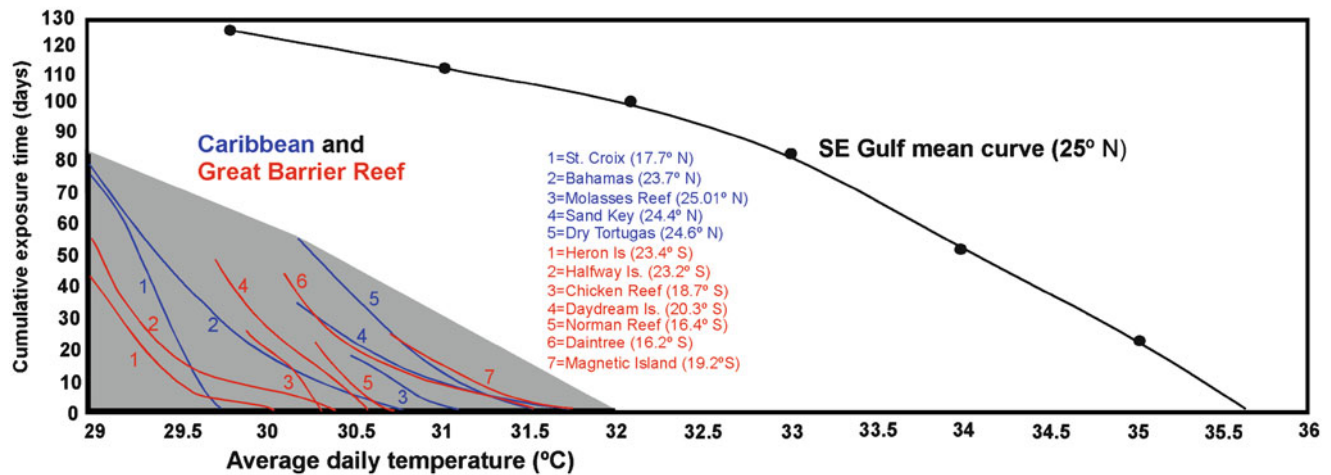


Fig. 6.8 Bleaching thresholds derived for a variety of Caribbean and Great Barrier Reef locations by Berkelmans (2002a, b) and Manzello et al. (2007) compared to the mean bleaching threshold from the SE Gulf.

The overall tolerance envelope for the comparative areas is shown in grey. The differential between the curve and the bleaching threshold is directly related to the physiological capability of corals to adapt to heat

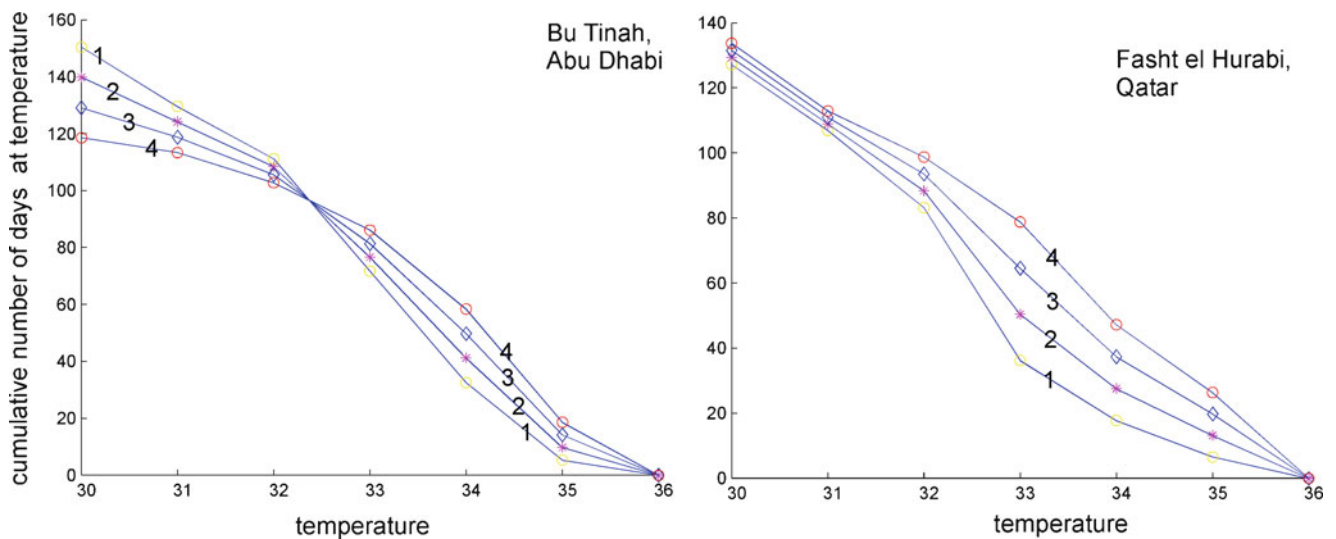


Fig. 6.9 Theoretical bleaching curves derived from Berkelmans' (2002b) equation if the bleaching severity is altered while all other parameters are held equal. The value on the curve is parameter s of equation 6.1

While local differences exist with regards to stress-loading at lower temperatures (30–32°C), the pattern is very similar at the higher temperatures (33–35°C) that are responsible for the onset of bleaching (Berkelmans 2009). Thus, Gulf corals can support approximately 5°C more heat than their relatives on the Great Barrier Reef and in the Caribbean.

We also followed Berkelmans (2009) in developing mortality curves (Table 6.2). We find that in the Gulf, mortality thresholds are close to the bleaching threshold (Table 6.2) but still exceed those known from any other region. Gulf corals are probably the most robust corals anywhere in the world with regards to bleaching, and mortality from bleaching.

The question arises whether the observed very high bleaching thresholds are already the result of acclimatization in response to rapidly recurring heat events (Maynard et al. 2008a, b; Riegl and Purkis 2009; Chap. 5). Riegl (2003) observed during the 2002 bleaching event that *Acropora*, which during the 1996 and 1998 events had bleached prior to and suffered more mortality than other taxa, locally (at Sir Abu Nuair) bleached later and to a lesser extent than other corals. Maynard et al. (2008a) observed that bleaching events indeed can lead to increased thermal tolerance. This may suggest a phenotypic shift in bleaching resistance in the surviving Gulf coral population. Temperatures in the Gulf region are indeed getting warmer and atmospheric temperatures in the region show more, and more closely

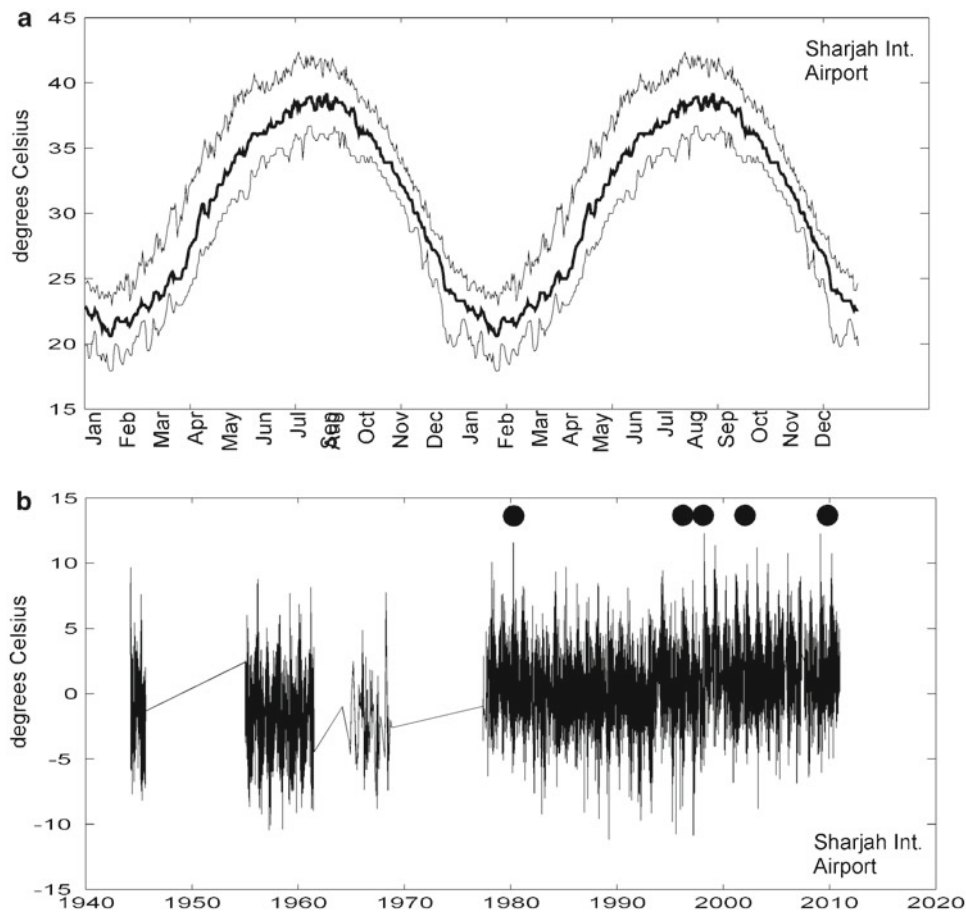


Fig. 6.10 Air temperatures measured at Sharjah International Airport ($25^{\circ}19'N$, $55^{\circ}30'E$). (a) Two mean annual temperature cycles based on the record from 1940 to 2010. Values are mean, 17% and 83% percentiles. (b) Anomalies with respect to the

annual cycle in (a). Known bleaching and coral mortality events (Purkis and Riegl 2005; Riegl and Purkis 2009, Chap. 5) are shown by *black dots*. Another local bleaching event occurred in Abu Dhabi in 2011.

spaced, positive anomalies since the 1980s. This has been interpreted as a global warming signature (Nasrallah et al. 2004; Al-Rashidi et al. 2009) and may therefore have contributed to raising bleaching thresholds over the past decade due to selection caused by closely-spaced bleaching events (Fig. 6.10).

The remarkable temperature tolerance of Gulf corals suggests that coral physiology is indeed capable of adapting to high temperatures and that some hope may exist that coral adaptation can track continuously increasing temperatures. If corals are not subjected to a host of other stressors, reasonable hope may exist that at least a subset of today's coral fauna may adapt to a heated world.

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Diseases, Harmful Algae Blooms (HABs) and Their Effects on Gulf Coral Populations and Communities

7

Bernhard M. Riegl, Andrew W. Bruckner,
Kaveh Samimi-Namin, and Sam J. Purkis

7.1 Introduction

Corals in the Gulf exist in a harsh environment, which only allows a small subset of the typical Indo-Pacific fauna and flora to persist and/or form viable populations (Sheppard and Sheppard 1991; Sheppard et al. 1992; Samimi-Namin and van Ofwegen 2009; Chaps. 11 and 12). Environmental factors have been identified as the major killers of corals and these factors regulate population dynamics and coral reef community structure (Chaps. 2, 5, 10 and 16). Among these, extreme temperature variability, salinity variability and turbidity (as a result of coastal construction, Chap. 16) have been isolated as prime killers.

However, a host of biological agents are also capable of wreaking havoc on coral populations. In the Gulf, several of the major invertebrate nemeses of corals that exist in the Indian Ocean are absent. The crown-of-thorns starfish (COTS) *Acanthaster planci* has only ever been reported in two individuals from a single locality in Iran (Price and Rezai 1996), although this may be changing as COTS appear to be spreading from the Gulf of Oman into the Gulf, with new records from the Musandam Peninsula near the Straits of Hormuz (Mendonça et al. 2010). Furthermore, the coralivorous snail *Drupella cornus*, that can form equally devastating outbreaks, does not occur and the

local *Coralliophila* spp. have not yet been reported to cause significant impacts on corals by predation as they do, for example, in the Caribbean.

Other biological agents do however take a significant toll on Gulf corals. In particular, coral diseases are one of the most destructive agents responsible for recent losses of coral. The Gulf harbors a unique disease, Arabian Yellow Band (AYB) that has a different dynamics from diseases with similar names observed elsewhere. Three other diseases have also been described (Riegl 2002; Benzoni et al. 2010; Samimi-Namin et al. 2010), and several uncharacterized syndromes are also known. While some diseases have been observed to be unusually common and have unusual dynamics (Riegl 2002), the 2010 bleaching event in the SE Gulf appears to have triggered locally significant outbreaks of a white syndrome that has taken a significant toll on UAE coral populations, similar to such phenomena in the Caribbean and Pacific (Bruno et al. 2007; Brandt and McManus 2009; Eakin et al. 2010; Bruckner and Hill 2009).

Highly destructible biological agents are Harmful Algae Blooms (HABs, or also called Red Tides) that have caused significant mortality lately both inside the Gulf (Samimi-Namin et al. 2010) and the Arabian Sea (Bauman et al. 2010; Foster et al. 2011). HABs have been occurring in all parts of the Gulf but appear to become more frequent, more lethal and more widespread, which is causing concern for reefs (Sheppard et al. 2010; Chap. 16).

This chapter describes the known coral diseases from the Gulf (Fig. 7.1) and explores their dynamics using simple mathematical models of the SIR (susceptible-infected-recovered) type (Anderson and May 1979; Mena-Lorca and Hethcote 1992). We explore the role of coral diseases in regulating populations of reef building corals and why some diseases are more frequent and persistent than others. Based on the outcomes of the models, we are able to speculate why, with increased ocean warming due to climate change (Sheppard and Loughland 2002) diseases have become more frequent and may become important agents that determine

B.M. Riegl (✉) • S.J. Purkis
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu; purkis@nova.edu

A.W. Bruckner
Khaled bin Sultan Living Oceans Foundation, Landover, MD, USA
e-mail: Bruckner@livingoceansfoundation.org

K. Samimi-Namin
Netherlands Centre for Biodiversity Naturalis, PO Box 9517,
2300 RA Leiden, The Netherlands
e-mail: kaveh_s_n@yahoo.com; kaveh.samimi@ncbnaturalis.nl

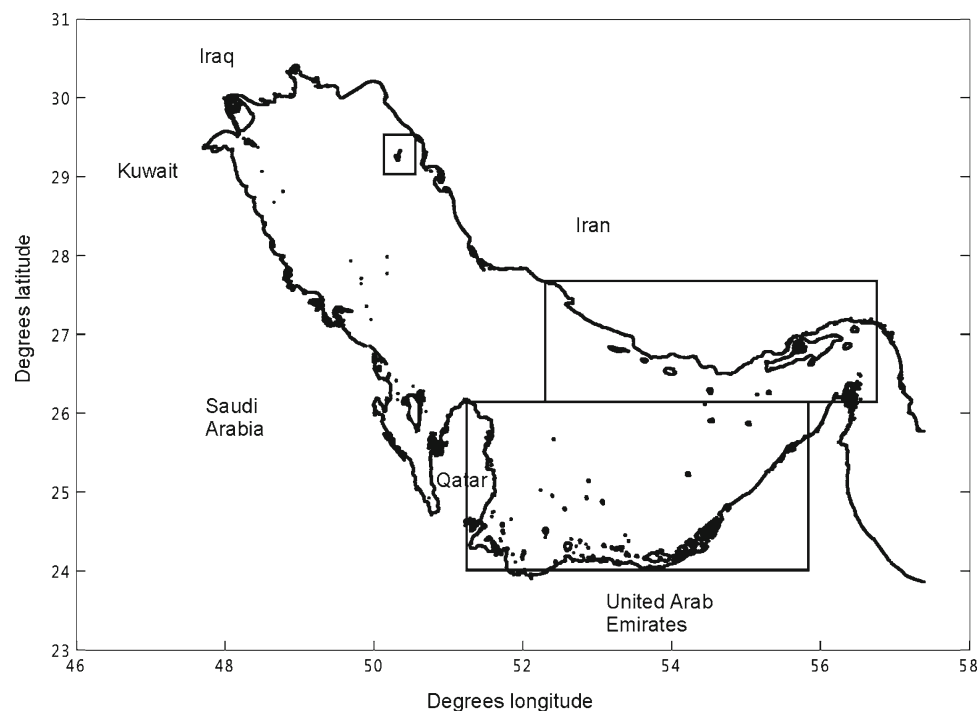


Fig. 7.1 Data for the present article were collected in the boxed area and concentrated on Iran, Qatar and the United Arab Emirates

future coral population structure and community dynamics much like the role of environmental stresses on reefs in the past. This chapter also discusses Harmful Algae Blooms and their importance in coral mortality dynamics in the Gulf.

7.2 Coral Diseases – Description and Etiology

Coral reef diseases occur globally, in most reef habitats and in most locations including reefs near human population centers and remote offshore locations. They generally affect a low proportion of the susceptible species, although localized outbreaks have produced significant mortalities to scleractinian corals, gorgonians, sea urchins, reef fish, sponges, algae and other coral reef organisms (Peters 1993; Harvell et al. 2001; Williams and Bunkley-Williams 2000). While coral reef diseases have not yet received much attention in the Gulf, diseases have been reported from other locations since the early 1970s (Antonius 1988). These first disease epizootics were reported as early as 1978 from the Caribbean and over the next two decades they caused large die-offs of two of the dominant structure forming corals, *Acropora palmata* and *A. cervicornis* (Bruckner 2003). Between 1982 and 1984, a disease of unknown cause spread throughout the western Atlantic, decimating populations of a keystone species, the herbivorous sea urchin, *Diadema antillarum*. These mortality events triggered massive increases in fleshy macroalgae and concurrent losses of coral cover, biodiversity and habitat in

many locations (Lessios et al. 1984; Hughes 1994). There are now over 30 named diseases in the Caribbean basin affecting 45 zooxanthellate scleractinian corals, 3 hydrozoan corals, 10 octocorals, 2 zoanthids, 9 sponges and 2 crustose coralline algae (Green and Bruckner 2000; Weil 2004; Bruckner 2009a, b, c). In contrast, there are only four types of coral disease known from the Gulf. While an unprecedented increase in disease has been documented in the Caribbean, much less is known about the status of disease in the Indo-Pacific and, in particular, the Gulf region.

Increasing discovery of diseases throughout many reefs of the world may suggest a rapid emergence and/or discovery of diseases, although there remain critical information gaps (Bruckner 2002). For example, current research has highlighted potentially important linkages between climate warming and disease, with thermal anomalies and bleaching events being followed immediately by outbreaks of disease (Miller et al. 2006; Miller et al. 2009; Bruckner and Hill 2009). This situation could also be confirmed for the Gulf after the 2010 bleaching event (Riegl and Purkis, personal observation). Changing environmental conditions could affect the coral holobiont, including the ability of the coral host to fight infection, and the virulence of potential pathogens (Rosenberg and Ben-Haim 2002). Pollution, including nutrient loading, sedimentation and other anthropogenic stressors could further reduce the health of the coral community, causing a disruption in the symbiosis with zooxanthellae, altering the composition and virulence of the microbial community

found in the surface mucopolysaccharide layer of the coral polyp, and reducing the resistance of the coral to pathogenic organisms. The prevalence of coral diseases has been found to correlate with ocean heat and coral disease outbreaks in the aftermath of bleaching events have been widely reported (Bruno et al. 2007; Brandt and McManus 2009).

Between 1972 and 2005 coral diseases were reported on 39 genera and 148 species worldwide, with disease observations in 63 countries (Bruckner 2009b). Although Pacific reefs exhibit a much higher diversity of reef-building corals relative to the Atlantic, and they constitute about 92% of the world's coral reefs (Spalding and Greenfell 1997), only 14% of the global observations of coral disease were from the Red Sea and Indo-Pacific (Green and Bruckner 2000; Sutherland et al. 2004; Bruckner 2009a, b, c). In the Gulf and the Arabian Sea, coral diseases are not rare and outbreaks and dynamics have been noted (Coles 1994; Korrrubel and Riegl 1998; Riegl 2002), but to date, little systematic or quantitative ecological work has been undertaken.

7.2.1 Yellow Band Disease

The term “Yellow Band Disease” describes a coral disease that primarily affects faviids in the Caribbean and Indo-Pacific, and *Porites* and *Acropora* in the Gulf (Fig. 7.2). In general, the term “YBD” appears to have been first used in 1994 in Florida (although not published as such) and corals manifesting similar signs have been observed and reported using different names in the past, including ring bleaching in the 1970s, yellow pox, yellow blotch disease and yellow band/blotch (Bruckner 2009a). Nomenclature developed by the Coral Disease and Health Consortium, and published in the Coral Disease Handbook (Raymundo et al. 2008), recommended the terminology Caribbean Yellow Band Disease (CYBD) for this condition in the western Atlantic. This is differentiated from a similar condition in the Pacific, termed Pacific Yellow Band Disease (PYBD). Arabian Yellow Band Disease (AYBD) was first described by Korrrubel and Riegl (1998) from Dubai. Arabian YBD shows important differences from both CYBD and PYBD in gross appearance, patterns of spread and coral species susceptibility. Arabian YBD is an aggressive affliction that is very fast-spreading on *Acropora* and slower-spreading, but persistent on *Porites*. In contrast, CYBD only affects faviid corals and is characterized by very slow rates of tissue loss (1–2 cm per month). Lesions originate at the margins of colonies or they form focal lesions that are completely surrounded by normal tissue having normal appearance. Affected tissue is pale to lemon yellow in coloration, in contrast to surrounding dark green or brown tissue associated with AYBD. Over time, tissue first affected by CYBD becomes darker and

dies, and the pale yellow band of blotch slowly expands outward, advancing across the colony. Rates of tissue loss from AYBD average 1–2 cm/week, while CYBD advances by only 1 cm/month or less in the Caribbean. Unless the coral is rapidly killed (which can be the case in Gulf *Acropora*), infections from both diseases may remain active for 5–10 years or more. The greatest rate and extent of tissue loss from AYBD occurs in summer, which is also observed in CYBD (Bruckner and Bruckner 2006a; Ballantine et al. 2008).

In Caribbean, Pacific and Arabian YBD, centers of infection generally coalesce with other bands as the patches of exposed skeleton increase in size, eventually killing the coral. Environmental drivers of these diseases are incompletely characterized, although infections have been reported to emerge as colonies began recovering from bleaching (Bruckner 2009a). There is some evidence from the Indo-Pacific suggesting that YBD is a disease of zooxanthellae associated with four species of *Vibrio* bacteria (Cervino et al. 2001, 2008). In some cases, the band may be associated with a microbial mat, including cyanobacteria.

YBD has been a common affliction in the Gulf and the Arabian Sea and has reached epizootic proportions over the last decade in the Caribbean, where it is devastating populations of the major framework corals in the genus *Montastraea* (Bruckner and Bruckner 2006a, b; Bruckner and Hill 2009). Similar disease signs are reported for *Diploastrea*, a faviid from Indo-Pacific reefs.

AYBD is a common affliction of corals observed throughout the Gulf and also in the northern Arabian Sea. It was first reported in 1998 from reefs near Jebel Ali in Dubai, United Arab Emirates (Korrrubel and Riegl 1998). So far, there have been no published reports of AYBD from outside the Gulf region, although a single case was observed on *Acropora* on the Yanbu barrier reef in the Saudi Arabian Red Sea in 2008 (Bruckner, personal observation). The following species have so far been confirmed as affected: *Acropora downingi*, *A. clathrata*, *A. pharaonis*, *A. valida*, *Porites lutea*, *P. lobata*, *P. harrisoni*, *Turbinariareniformis*, *Cyphastreamicrophthalma*. Four other taxa of corals have also been reported with this condition in the Indo-Pacific (Sutherland et al. 2004). The disease is active in all seasons, which is in contrast to black band disease which, in the Arabian region, almost completely disappears in winter. Infections progress faster in summer (~2 cm per week) than in winter (~1 cm per week). It is the most common disease on corals in the Gulf, but rapidly decreases in importance outside the Gulf.

AYBD forms a bright yellow band of one to several cm in diameter at the interface of healthy and dead coral. In *Acropora*, it is well-developed and defined, forming a band up to a few centimeters in width. In *Porites*, it can either be a band (on the finger-like protuberances of *Porites harrisoni*) or a large yellow, greenish blotch on massive *Porites*,

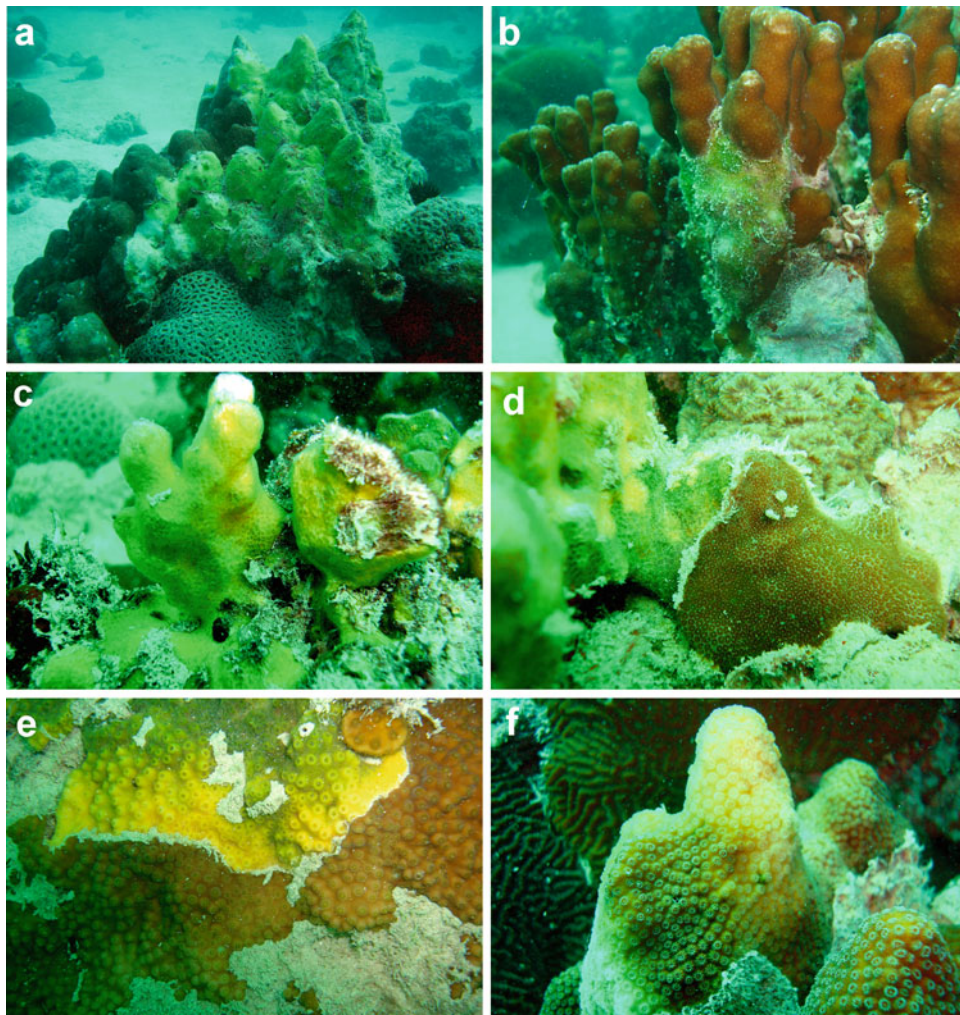


Fig. 7.2 Yellow Band Disease on massive corals: (a) *Porites lutea*; (b) *Porites harrisoni*; (c) *Porites harrisoni* entirely killed by YBD (Oct. 2009, Abu Dhabi); (d) *Porites lutea* (Abu Dhabi, May 2008);

(e) *Turbinaria reniformis* (Abu Dhabi, May 2008); (f) *Cyphastrea microphthalma* (Abu Dhabi, October 2008)

depending on location. The band migrates across the coral, producing a margin of decaying tissue adjacent to healthy tissue and leaving behind dead skeleton that may retain a yellow pigmentation, remain greenly discolored (particularly in the genus *Porites*) or, in *Acropora*, is usually pure white. The yellow band is raised above the surrounding tissue and appears often to have a thin mucous envelope (it can look “puffy”); affected tissue is slimy to the touch. No filaments are visible (as in the black band), rather it appears completely homogeneous.

The AYBD seems to also have an inactive stage with different gross visible signs. Once the advance of AYBD stops and recent tissue loss is no longer apparent, the exposed skeleton may retain a green coloration; tissue immediately adjacent to the lesion has clearly stopped to die back and can even begin to lay down new skeleton to reclaim the lost area. This situation is commonly observed on *Porites harrisoni*

and *Porites nodifera*. It is rarely observed in *Acropora*, which tend to be completely killed by AYBD once affected.

On *Acropora*, progress of the disease band is rapid (up to 2 cm per week in the warm season). The disease frequently initiates at the center of the colony (potentially being spread through damsel- or butterfly fish bites) and spreads outwards (Fig. 7.3). Once afflicted, the entire colony dies. Whenever adjacent colonies are in tissue-contact (as is frequently the case in dense *Acropora* thickets), the disease passes seemingly unhindered from one colony to the next. It only appears to stop where physical contact among colonies is broken.

No work to identify possible etiologic agents or experimental work to characterize linkages with environmental parameters is reported. The disease can be readily transmitted among certain corals, suggesting the presence of a microbial agent as the cause. Placement of an infected colony onto unaffected tissue of a neighboring coral is sufficient to

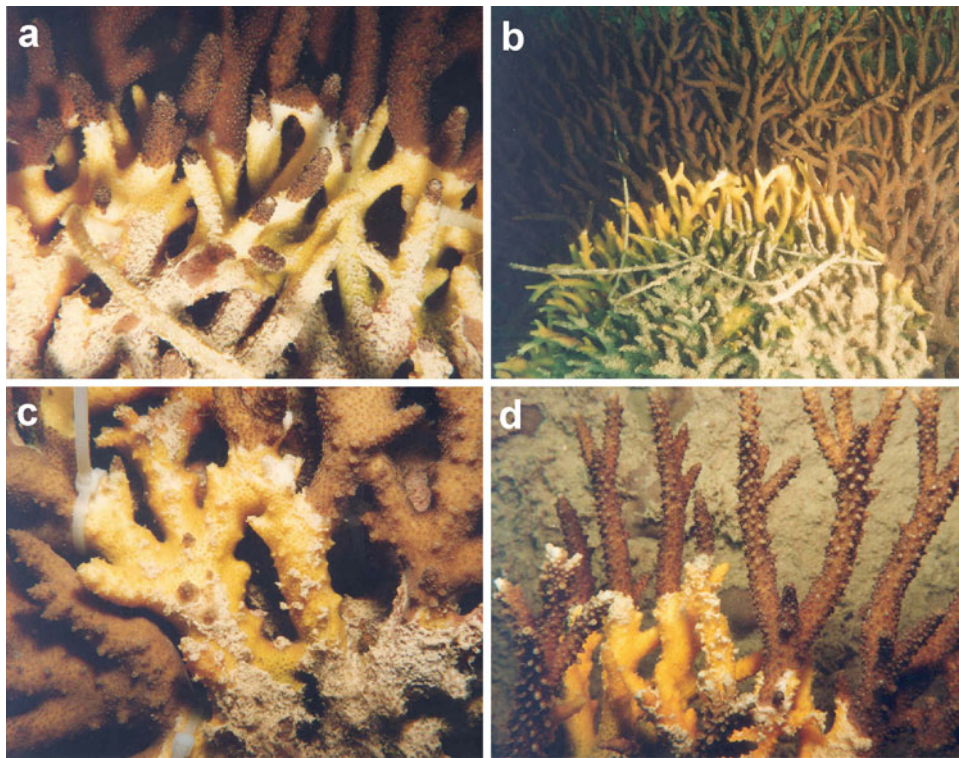


Fig. 7.3 Yellow Band Disease on *Acropora*. (a) *Acropora clathrata*. Cable ties were attached 1 week prior to this photograph being taken. Disease spread was ~2 cm in this week (January 1996, Jebel Ali, Dubai). (b) *Acropora clathrata* colony being killed from the

centre outwards. This is a common pattern (January 1996, Jebel Ali, Dubai). (c) *Acropora downingi* marked to measure spread of YBD (January 1996, Jebel Ali, Dubai) (d) *Acropora pharaonis* (January 1996, Jebel Ali)

transfer and spread the disease. If infected *Acropora* branches are broken off and transplanted, so that an active, yellow band comes in contact with the healthy tissue, then infection usually takes place within a week. When inactive yellow bands (i.e. the dead but greenish stain) were placed in contact with healthy tissue, successful trans-infection was neither achieved in *Porites* nor *Acropora*. The spread of the disease can be stopped by creating a “disease break” by removing all live tissue adjacent to the yellow band. Removal of tissue either by water jet, breaking of *Acropora* branches or chiseling away sections of *Porites* tissue plus skeleton was equally successful.

The term “Yellow Band Disease” has been used to describe coral diseases from different regions and likely include conditions that are not necessarily caused by the same etiologic agent. Cervino et al. (2001) indicate that yellow band has been around for a long time, with the first reports by Dustan in the 1970s using a different name (ring bleaching). Yellow blotch disease and yellow band/blotch disease have been used interchangeably with YBD in publications about Caribbean YBD. While Cervino et al. (2008) compare Indo-Pacific YBD with Caribbean YBD, linkages between these two conditions are not fully understood. Gross signs of YBD on faviid corals from the Caribbean are similar to YBD on

Diploastrea spp. However, gross signs on *Fungia* spp. are different, but similar etiologic agents have been observed among all tested species (Cervino et al. 2008). Four *Vibrio* species (*V. rotiferianus*, *V. harveyi*, *V. alginolyticus* and *V. proteolyticus*) have been isolated from YBD tissue in the Caribbean genus *Montastraea* and the Indo-Pacific genera *Diploastrea* and *Fungia*. Cervino et al. (2008) noted that the consortium attacks zooxanthellae within gastrodermal tissues, causing degenerated and deformed organelles and reduced photosynthetic pigments. Zooxanthellae from infected corals also had decreased cell division compared with zooxanthellae from the healthy corals. At present, it is not known whether the AYBD indeed belongs into the same group of diseases.

7.2.2 Black Band Disease

This is the oldest known coral disease and was originally described from the Caribbean (Antonius 1988), and subsequently found in all oceans (Antonius 1985). The name stems from the microbial consortium formed at the interface of healthy and diseased tissue, which is dominated by a filamentous cyanobacterium that retains a black to reddish

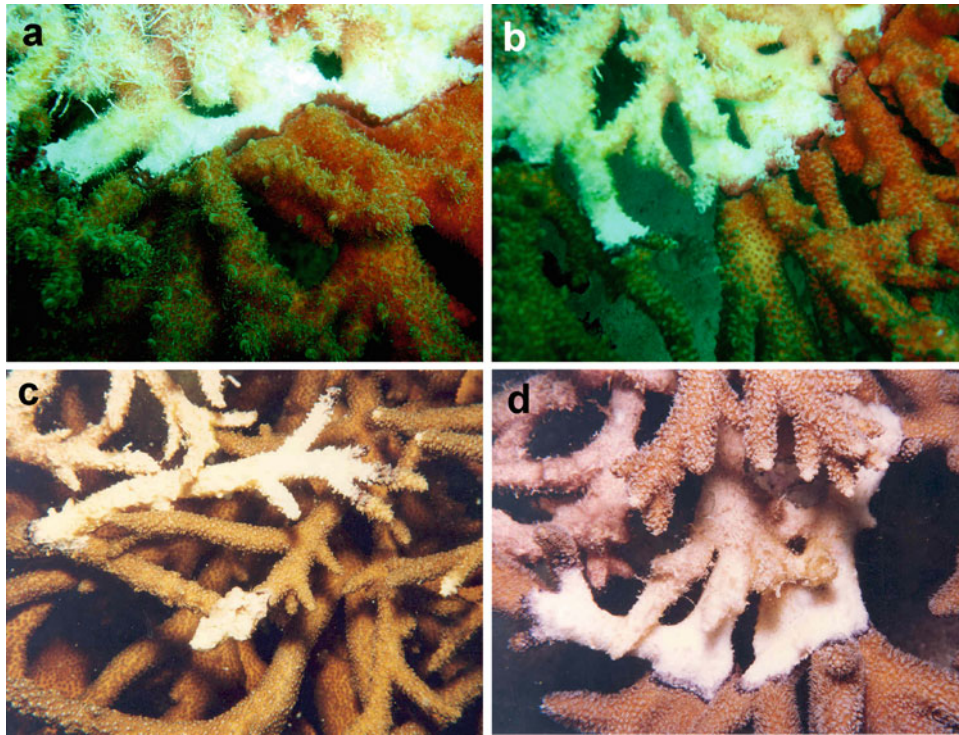


Fig. 7.4 Black Band Disease is relatively rare in the Gulf and has so far only been described from *Acropora* (a), (b) BBD on *Acropora downingi* in September 2009 in Abu Dhabi (Ras Ghanada), (c) on

Acropora clathrata in September 1995, (d) on *Acropora downingi* in October 1995 in Dubai (Jebel Ali)

black pigmentation. BBD is global in distribution. Throughout its range in the Indian and Pacific Oceans, and so also in the Gulf, this disease primarily affects *Acropora*. In the western Atlantic it has been identified on 25 scleractinian corals, 6 branching gorgonians and sea fans but not on *Acropora* spp. (Green and Bruckner 2000). BBD generally affects a low percentage of corals (<1%) at the community level (Edmunds 1991; Kuta and Richardson 1996; Bruckner et al. 1997), but it occurs in most reef environments, and localized epizootics have been observed in the USVI, Jamaica, Florida and Puerto Rico (Peters 1984; Bruckner and Bruckner 1997; Bruckner 1999; Bruckner 2002) and in 2011 in Abu Dhabi. The disease may exhibit a clumped distribution (Kuta and Richardson 1996; Bruckner et al. 1997), affecting up to ten corals within a 2 m radius area (Peters 1984). A greater percentage of the corals may be affected by BBD in areas with high coral cover, and in habitats with a high density of colonies or dominance by susceptible species, and also in areas with unusually clear water (Bruckner 1999). BBD shows similar dynamics in Arabia, although the target species differ (Fig. 7.4). It is a moderately aggressive affliction that is fast-spreading on *Acropora* and also occurs on other coral genera. Affected tissue is covered by a thick, well-defined black band of cyanobacteria and other microorganisms; the band frequently starts in the center of an *Acropora* colony or the tops of faviid colonies and slowly expands outward, as the tissue affected

dies. Rates of tissue loss have not been ascertained, but are slower than in YBD. In the Gulf, BBD advances with greatest rate and extent of tissue loss occurring in summer. It becomes rare, or disappears completely, in winter (Riegl 2002). There also seems to be some density dependence in its occurrence, since the disease became rarer after the 1996 *Acropora* mass mortality. This decrease in frequency could have been a result of the disease's preferred host (*Acropora* spp.) having virtually disappeared from the area, or a reaction to the generally decreased coral frequency with resultant lessened opportunity for infection. More than one center of infection can occur on a single colony and they can coalesce with other bands as exposed skeleton increases in size, eventually killing the coral. Environmental drivers of the disease are incompletely characterized, but Antonius (1985) found increasing prevalence near a phosphate terminal.

In the Gulf, the following species have so far been confirmed as affected: *Acropora downingi*, *A. clathrata*, *A. pharaonis*, *A. valida*, *Favia pallida*, *F. speciosa*, *Platygyra daedalea*, *P. lamellina*, *Cyphastraea microphthalmia*. It is not unlikely that the disease is as species-unspecific as it is in other regions and that more thorough search in future will reveal more dynamics than is presently known. BBD has not been reported from the Arabian Sea but likely occurs there.

In the Caribbean, BBD typically advances at rates of about 3 mm/day (Rützler et al. 1983), and occasionally increases to

a maximum of 1 cm/day (Antonius 1981). Considerable variation in spreading rates is observed over the duration of individual infections (Rützler et al. 1983) and also between species, depths, seasons and locations (Bruckner 1999, 2002). BBD occurs year round on tropical Caribbean reefs, while infections often disappear in winter months in Florida and other northern reefs, such as the Gulf, when temperatures decline below 20°C. BBD can kill small (<50 cm²) corals in several days while larger corals experience partial mortality before signs of BBD disappear (Bruckner 2002). However, BBD may reappear later that season or the following year, and individual colonies can be affected by BBD for multiple years (Feingold 1988; Kuta and Richardson 1996; Bruckner and Bruckner 1997). While BBD does not appear to have caused large die-offs of important reef-building corals, individual colonies lose substantial amounts of tissue that may affect their reproductive potential or their ability to resist other stresses (Edmunds 1991). Kuta and Richardson (1996) noted that corals continue to lose tissue after signs of BBD disappear. In the Gulf, the first major BBD epidemic was observed in 2011, as a consequence of that year's bleaching event.

7.2.3 White Syndromes

Since the first report of White Band Disease (WBD) by Antonius (1985) in the Red Sea and Indo-Pacific, corals with similar disease signs have been reported from throughout the Pacific and Indian Oceans using a highly varied terminology including WBD, white plague, plague-like and white syndrome (Sutherland et al. 2004; Willis et al. 2004; Bruckner 2009b). Because gross signs of these conditions are similar, and they can be readily confused by mortality from other biotic agents including predation by COTS and *Drupella*, differentiation of the various types can be difficult. The term "White Syndrome" was first used in the Red Sea in 1996 and Australia in 2001. In the Gulf, syndromes that resemble these conditions are becoming increasingly common.

WBD, which was first documented on corals from the Red Sea off Saudi Arabia and Egypt in 1981, and the Philippines also in 1981 (Antonius 1985), shares many similarities with regards to species affected and patterns of tissue loss in the Gulf. Antonius (1981, 1985) reported WBD in the Red Sea on 17 genera and 31 species of corals, including 11 acroporids (Egypt, Saudi Arabia) and 22 species (13 genera) in the Philippines, including two hitherto unrecorded genera (*Montipora* and *Podabacia*). Cases were also reported over the last 10 years in Australia, Egypt, Guam, Oman, UAE, India, Malaysia, Mauritius, Palau, Papua New Guinea and the Philippines (Coles 1994; Riegl 2002). Willis et al. (2004) observed a 20 fold increase in the number of corals affected by white syndrome between 1998 and 2003, infections spread from 75% of the regions and 45% of the reefs in 1998 to all

regions and 89% of the reefs by 2003 (Willis et al. 2004). Also in the SE Gulf, a locally dramatic increase in the frequency of white syndrome has occurred, in particular in the aftermath of the 2010 bleaching event (Figs. 7.5 and 7.6). A disease that is similar to white syndrome and white plague was also reported in a subtropical location (Solitary Islands) off Australia. Six coral genera were affected, with new observations for *Turbinaria* (2 species). Disease incidence in the Gulf and in the Solitary Islands varied throughout the year and was lowest in winter. This, and disease frequency was comparable to AYBD dynamics in the Gulf (Gulf AYBD: 7%, Solitary Islands WS: 6.2%) and highest in summer (Gulf AYBD: 14%; Solitary Islands WS: 13.6%; Riegl 2002; Dalton and Smith 2006).

WBD was, like BBD, originally described from the Caribbean. It played a dominant role in the precipitous (90–98%) decline of *A. cervicornis* and *A. palmata* populations during the 1980s and 1990s (Bruckner 2002; Aronson and Precht 2001; Gardner et al. 2003). It is the only disease to date that has caused major changes in composition and structure of reefs over large areas of the Caribbean (Green and Bruckner 2000). WBD was first documented on reefs around St. Croix, USVI in 1978, and later throughout the Caribbean. During the 1980s, the prevalence of WBD varied from 1–2% to 26% in the British Virgin Islands (Davis et al. 1986), up to 33% in Parguera, Puerto Rico (Goenaga and Boulon 1992), 40% in Florida and Belize (Antonius 1981), 64% in the USVI (Gladfelter et al. 1977) and as high as 80% in Jamaica and the Netherlands Antilles (Rogers 1985). It has been described from the Gulf (Riegl 2002) where, like in the Caribbean it occurs on most coral species but seems to affect some more severely. These unfortunately appear in both cases to be the dominant frame-builders (*Acropora* spp. and *Porites harrisoni* in the Gulf, and *Acropora* in the Caribbean).

7.2.4 Pink Spots and Pink Line Disease

Originally described from the Indo-Pacific, discolored tissue on acroporids that manifest as pink bands, spots or blotches have received some attention in the Gulf (Benzoni et al. 2010). Abnormal pigmentation in *Porites* characterized by circular spots, irregular blotches, lines, rings with a pink coloration can occur in response to physical and/or pathogenic stress, including fish bites, parasite infections, burrowing or boring invertebrates, and microorganisms (Ravindran et al. 2001; Ravindran and Raghukumar 2002; Willis et al. 2004; Raymundo et al. 2008). For example, pink, swollen nodules can occur on the coral colony as a reaction to trematode infections (Aeby 2003), to physical and chemical changes due to cyanobacteria (Ravindran and Raghukumar 2006), and to mechanical/chemical stress caused by barnacle larvae

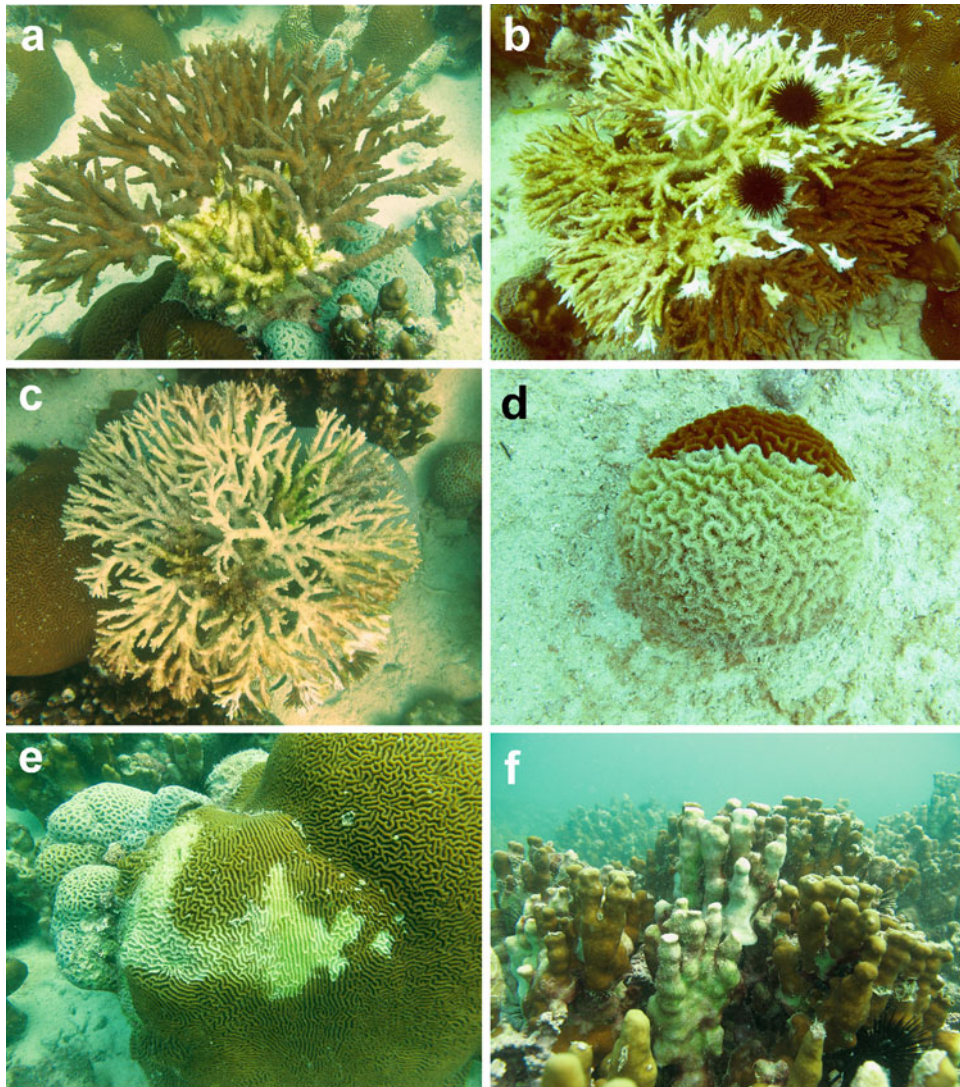


Fig. 7.5 White syndromes in the immediate aftermath of the 2010 bleaching event. (a, b, c) *Acropora clathrata* in various stages of infection. Images were taken about 1 month after the end of the thermal anomaly. Disease spread in colony (c), which has only remnant live tissues at its tips, was ~5c per week. (d) *Platygyra daedalea*

mostly killed by a *white syndrome*. (e) In this *Platygyra daedalea* it is unclear whether the *white area* is remnant bleaching, or the onset of a *white syndrome*. (f) *Porites harrisoni* convalescing from bleaching (tips in foreground still pale) and ravaged by a *white syndrome* (*white tips* are dead)

(Benzoni et al. 2010). Pink coloration can also be the result of serpulid larvae growing on the surface of *Porites* colonies and causing mechanical and/or chemical irritation. During a catastrophic coral mortality associated with a red tide in the Gulf in 2008–2009 (Samimi-Namin et al. 2010) the pink pigmentation was found on almost all surviving massive *Porites* colonies (Fig. 7.7a). Pink coloration was mainly due to serpulid worms overgrowing the colonies surfaces (Fig. 7.7b–c) but was also observed around barnacles (Fig. 7.7d) and adjacent to recently smothered coral tissues. It is not known whether trematode larvae or cyanobacteria were also associated with these lesions.

The occurrence of pink spots may also be related to other cases of altered pigmentation such as the various dark spot/band diseases that collectively affect 14 species of coral in the Caribbean (Gil-Agudelo et al. 2004; Weil 2004) and several taxa in the Indo-Pacific and Red Sea (Bruckner, personal observation). DSD was first noticed in Colombian reefs in 1992 during a bleaching event (Solano et al. 1993; Garzón-Ferreira and Gil 1998) which is an interesting parallel to the emergence of the pink spots in the Gulf. DSD affected >16% of six species (over 1,545 colonies); the two most abundant species (*Montastraea annularis* and *Siderastrea siderea*) had the highest number

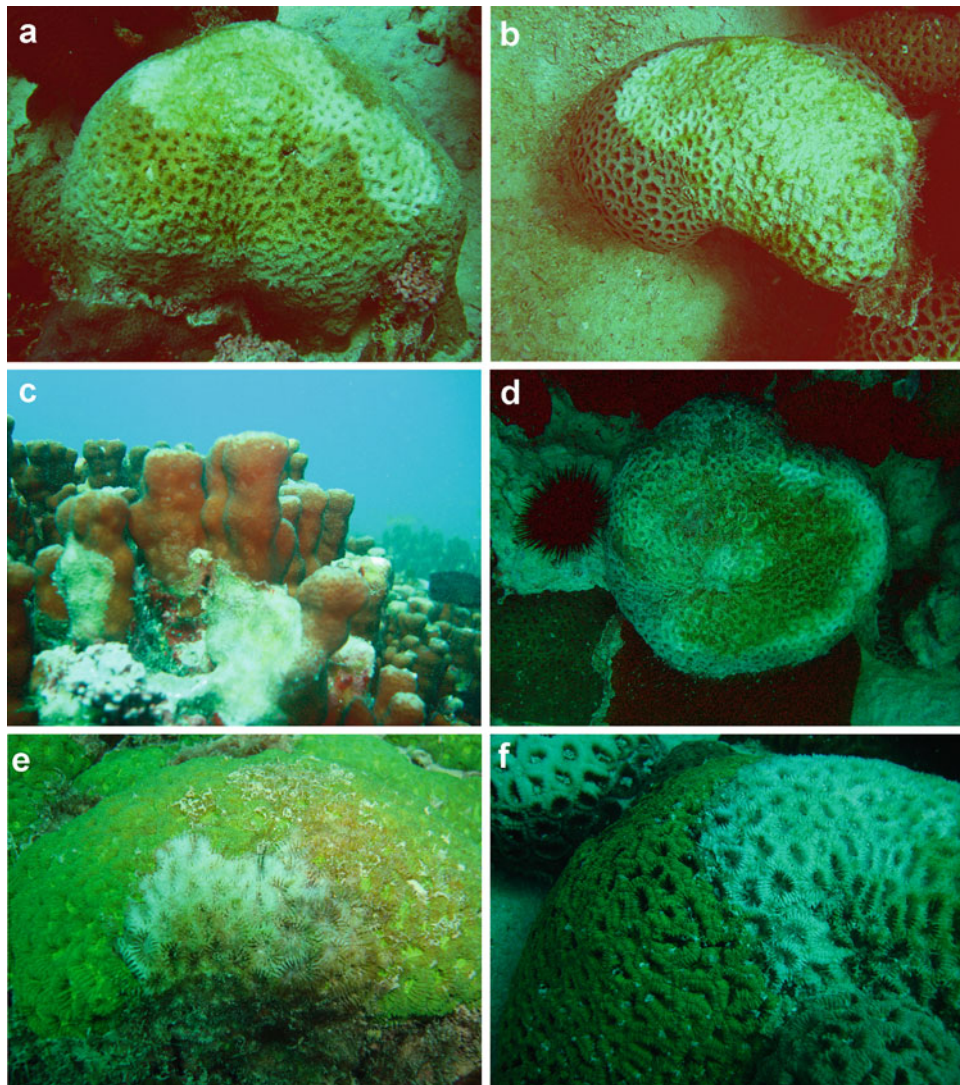


Fig. 7.6 White syndrome prior to the 2010 bleaching event (a, b) *Favia pallida* with tissue necroses from a rapidly-spreading white syndrome (Abu Dhabi, May 2009), (c) either a white syndrome or an unusually pale YBD on *Porites harrisoni* (Abu Dhabi, October 2008), (d, e) *Favia fавus* with slowly-spreading white syndrome, (f) *Favia speciosa* with

rapidly-spreading white syndrome. The speed of spreading can be deduced from the width of the bright white band. Greenish areas are overgrown by algal turf. The wider the white band, the wider the recently denuded area of skeleton and the faster the progression of the disease

of infections (Gil-Agudelo and Garzón-Ferreira 2001). Cervino et al. (2001) reported prevalence rates of 42–56% for *Stephanocoenia intersepta* and *S. siderea* in Bonaire, Turks and Caicos, and Grenada. Gochfeld et al. (2006) reported a mean prevalence of 31.5% on St. Thomas, USVI, 50.3% on Culebra, Puerto Rico, and up to 80% in the Bahamas for *S. siderea*, with the highest incidence during August and sudden declines each year in October. Galloway et al. (2007) and Work and Aeby (2008) suggest DSD to be the result of fungal invasion, while Borger (2005) noted it to be associated with stress, including physical stress like pink spots. Thus, the frequency of pink spots and DSD may be related, but evidence from the Gulf is yet to be forthcoming.

7.2.5 Ciliate Infections

Two other conditions are widely reported from the Indo-Pacific, skeletal eroding band (SEB) and brown band disease (BrBD). Brown band disease is characterized by a brown band of variable width flanked by healthy tissue at the advancing front of the disease, adjacent to live tissue, with exposed white skeleton at the trailing edge (Willis et al. 2004). The band moves in both directions along the branch, destroying coral tissue. Dense populations of ciliates, packed with zooxanthellae from coral cause brown coloration. Skeletal Eroding Band is characterized by masses of black loricae of *Halofolliculina corallasia*, a colonial

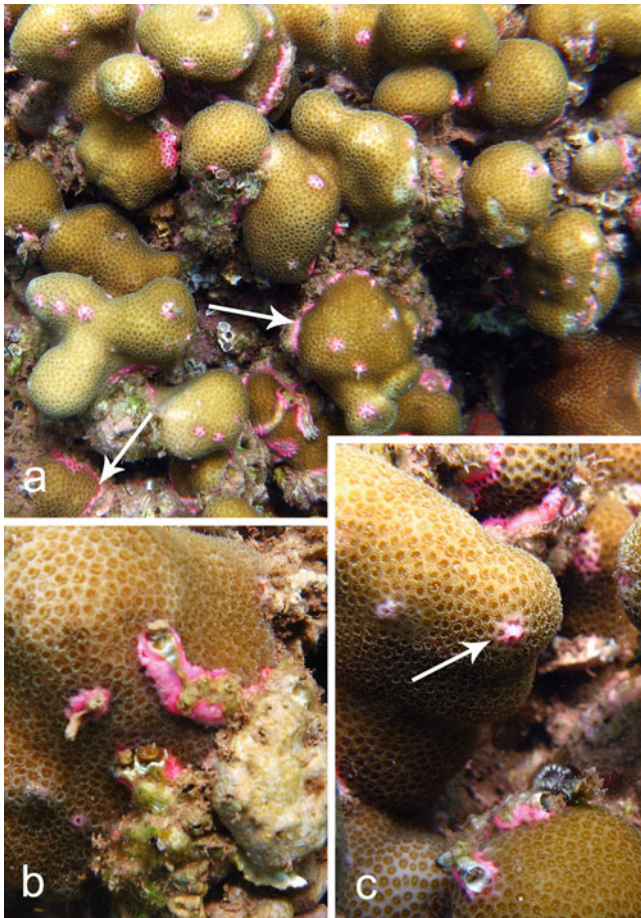


Fig. 7.7 Pink pigmentation on *Porites* colonies at Qeshm and Larak Islands, Iran, at 4 m depth. (a) Pink coloration is always adjacent to tissues recently smothered by serpulid worm overgrowth. (b) Serpulid worms overgrowing *Porites* tissues leads to pink discoloration. (c) Swollen coral tissues around a barnacle aperture

heterotrich ciliate embedded within the skeleton of corals. The ciliates form a front separating live tissue from a white zone of recently denuded skeleton (Antonius 1999; Riegl and Antonius 2003; Winkler et al. 2004). The front advances like BBD, causing progressive tissue loss at rates of up to 1 cm per day; it differs, though, in that it is also associated with skeletal damage from the embedded loricae.

A condition similar to SEB has been reported from the Caribbean, and both SEB and BrBD have been observed in the Red Sea (Antonius 1999; Bruckner, unpublished observation). These conditions both manifest with signs that are similar to BBD in gross appearance, which may explain why they have not been reported from the Gulf (Fig. 7.8). Also, the species susceptible to these conditions in the Indo-Pacific are among the dominant corals in the Gulf. While not yet reported, it is likely that these diseases can also be found in the Gulf.

7.3 Dynamic Models of Coral Diseases

The above review shows clearly that coral diseases are a typical feature of Gulf communities, as indeed of any coral communities in other oceans as well. In the Gulf they vary in their visible impact from almost negligible (BBD), to a regular and/or sometimes common feature (AYB, PS), to worrying epidemics taking a significant toll on local coral populations (WS, BBD, especially in the aftermath of bleaching events, such as in 2010 in the SE Gulf). Since diseases have long been identified as one of the most important regulators of animal populations (Anderson and May 1979), it is worthwhile to examine their dynamics in the Gulf from a theoretical viewpoint.

Simple disease models of the SI or SIR-type divide populations into healthy but susceptible (S) individuals, such that are infected and infectious (I) and such that are recovered and (in some cases) immune (R). SIR models have been used with great success to explain the dynamics of microparasites and hosts (Anderson and May 1979; Edelstein-Keshet 2005). Variations (Pybus et al. 2001; Mena-Lorca and Hethcote 1992; Mangel 2006) shall be used in the following to explore the dynamics of Gulf coral diseases, their effects on population and thus community dynamics and how this may change under climate change.

The distribution and dynamics of Gulf corals is largely defined by the availability of suitable substratum, such as rocky areas of capstone or, in the rare instances where these are available, true reef substrates (Riegl 1999; Purkis and Riegl 2005; Chaps. 2, 3 and 5). Thus, while an upper carrying capacity is set for corals by the environment (Riegl and Purkis 2009; Chap. 5), we can accept their birth rate, i.e. the production of gametes and larvae and presumably also the settlement rate, to be exponential. Population size would then be, if we exclude at the moment competition and space limitations:

$$dN/dt = (b - d)N \quad (7.1)$$

Where b denotes a birth-rate constant, and d is a death rate constant. Net growth rate is then $r = b - d$, leading to exponential growth when $r > 0$, stagnation when $r = 0$, and decline otherwise (which can realistically be achieved by adding competition and space limitations into Eq. 7.1). Corals will settle on all suitable substrata, and grow unfettered until competitive interaction limits their expansion when they come into physical contact with their neighbors (for dynamic expression see Riegl and Purkis 2009, and Chap. 5). Direct physical contact without aggressive reaction is sometimes possible with conspecific or congeneric individuals but rarely with less related individuals.

Fig. 7.8 Diseases that might exist in the Gulf but have so far been overlooked. (a) Brown Spots on *Gardineroseris planulata* in the Saudi Red Sea. (b) Brown Band Disease in *Acropora hemprichi* in the Saudi Red Sea

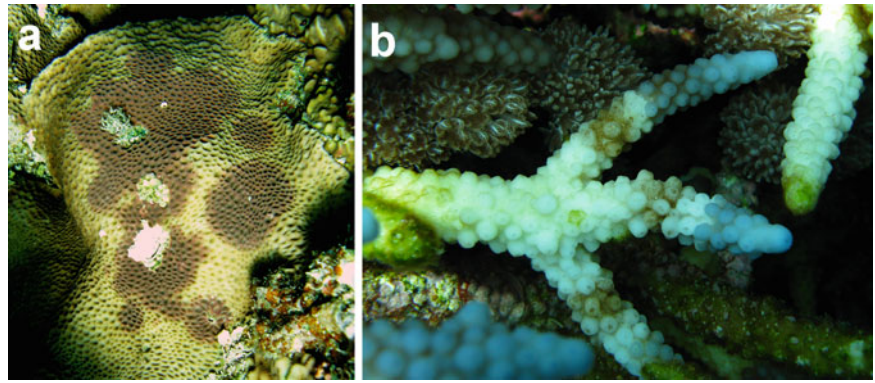


Table 7.1 Observed population parameters for some Gulf diseases and their relevance to persistence or outbreak in a coral population of the size given in column 1 according to the SI model. Densities were standardized to 10,000 corals. *obtained by further decomposition of eq.7.4

	N corals in diseased patch	i proportion of infected corals	β , simple mass action incidence	ν , rate of loss due to death or healing	$\beta - \beta i > \nu?^*$	Disease will spread in coral population
BBD	10,000	0.00001	0.1	0.5	<0.5	No
AYBD	10,000	0.01	0.25	0.3	$0.2475 < 0.3$	Mostly not
WS	10,000	0.5	0.75	0.3	$0.56 > 0.3$	Yes

Thus, especially *Acropora* are capable of forming dense thickets within which branches of adjacent colonies may touch or even intergrow (Fig. 7.8). Disease transmission among individual colonies will occur unhindered across such tissue bridges (personal observation). It will also occur easier among individuals that are closely-spaced than among individuals with greater distances. These observed dynamics suggests that the greater the density of corals susceptible to a diseases, the more frequent will disease transmission occur. If λ is the average number of adequate contacts for disease transmission per unit time, the dependence on density suggests a transmission coefficient β of:

$$\beta = \lambda / N \quad (7.2)$$

The total population N , consists of healthy corals that become infected (S for susceptible colonies), infected ones that can pass the disease on (I for infectious) and such that have not been killed by the disease ($1 - \nu$ corals are killed) and recover (R for recovered), $N = S + I + R$. The rate at which healthy individuals then become infected due to contact with infectious individuals is:

$$I' = \beta SI \quad (7.3)$$

This is known as the simple mass action principle and it assumes that a doubling of N (S , I and R) would also double the per-time unit contact rate λ . This is plausible for the situation in the Gulf: in thickets, more than one coral will be situated close to a diseased coral, so the radially spreading

disease (see Sect. 7.2) could then infect several, instead of just one neighbor in the same unit of time.

It is illustrative to first consider the infective behavior of the diseases in a closed population that only consists of susceptibles (S) and infectious (I), so that $N = S(t) + I(t)$. Infections spread, as outlined above, according to the simple mass action principle (βSI which is, due to the closed population $\beta(N - I)I$) and infected individuals can be lost from the infected pool due to death or healing according to νI . Combined, this gives the equation of infection dynamics:

$$I' = \beta I(N - I) - \nu I \quad (7.4)$$

The similarity to the logistic equation with an additional loss term (analogy to the Schaefer-model of fisheries) is readily visible. Combining linear terms allows us to draw more conclusions. From

$$I' = I(\beta N - \nu) - \beta I^2 \quad (7.5)$$

it can be seen that only if $\beta N > \nu$, can the number of infected increase from their initial value.

We can use this relationship immediately to evaluate how Gulf coral diseases will behave within the community. Table 7.1 shows estimates of β based on field work and published and unpublished data from Korrubel and Riegl (1998) and Riegl (2002), approximate N values based on mapping work by Purkis and Riegl (2005) and population extrapolations by Riegl and Purkis (2009). The values in the table show clearly that BBD at its usual frequency is a rare

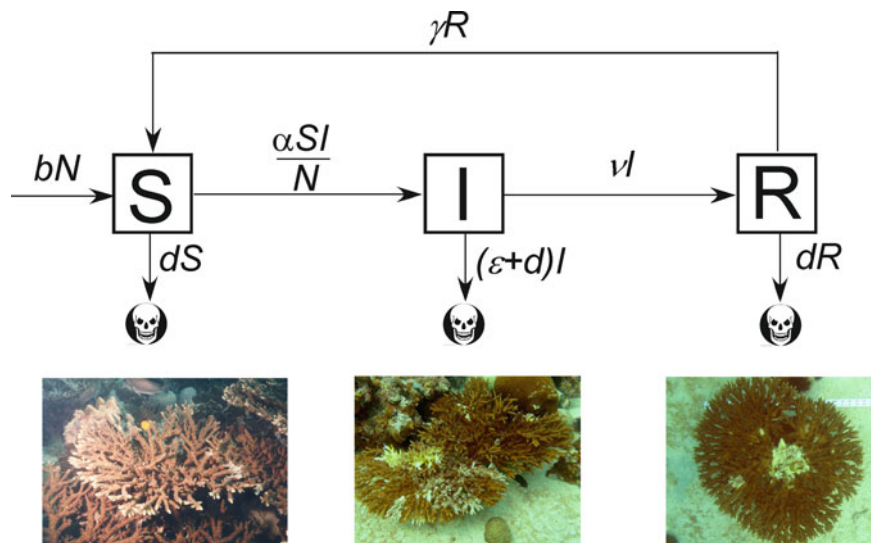


Fig. 7.9 SIRS model of coral diseases in the Gulf. S susceptible population, I infectives, R recovered, d natural mortality, b births, α rate of contacts, n rate of recovery, γ $1-d$, ϵ mortality due to disease, ν rate of infectives becoming resistant ('healing') $N=S+I+R$. *Acropora downingi* is used as model coral. Susceptibles (S) are in particular those corals

that grow in dense thickets where often direct tissue contact occurs between adjacent colonies (image from Jebel Ali, 1995). Infected colonies (I) are such that have contracted the disease and show a front of active tissue loss (image from Abu Dhabi, 2010). Recovered (R) are colonies in which tissue loss has been arrested (image from Abu Dhabi 2010)

disease unlikely to spread and to become more common. Until 2011, it has never been observed at outbreak proportions although it can be common at high coral density (see Eq. 7.3). AYBD, although highly visible, also has not been observed to readily pass to an outbreak (Table 7.1), but in some locally constrained areas, high concentration of infected individuals as well as contagiousness has been observed. Spread to new colonies often only occurs once the originally infected colony has almost completely died, since tissue contact usually only occurs at the periphery of two touching corals. Since AYBD often spreads from the center of coral colonies towards the periphery, contagion often does not increase the number of infected individuals since the originally infected colony dies shortly after passing the disease. Locally, however, AYBD has been observed at densities high enough that would suggest them passing above threshold. WS is so far the only disease that has been observed in sufficient density and numerical frequency to make an epidemic (an outbreak exceeding a usual maximum prevalence of ~5–10% infected individuals) likely. Such a situation has occurred locally in the SE Gulf after the 2010 bleaching event. Presumably the generally weakened condition of all corals allowed a pathogen easy access to a large proportion of the population (locally >30% of all corals were found to be infected, varying in patches from 0 to >90%) and coupled with apparent contagiousness on contact, fulfilled all requirements for developing into an epidemic.

The SI model allowed evaluation of the overall behavior of the diseases, but much dynamics remains unexplored. Gulf coral populations are, for example, not closed thus we

may wish to add some demographics to the above model. Not all corals always die after contracting a disease. Many cases have been observed where AYBD or BBD stopped being virulent or were successfully combated by the coral. In these cases, the coral has recovered but not obtained immunity since later re-infections have been observed. Thus we can assume that a constant proportion ($\gamma = 1 - d$, d = death rate) of recovered corals (R) move back into the susceptible (S) bin.

Above assumptions allow us to model the dynamics of a coral disease using the following formalism as a SIRS model (susceptible corals can be infected, some recover but become susceptible again; Fig. 7.9). The differential equations for such a model are

$$\begin{aligned} S'(t) &= bN - dS - \alpha SI / N + \gamma R \\ I'(t) &= \alpha SI / N - (\nu + \epsilon + d)I \\ R'(t) &= \nu I - (\gamma + d)R \\ N'(t) &= (b - d)N - \epsilon I \end{aligned} \quad (7.6)$$

While we have already shown theoretical differences in the persistence of the different diseases, Figs. 7.9 and 7.10 show the dynamics these diseases can impart on coral populations. One of the most sensitive parameters determining whether a coral population can sustain a disease or not, is the reproductive rate of corals in relation to the infection and mortality rates in Fig. 7.10. A threshold existed between 1.1 and 1.15 (i.e. whether the population was augmented with recruits to 10% or 15% of its overall population level) below which coral populations tended towards a strongly depressed

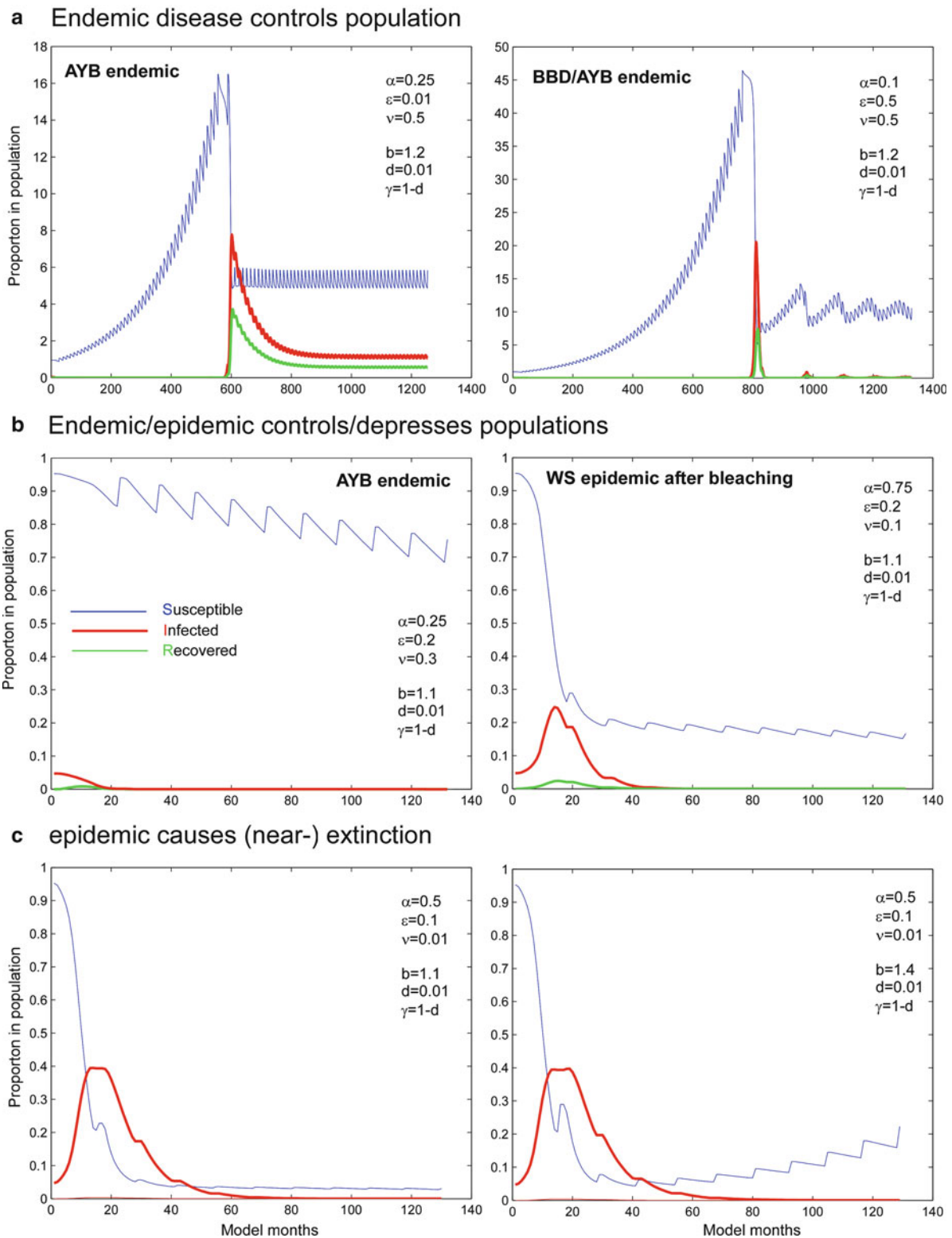


Fig. 7.10 SIRS Model results with the demographic parameters exponential reproduction (b), natural (d) and disease-induced mortality (η) added to healing (v) and re-acquired susceptibility (γ). Movement from the recovered class into the susceptible class is automatic and no immunity is ever acquired (hence $g=1-d$). Models in (a) run for

100 years (1,200 months) models in (b) and (c) for 10 years (120 months). In (a) the proportion rises above 1, which suggests population densities at a multiple of the original starting level. Recruitment occurs as discrete event once every 12 mo (unlike Eq. 7.6) by multiplication of N by b.

population level (~20% of starting population) and above which they tended towards exponential increase. However, as Fig. 7.10a shows, once populations had multiplied several-fold, enough susceptible corals existed to trigger an outbreak of even normally rather benign diseases ($\alpha=0.1$). After the outbreak, depending on the behavior of the disease, it coexisted with the corals either at one stable level or in dampened oscillations. Either way, the models show that diseases clearly are capable of controlling coral population levels and identify them as important demographic factors for coral population maintenance in the Gulf (Fig. 7.10b). Aggressive diseases, such as WB, form short-lived (2-year, Fig. 7.10b) epidemics that reduce coral populations to low levels at which the corals can presumably stabilize until the next epidemic. Such dynamics has been repeatedly observed in the Caribbean. Depending on the fertility level of the affected corals, diseases can indeed drive a population, at least theoretically, almost or totally to extinction (Fig. 7.10c).

7.4 Red Tides (Harmful Algae Blooms)

An increasingly potent killer of reef corals are blooms of harmful planktonic algae, also known as Red Tides or Harmful Algae Blooms. They usually occur in summer, at high surface water temperatures, low wind speeds, good light and nutrient levels (Gilbert et al. 2002). Well-known, and cyclic in their occurrence in the Arabian Sea due to large-scale oceanographic drivers, they have become increasingly frequent inside the Gulf. The blooming algae can either be toxic themselves, or significantly increase biological oxygen demand of the water upon decay after the bloom, which can result in kills of fish and coral (Al-Ansi et al. 2002). Toxins produced by the algae may also lead to fish kills, and can accumulate in shellfish (e.g. paralytic shellfish toxins; Gilbert et al. 2002) with negative commercial implications. Since surface water temperatures in the Gulf seem to be rising (Sheppard and Loughland 2002), the increasingly suitable conditions for red tides may lead to a more frequent recurrence of such events with obvious implications for reef health (Bauman et al. 2010; Samimi-Namin et al. 2010; Foster et al. 2011).

There are clear indications that the frequency of HABs is indeed increasing, with examples being reported from almost all areas (Sheppard et al. 2010; see also Chap. 16). In Kuwait Bay a HAB incident by *Karenia selliformis* and *Prorocentrum rathymum* caused a massive fish kill in 1999 (Al-Yamani et al. 2000). HAB incidences accompanied by massive fish kills have been reported from Abu Dhabi, Dubai, Ajman, Fujaira, the waters of Iran and Oman during August 2008–May 2009 (Fig. 7.11). The main HAB species causing mortality was *Cochlodinium polykrikoides* (Matsuoka et al. 2010; Richlen et al. 2010; Sheppard et al. 2010; see also Chap. 18). The recent red tide in the Gulf and Gulf of Oman started at

Dibba, north-western coast of the Gulf of Oman, in August–September of 2008 and extended towards the north, reached the Strait of Hormuz at the Iranian coast, and expanded west- and southward from there (Fig. 7.11). The bloom also extended along the Omani coastline following the current patterns. The bloom was unique in terms of its duration and geographical range (Matsuoka et al. 2010). Before this bloom, the longest previous duration of bloom caused by the same species was one and one-half months in Korea (Kim et al. 2004), and almost two months in Japan (Kim and Honjo 2005).

In the affected reefs, corals (predominantly *Porites* species) suffered mortality and subsequent mass-settlement and overgrowth by serpulids. This infestation was not limited to dead surfaces, but also occurred on live corals. Three months after the red tide, infestation levels had reached 47 ± 9 serpulids 25 cm^{-2} coral, which led to the death of 90% of all local *Porites* tissues. Several other coral species were also affected with *Goniopora* sp. the only species immune to the overgrowth (Fig. 7.12). In 281 coral colonies, less than 10% percent appeared in normal condition (8.90 ± 0.26) and the rest of colonies showed partial or complete mortality (Fig. 7.13), where before red tide, the community had 40–70% live corals (Samimi-Namin, unpublished data).

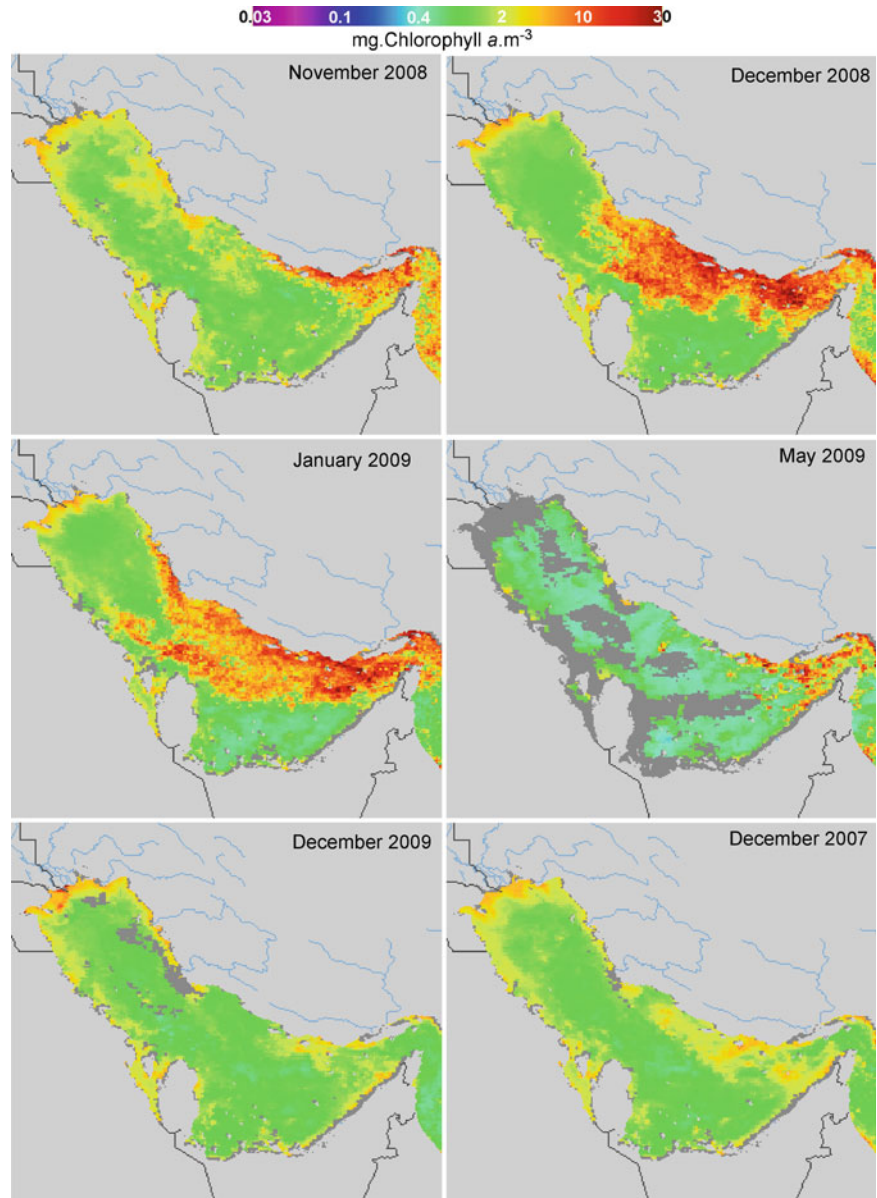
The main cause for the mortality of *Porites* species was the high infestation by the serpulid worms, but for other species it was likely a combination of increase in surrounding nutrient levels, higher sedimentation, higher mucus secretion, depletion of oxygen, and higher light attenuation, which apparently favoured the settling conditions of the fouling organisms. Samimi-Namin et al. (2010) speculate that the increased food availability to the filter-feeding serpulids may have allowed their populations to explode. This suggests that their populations might be controlled by food limitation, rather than the competitive ability of the corals. Thus corals would be defenseless if release from food limitation would allow increased serpulid survival.

7.5 Discussion

The microbial afflictions of corals in the Gulf, such as diseases and harmful algae blooms, have only recently received attention and much remains to be learned. In analogy to diseases of vertebrates, corals also seem to be faced primarily with microparasites causing diseases (the microorganisms causing AYB, BBD and WS) but when weakened, or under changed environmental conditions macroparasites can also become a problem (trematode and serpulid infections causing pink spots).

Some regionally unique features are observed in the Gulf but the diseases seem to be similar to those in the other ocean basins. More importantly, only a subset of all known diseases seems to occur in the Gulf. Some diseases, like BBD and, to a lesser extent, WS seem to be seasonal, or at least

Fig. 7.11 Monthly averaged MODIS Chlorophyll *a* levels show the strong anomaly associated with the long-lasting *red tide* that caused significant coral mortality in Iran, Fujairah and Oman, and fish kills in Abu Dhabi, Dubai and Ajman over winter 2008/9. Chl *a* levels in December of the preceding and following year are shown for comparison (Data courtesy NOAA (<http://coastwatch.pfeg.noaa.gov/erddap>))



influenced by temperature. BBD has never been observed in winter, like in other high latitude areas (Florida, Kuta and Richardson 1996). WS and BBD have shown a clear spike in frequency following the 2010 and 2011 bleaching events and thus follow a pattern also observed in other places (Bruno et al. 2007; Brandt and McManus 2009) that may be linked to altered bacterial dynamics (Rosenberg and Ben-Haim 2002).

AYBD differs from all other diseases in not being affected by seasonal or extreme temperature excursions. No increase was noted after the 1996, 1998, 2002, or 2010 bleaching event. Rather, the disease decreased markedly in frequency after 1996/8 probably largely due to the reduced availability of victim corals, that had died during the extreme bleaching and mortality events of that year, suggesting simple mass action dynamics of spread.

The obvious differences in the dynamics of AYBD, BBD and WS allowed several interesting questions to be theoretically pursued. AYBD is a disease that persists at relatively high levels in coral populations, BBD is rare when corals (esp. *Acropora*) are at low density, but WS can only generate transient, albeit devastating, outbreaks. The density dependence of disease frequency observed by Riegl (2002) strongly supports the mass action principle to govern infection and the use of SI and SIRS models (McCallum et al. 2001; Edelman-Keshet 2005). Exploration of such a model showed coral diseases as potentially important drivers of community dynamics in Gulf reefs. The force of infection (parameter β in Eq. 7.5 or α in Eq. 7.6 and Fig. 7.10.) relates to the speed of disease spread (strictly speaking it is “the instantaneous per capita rate at which susceptible individuals

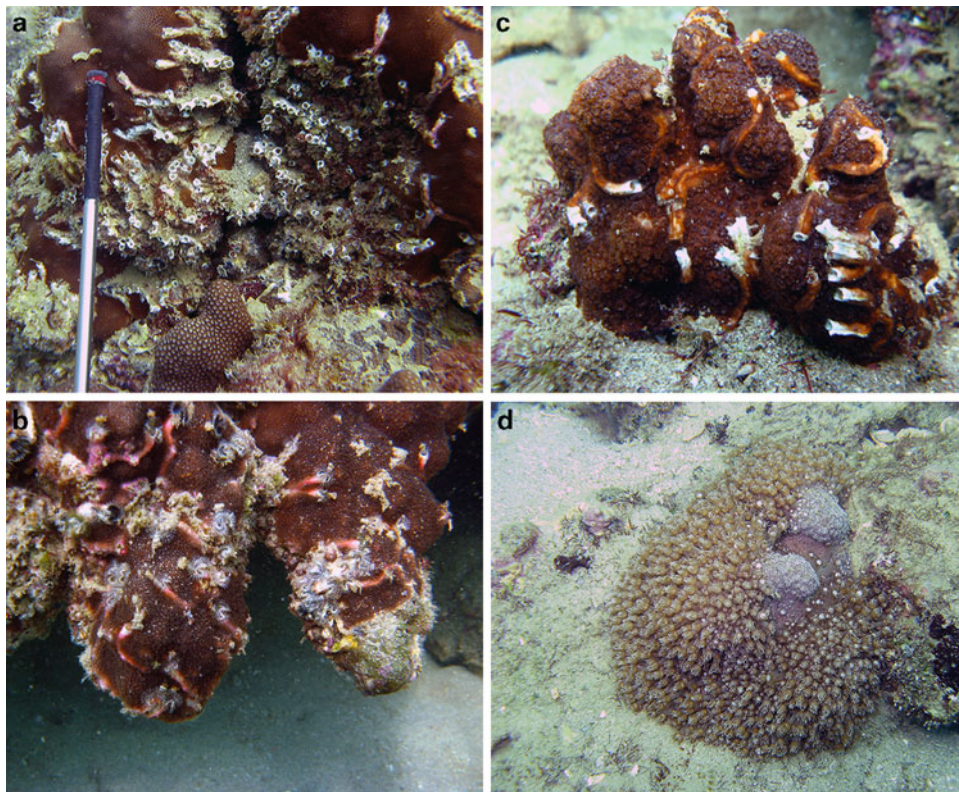


Fig. 7.12 (a, b) High density of serpulid worms on *Porites* colony, (c) overgrowth by serpulid worms on a *Cyphastrea* colony, (d) unaffected *Goniopora* colony. Scale in (a)=3 cm

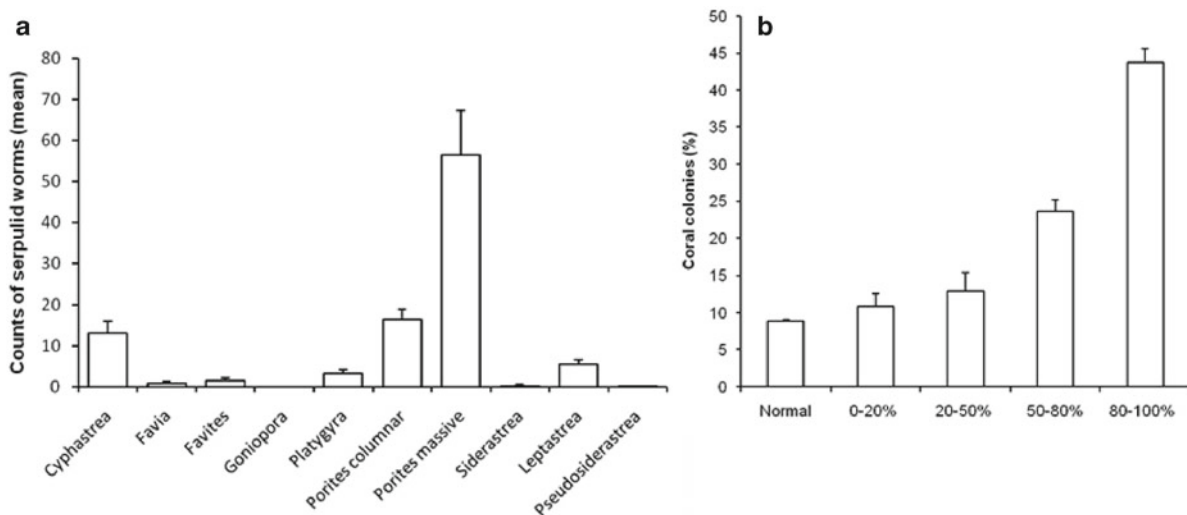


Fig. 7.13 (a) The infestation levels of serpulid worms on coral colonies on 100 cm² (n=10) of coral. (b) The percentage of coral mortality about 3 months after starting of the red tide

acquire the disease"; Grenfell and Anderson 1985) and in the case of the Gulf is WS>AYBD>BBD. The measured rate of spread in WS after the 2010 bleaching events was at least twice that of YBD and many times that of BBD in a near-equilibrium *Acropora*-dominated community before the 1996 event

(Riegl 1999). Also, mortality due to WS in *Acropora* was locally near-total in 2010, while in 1995 at least some colonies showed the capability to survive AYB and BBD was not observed to kill the majority of infected corals, probably due to a temperature refuge in winter when the disease is inactive.

The high force of infection in WS and its efficiency in killing the host, coupled with a low outbreak density may suggest that WS may not maintain itself as an endemic disease at low level in a population but that a true infection into the coral population has to take place from the outside every time. Recent findings clearly linked incidence of coral disease with bleaching (Brandt and McManus 2009) and found that otherwise harmless strains of bacteria can become virulent at raised temperatures (Rosenberg and Ben-Haim 2002). Also the specific pathogens causing WS and other “white diseases” have remained elusive. This suggests several possible mechanisms triggering WS outbreaks. Firstly, WS may be linked to otherwise non-pathogenic micro-organisms that become virulent at the raised temperatures causing the bleaching event. Or, weakened from the bleaching event, corals lose resistance to an otherwise only mildly pathogenic organism that now can overwhelm the corals’ compromised immune system. Or, by coincidence, pathogenic bacteria may arrive at the same time in the system as the bleaching disturbance and, besides being virulent anyway, can now exploit the corals’ weakened state (in a form analogous to a superinfection; Nowak and May 1994).

The dynamics of AYBD is markedly different. This is the most common disease in the Gulf and has a different outbreak threshold. N_T (the threshold number of corals per defined area required for an outbreak) is within the realm that can realistically be reached by Gulf coral populations and although the frequency of AYBD is density-dependent it also persists in sparse coral populations. This suggests that alternations of endemic and epidemic phases (as shown in Fig. 7.9a) are indeed plausible. While AYBD was observed on a variety of genera, it clearly favors *Acropora* spp. and its outbreak cycles appear to be primarily driven by these species’ dynamics. At high *Acropora* density, as can be achieved after only a decade or two without major disturbances, outbreaks of AYBD may have an important function as compensatory mortality. Riegl and Purkis (2009) have shown *Acropora*, faviids and poritids to exist in a competitive environment that tends to favor dominance by the aggressive and fast-growing *Acropora*, unless faviids and poritids are allowed to reach a size- or density refuge in which they can no longer be displaced by the superior competitor. Cyclic outbreaks of AYBD at high *Acropora* density would thus exert an important “culling” effect that serves not only to control the disease, but also allows inferior competitors to reach a size-refuge, thus maintaining community diversity. Such dynamics would strengthen and potentially even overprint the purely environmentally-driven dynamics envisaged by Riegl (1999), Purkis and Riegl (2005) and Riegl and Purkis (2009).

BBD in the Gulf is a disease with a very low force of infection and its theoretical N_T is so high that is unlikely to be achieved. However, it can be achieved (Fig. 7.10) and also BBD could have a long-term effect as coral population regulator.

In 2011, it was for the first time observed at outbreak levels following a bleaching event.

Climate change is likely to have strong influence on the herein discussed interplay of corals with their diseases. Positive thermal anomalies have markedly increased in the region (Nasrallah et al. 2004; Al-Rashidi et al. 2009) and with them bleaching, or at least thermal-stress events. While in the late 1990s and early 2000s it was bleaching that led to marked coral mortality, the 2010 event was primarily marked by mortality of corals regenerating from the bleaching and infected by WS. No such observations exist for the 1996 or 1998 event, and it is possible that these epidemics are a novelty. Figure 7.10 shows how devastating these disease events can be on coral populations. If they were to recur at every thermal anomaly, coral populations could potentially be depressed to a level at which at least functional, if not total, extinction was easily within the realm of the possible. Since corals are apparently at their most vulnerable to diseases when subjected to other stressors, it should be attempted at all costs to reduce stress levels on the Gulf’s corals and reefs. This can be achieved by rigorous control of overfishing, pollution, and reduction of construction in the coastal zone.

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Edwin Grandcourt

8.1 Introduction

The waters of the Gulf are characterized by extreme temperature (11.5–36°C) and salinity (37–50‰) ranges which are likely to at least periodically approach or exceed the tolerance limits of many reef fish species (Coles 1988; Coles and Tarr 1990). The narrow Strait of Hormuz constrains the influx of larvae from adjacent seas which also limits species diversity. Whilst the Gulf is a relatively young sea that originated about 16,000 BP, the sea surface did not reach its current level until around 6,000 BP during the Holocene (Sheppard et al. 1992). The present day fish fauna was thus established by the penetration of species from the Indian Ocean through the Gulf of Oman and Strait of Hormuz (Beech 2004). Its small size, limited habitat types and restricted depth also constrain faunal diversity, which is particularly apparent among the families of reef fishes (Randall 1995; Bishop 2003). Consequently, many major shallow water taxonomic groups that are prevalent at similar latitudes throughout the Indo-Pacific and adjacent waters are completely lacking in the area and there are few endemics, with only 16 species of fishes known to occur uniquely within the Gulf (Coles and Tarr 1990; Randall 1995; Carpenter et al. 1997).

Although the water column of the Gulf is generally well mixed, primary production is higher than in the Red Sea but lower than in the Arabian Sea (Sheppard et al. 1992). Nevertheless, high benthic productivity makes the Gulf one of the most productive water bodies in the world as a result of the majority of the sea bed lying within the photic zone (Sheppard 1993). Extensive sea grass beds, macroalgal beds and cyanobacteria mats support rich benthic communities. In addition, widespread mud flats contain organic material that supports abundant infaunal organisms (Carpenter et al. 1997).

Whilst the primary producers, organic matter and associated epifaunal and infaunal invertebrates of the soft sediment benthos form the basis of a highly productive ecosystem, coral reefs are also critically important habitats for the principal fin fisheries resources (Figs. 8.1 and 8.2). In the Gulf waters of the United Arab Emirates, total fish biomass density varies between 0.8 and 1.4 mt/km² in trawlable areas (Shallard and Associates 2003a), contrasting with densities of up to 290 mt/km² on coral reefs (Grandcourt unpub data).

Next to oil and gas, fisheries represent the second most important natural resource and the most important renewable resource in the Gulf. They provide a source of income, employment and recreation whilst contributing to the cultural heritage and food security of inhabitants of the coastal states (Grandcourt 2008). With an average depth of only 36 m, the Gulf yields on average one ton of commercially valuable fish and shellfish annually for each square kilometer of surface area (Bishop 2003). The region's economy was actually based on the pearl fishery for hundreds of years before the discovery and exploitation of oil and natural gas (Lorimer 1915) and archaeological records indicate that fisheries have been an important economic activity for the indigenous people of the region since the 6th millennium BC (Beech 2002).

The fisheries of the Gulf are typically multi-species and multi-gear. They are often described as being artisanal because of the traditional methods used. However, there are many 'artisanal' fisheries that operate on a scale that is clearly commercial in nature. There are essentially four capture fisheries sectors in the region (i) recreational (ii) traditional (iii) commercial and (iv) industrial. Recreational fishers may use small motor boats or fish from the shore. Hook and line is the most commonly used method although fish traps (gargoor) are also popular in some areas. Traditional fisheries operate on a subsistence level and are common in mainland coastal areas and islands. A variety of methods are employed including fence nets and harpoons. Both the recreational fishery (even though it is a rapidly growing sector) and the traditional fisheries are relatively benign in terms of their

E. Grandcourt (✉)
Environment Agency-Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: egrandcourt@ead.ae

impact on the resource base. The commercial fisheries are largely operated from traditional wooden dhows using traps (gargoor) to target demersal species, particularly those that are reef associated. Commercial trawlers target shrimp during the open season and finfish during the closed season (Carpenter et al. 1997). To a lesser extent, purse seiners have exploited small pelagic species in the northeastern and southwestern parts of the region (Sheppard et al. 1992).

The human population in the Gulf has increased dramatically since the discovery of oil, which has subsequently



Fig. 8.1 Whilst diversity is extremely low, the biomass density of reef fish in the Gulf can be high, with values of up to 290 mt/km² being recorded for some reefs in the United Arab Emirates (Photo: E. Grandcourt)

driven an increase in the rate of exploitation of living marine resources. The increased demand coincided with mechanization of the fishing fleets and the introduction of new technology that enhanced fishing capacity. The pressure on the resource base was further exacerbated by habitat loss and fragmentation associated with coastal development. Consequently, most of the fisheries in the area are either fully or over exploited (Samuel et al. 1987a; Sheppard et al. 1992; Morgan 2006; Grandcourt 2008). Large declines in abundance of stocks of reef associated demersal species have been observed. In the southern Gulf, the stocks were reduced to 19% of the levels present three decades ago (Shallard and Associates 2003a). Threats to reef fisheries resources also include climate change impacts, particularly the loss of habitat associated with mass coral mortalities that occur as a result of an increase in the frequency and prolongation of positive seawater temperature anomalies (George and John 1999, 2000, 2002; Riegl 2002).

The existing status of the fisheries in the Gulf can also be attributed to poor resource management practices. The activities of fisheries agencies for example are largely based on administration, rather than management in accordance with a well defined long-term strategic plan to ensure sustainability. In addition, the shared nature of many fish stocks contrasts with the poorly developed institutional arrangements for regional management (Morgan 2006). Other critical issues include the availability of a cheap migrant labor force and low operating costs which have acted as subsidies and maintained the viability of fishing units despite the depletion of stocks.



Fig. 8.2 An early morning scene at the major fish landing site in Abu Dhabi, the capital of the United Arab Emirates, showing a typical multi-species catch prior to auction (Photo: E. Grandcourt)

8.2 Fishing Methods, Target Species and Yields

There are four primary capture fisheries sectors in the region (i) recreational (ii) traditional (iii) commercial and (iv) industrial. Many of the recreational, traditional and commercial fisheries are associated with coral reef habitats. Whilst some reef associated species are caught by trawling during the closed season for shrimp, this method is only conducted on low relief hard bottom and soft substrates, where some reef associated species may also occur.

Recreational fisheries may rely on small motor boats or be shore based. They often employ hook and line based methods although fish traps (gargoor) may also be used. Recreational fisheries are expanding although total productivity and harvest pressure is still minimal compared to the commercial and industrial fisheries (Carpenter et al. 1997).

Traditional fisheries are typically small scale subsistence fisheries conducted using a wide variety of traditional techniques, like recreational fisheries, they may be shore based or use small outboard powered vessels. Shore based operations mostly fish with hook and line along rocky shores and jetties or along beaches or extensive intertidal areas with beach seines, gill nets or fence nets (Carpenter et al. 1997).

Commercial fisheries are largely conducted from traditional wooden dhows (Fig. 8.3). These are the 12–20 m long traditional sailing craft of the region and are powered by 150–300 horsepower inboard diesel engines. More recently they have been constructed of fiberglass. These boats typically fish with traps although trawls, driftnets, gillnets, hook and line and trolling lines may be used (Carpenter et al. 1997). Small outboard powered vessels may also operate in the commercial fisheries.

Industrial fisheries mostly utilize modern trawlers that target shrimp during the open season and finfish during the closed season. To a lesser extent, commercial purse seining for small pelagic species has also been undertaken (Carpenter et al. 1997). The industrial fisheries are not associated with coral reef habitats (Fig. 8.4).

Fishing methods used in the Gulf are diverse, in a guide to the fishing gears and methods used in the Emirate of Abu Dhabi, Hartmann (2008) list 12 methods that use nets, 6 line fishing techniques, 2 types of trapping and 2 types of spearing. Whilst many methods are not used directly on coral reefs they often exploit reef associated species occurring in different habitat types. The current techniques are much the same as those used in the past although the design



Fig. 8.3 Common fishing vessels used in the Gulf: (a) traditional dhow and (b) open dory (Photos: E. Grandcourt and S. Hartmann)

of the fishing gear and materials used have often changed. For example, the gargoor, a hemispherical fish trap now constructed of galvanized wire mesh, was previously cylindrical in shape and made of interwoven palm fronds (Beech 2004).

Fish traps are of two types, the baited basket trap or “gargoor” and the intertidal fence net called “hadhra”. The gargoor is a wire mesh, dome-shaped trap with a funnel like entrance. The base is usually reinforced with steel bars and they range in diameter from 1 to 2.5 m and the traps are often set in strings around rocky or coral reef areas. Bait types include dry fish, bread, shrimp and green algae (*Ulva*). A wide range of demersal and semi-pelagic species are caught. Target species include; groupers (Serranidae), seabreams (Sparidae), emperors (Lethrinidae), snappers (Lutjanidae), sweetlips and grunts (Haemulidae), jacks (Carangidae) and parrotfishes (Scaridae) (Carpenter et al. 1997).

The intertidal fence net (“hadhra”) is a semi-permanent tidal barrier trap, steel poles covered with nylon netting or galvanized steel mesh have replaced the traditional materials

Fig. 8.4 Representative catches of the main fisheries sectors in the Gulf: (a) recreational, (b) traditional, (c) commercial, and (d, e) industrial (Photos: S. Hartmann, A. Cibahy and E. Grandcourt)



(palm fronds and wooden stakes). A barrier perpendicular to the shore and wings of the trap channel fish first into an outer and then an inner chamber. Fish are harvested at low tide. Fish trapped by hadhra include mullets (*Mugilidae*), rabbitfishes (*Siganidae*), jacks (*Carangidae*), barracudas (*Sphyraenidae*), needlefishes (*Belonidae*), snappers (*Lutjanidae*) and seabreams (*Sparidae*) (Carpenter et al. 1997). Whilst they are set in intertidal coastal locations, hadhra do exploit a variety of species that are also found on coral reefs (Fig. 8.5).

There are other variants of tidal barrier traps. The “sakkar” is a wide fence net set near to the coastline, often across gaps in lagoons in the intertidal zone. This technique is used to capture snappers (*Lutjanidae*), rabbitfish (*Siganidae*), mullets (*Mugilidae*), mojarras (*Gerridae*) and the goldstriped seabream (*Rhabdosargus sarba*) amongst other small coastal species (Beech 2004; Hartmann 2008).

There are a wide variety of fishing methods that use nets. The “halaq” and “defara” are both encircling gillnets used to target large pelagic and reef associated demersal species respectively. Other active nets include drag gillnets, scoop nets, cast nets and beach seines which are all operated in

shallow water and not directly associated with coral reef habitats. Bottom set gill nets, which are often set near coral reefs, catch a variety of fish including pomfrets (*Stromateidae*), seabreams (*Sparidae*), emperors (*Lethrinidae*), sweetlips (*Haemulidae*), rabbitfishes (*Siganidae*), goatfishes (*Mullidae*) and others. Trammels nets consisting of three layers of monofilament gillnet are also used to target demersal species. The drift gill net (“hiyaal”) was the main method used for one of the most important seasonal fisheries for the narrow barred Spanish mackerel (*Scomberomorus commerson*) during the winter and spring months. Other species caught by drift gillnets include tunas (*Scombridae*), jacks (*Carangidae*) and cobia (*Rachycentridae*) (Carpenter et al. 1997; Hartmann 2008). Due to the destructive nature of this fishing method, it is banned throughout in the region.

Both handline (“hadaq”) and trolling lines (“lafaah”) are used to target coral reef fishes. A variety of handline fisheries target the main demersal species including emperors (*Lethrinidae*), sweetlips and grunts (*Haemulidae*), seabreams (*Sparidae*) and groupers (*Serranidae*). Longlines having between 10 and 20 baited hooks (known locally



Fig. 8.5 (a) Recreational fisheries are common throughout the Gulf; (b) the gargoor, a hemispherical trap made of galvanized bar and wire mesh is the most commonly used method used to target reef fish.

Traditional fishing methods in coastal areas include the (c) harpoon and (d) intertidal fence net (Photos: S. Hartmann)

as “manshalla”) are used to target requiem sharks (*Carcharhinidae*) and groupers (*Beech 2004*). Whilst trolling lines usually target large pelagic species, they are often used to catch reef associated fish in particular the orangespotted grouper (*Epinephelus coioides*). Other methods include recreational saltwater flyfishing which is becoming increasingly popular in shallow areas, particularly in association with tourism developments. Traditional wooden spears are used to catch large species such as sharks and rays and some free-dive based spear fishing is also conducted on coral reefs. In the 1950s, poison, derived from the seeds of the Persian Lilac (*Melia azedarach*) was commonly employed as a method of fish capture (Bishop and Al-Husaini 2002). Fisheries statistics for Abu Dhabi (Hartmann et al. 2009) provide an insight into the species composition of the major fishing gears used in the southern part of the Gulf (Figs. 8.6 and 8.7).

Trawls, whilst banned in some countries such as the United Arab Emirates, are the main gear type used to target shrimp. Shrimp fisheries in the Gulf were initially conducted using traditional dhows until industrial trawlers were introduced to Kuwait and Saudi Arabia in the 1950s and 1960s. Trawls are used over the shrimp grounds during the open season, which varies between countries and mostly over sandy bottoms for fish during the closed season. Whilst they are not used on coral reefs, reef associated species are often caught including emperors (*Lethrinidae*), sweetlips and grunts (*Haemulidae*),

threadfin breams (*Nemipteridae*), seabreams (*Sparidae*) and groupers (*Serranidae*). In addition, a number of sharks and rays are often caught and utilized (Carpenter et al. 1997).

Purse seining has taken place in the northeastern and southwestern parts of the region (Sheppard et al. 1992), however, this method targets small pelagic species and is not operated over coral reefs. The pearl oyster fisheries used to be run from traditional dhows using breath hold divers. This was the most important economic activity in the eighteenth and beginning of the nineteenth centuries until its decline, which was driven by the competition from cultured pearls, the depression of the 1930s, World War II and the development of the oil and natural gas sector (Carpenter et al. 1997; Bishop and Al-Husaini 2002).

Yields. Analyses of fisheries statistics compiled by the Food and Agricultural Organization of the United Nations (FAO 2009), indicates that 181,972 mt of reef fish was landed in the Gulf on average each year between 1986 and 2007. Landings ranged from a minimum of 117,984 mt in 1896 to a maximum of 231,012 mt in 1992. The yield of reef fish has followed an increasing trend over the period for which time series data is available, similar to that of the total finfish production for the area (Fig. 8.8). Reef associated species represent 70% of the total landed weight of finfish catches in the Gulf, which is an attestation of their socio-economic importance to the fisheries sector.

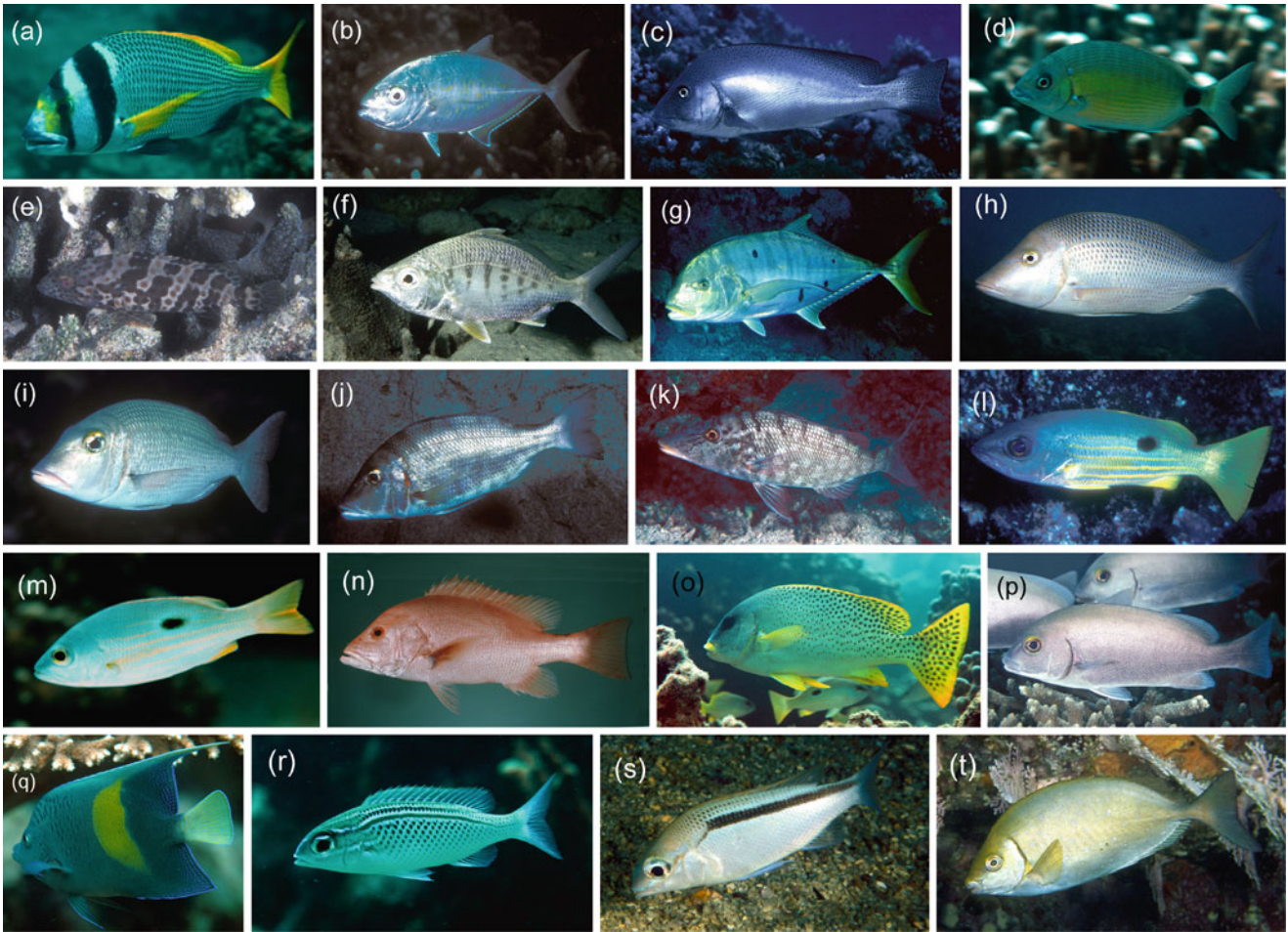


Fig. 8.6 Commonly exploited reef fish in the Gulf: (a) *Acanthopagrus bifasciatus*, (b) *Carangoides bajad*, (c) *Diagramma pictum*, (d) *Diplodus sargus kotschy*, (e) *Epinephelus coioides*, (f) *Gerres longirostris*, (g) *Gnathanodon speciosus*, (h) *Lethrinus nebulosus*, (i) *Lethrinus borbonicus*, (j) *Lethrinus lentjan*, (k) *Lethrinus microdon*, (l) *Lutjanus*

ehrenbergii, (m) *Lutjanus fulviflamma*, (n) *Lutjanus malabaricus*, (o) *Plectorhinchus gaterinus*, (p) *Plectorhinchus sordidus*, (q) *Pomacanthus maculosus*, (r) *Scolopsis ghanam*, (s) *Scolopsis taeniatus*, (t) *Siganus canaliculatus* (Photos: J. Randall and E. Grandcourt)

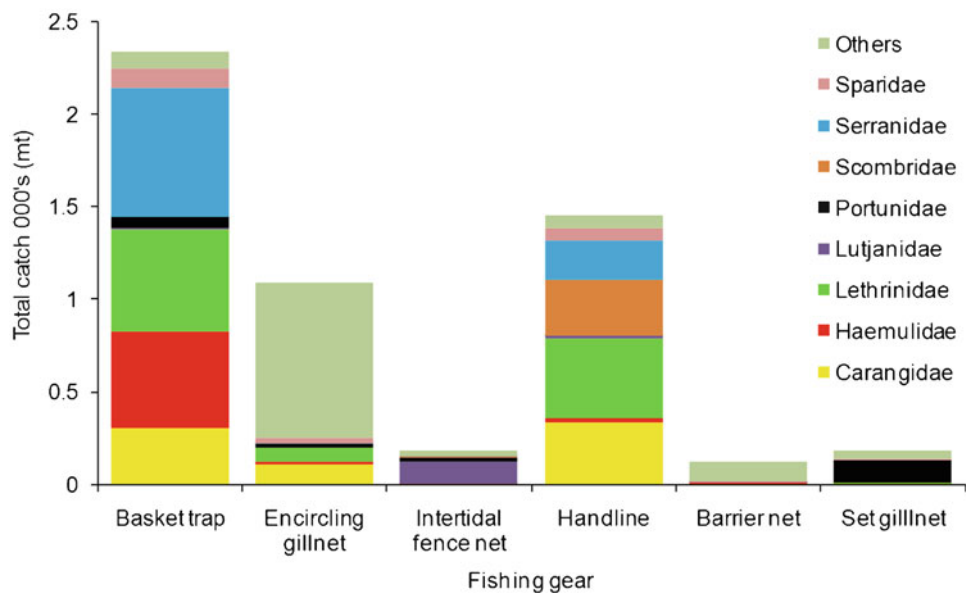


Fig. 8.7 Total landed catch by major family and gear type for the Emirate of Abu Dhabi in 2008 (Adapted from Hartmann et al. 2009)

Fig. 8.8 Total yield of all species of fish (All finfish) and reef associated species only (Reef fish) in the Gulf between 1986 and 2007 (Data source: FAO 2009)

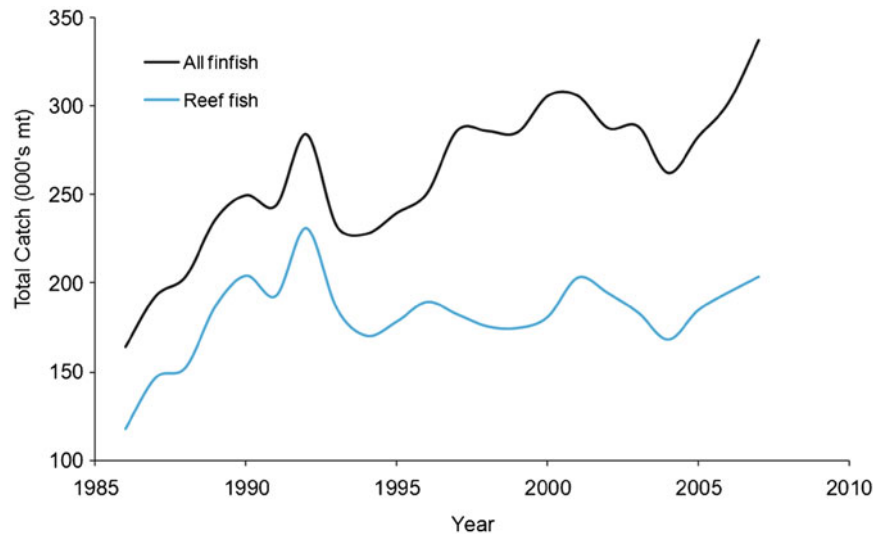
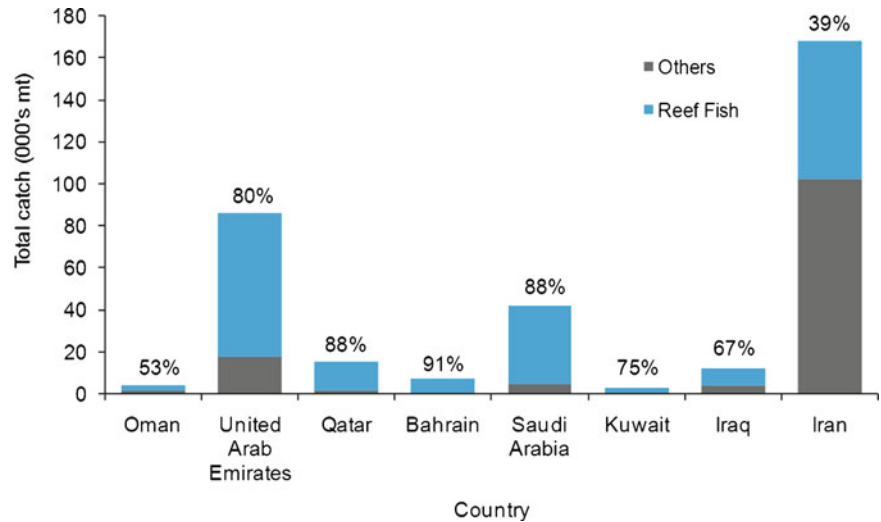


Fig. 8.9 Fishery yields by country in the Gulf during 2007 showing reef fish as a proportion of the total of all finfish species (data labels). Note: landings for Oman, Iran, the United Arab Emirates and Saudi Arabia relate to those derived from Gulf waters only (Data source: FAO 2009)



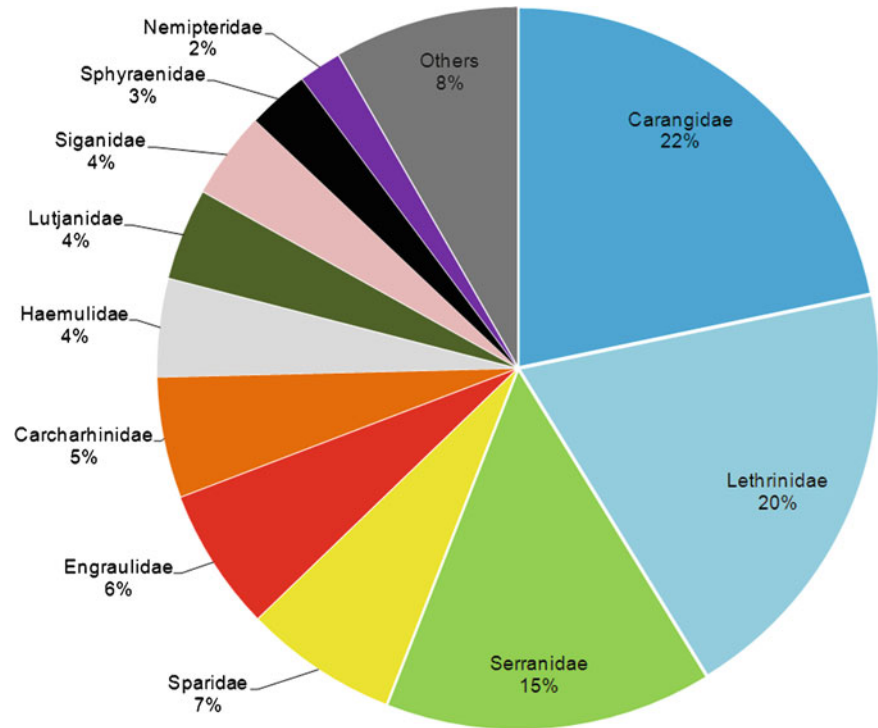
During 2007, the United Arab Emirates landed the greatest quantity of reef fish (68,680 mt) whilst Kuwait's landings were the lowest (2,131 mt). Iran had the largest overall catch by far (167,709 mt) although the proportion of this which was composed of reef associated species (39%) was the lowest of all the littoral states (Fig. 8.9). Whilst there are notable differences in the species composition of yields between countries, the most important families for the whole Gulf (>10% of mean annual landings) are the Carangidae, Lethrinidae and Serranidae, other important families include the Sparidae, Engraulidae, Carcharhinidae, Haemulidae, Lutjanidae, Siganidae, Sphyraenidae and Nemipteridae (Fig. 8.10).

In addition to large differences in the volume of landings of reef fish between countries, there is a high degree of inter-annual variability in yields for all countries. General trends

indicate an overall increase in catches for the majority of states (Bahrain, Iraq, Oman, Qatar, Saudi Arabia and the United Arab Emirates). Large scale increases in the overall catches of Qatar between 1980 and 1992 have been attributed to increases in the numbers of vessels, their effective fishing power and the number of fishermen (Al-Ansi and Priede 1996). The landings of reef fish in Iran increased dramatically from 46,000 mt in 1986 to 148,000 mt in 1992 and subsequently declined to 66,000 mt in 2007. There was an overall decline in the catches of reef fish from Kuwait with a particularly dramatic reduction from 4,509 mt in 1986 to 388 mt in 1991 (Fig. 8.11).

The locations and habitats where fishing is conducted, capture techniques and seasonal changes in abundance all contribute to the differences in species composition among the littoral states of the Gulf (Fig. 8.12). Bahrain has the

Fig. 8.10 Species composition of reef associated families in the Gulf. Note: values are calculated from combined landings between 1986 and 2007 (Data source: FAO 2009)



highest proportion of Siganidae (29%) in landings presumably because of its extensive seagrass beds and other shallow areas which are favored by these species. The composition of landings in the United Arab Emirates, Qatar and Saudi Arabia are dominated by the Lethrinidae, Serranidae, Carangidae and Sparidae. Kuwait has the highest proportion of Haemulidae (15%) and Sparidae (34%) in landings whilst Iran has the highest proportion of Carcharhinidae (15%) and Nemipteridae (9%). The Carangidae (39%) are the most important family in the landings of Oman's fisheries around the entrance to the Gulf in the Musandam area.

A notable characteristic of reef fish landings in the Gulf is the seasonal difference in catches between winter and summer months. Catch data from the southern Gulf in the waters of the Emirate of Abu Dhabi (Hartmann et al. 2009) indicate that yields during the summer are approximately half of those obtained during the winter (Fig. 8.13). This can be attributed to a combination of the reduction in abundance of target species associated with the increased water temperature and less fishing activity during the summer.

8.3 Diversity, Distribution and Abundance

The diversity of reef fishes in the Gulf is much less than elsewhere in the Indo-Pacific due to the extreme environmental conditions and consequent constraints on larval supply (Coles and Tarr 1990). Some species are considered to

live within 1°C of their thermal tolerance limits, at least for some of the year. The tolerance of larval stages may be even more restricted than those of adults, and in some cases, adult distributions may be limited by larval biology (Sheppard et al. 1992). Endemism is also low with only 16 species of fishes known to occur uniquely within the Gulf. Furthermore, like other species initially believed to be endemic, some of the presumed endemics may eventually be found to extend their distribution into the Gulf of Oman or beyond. Another factor which has also contributed to the lack of diversity of marine life is the Gulf's relative youth and – geologically speaking – ephemeral nature. Because it is so shallow (36 m on average), the water body ceased to exist when the sea level dropped during ice ages, the most recent of which was only 20,000 years ago (Randall 1995). Its small size, limited habitat types and restricted depth also constrain faunal diversity, which is particularly apparent among the families of reef fishes (Randall 1995; Bishop 2003).

Fish lists and books on marine fishes have been produced by all the littoral states of the Gulf: eg. Assadi and Dehghani (1997) for Iran; Mahdi (1971) for Iraq; Kuronuma and Abe (1972) for Kuwait; McCain et al. (1984) for Saudi Arabia; Al-Baharna (1986) for Bahrain; Sivasubramaniam and Ibrahim (1982) for Qatar; White and Barwani (1971) for the United Arab Emirates; Randall (1995) for Oman. Some publications relate to the Gulf in general such as Kuronuma and Abe (1986) and Relyea (1981) while some also include the

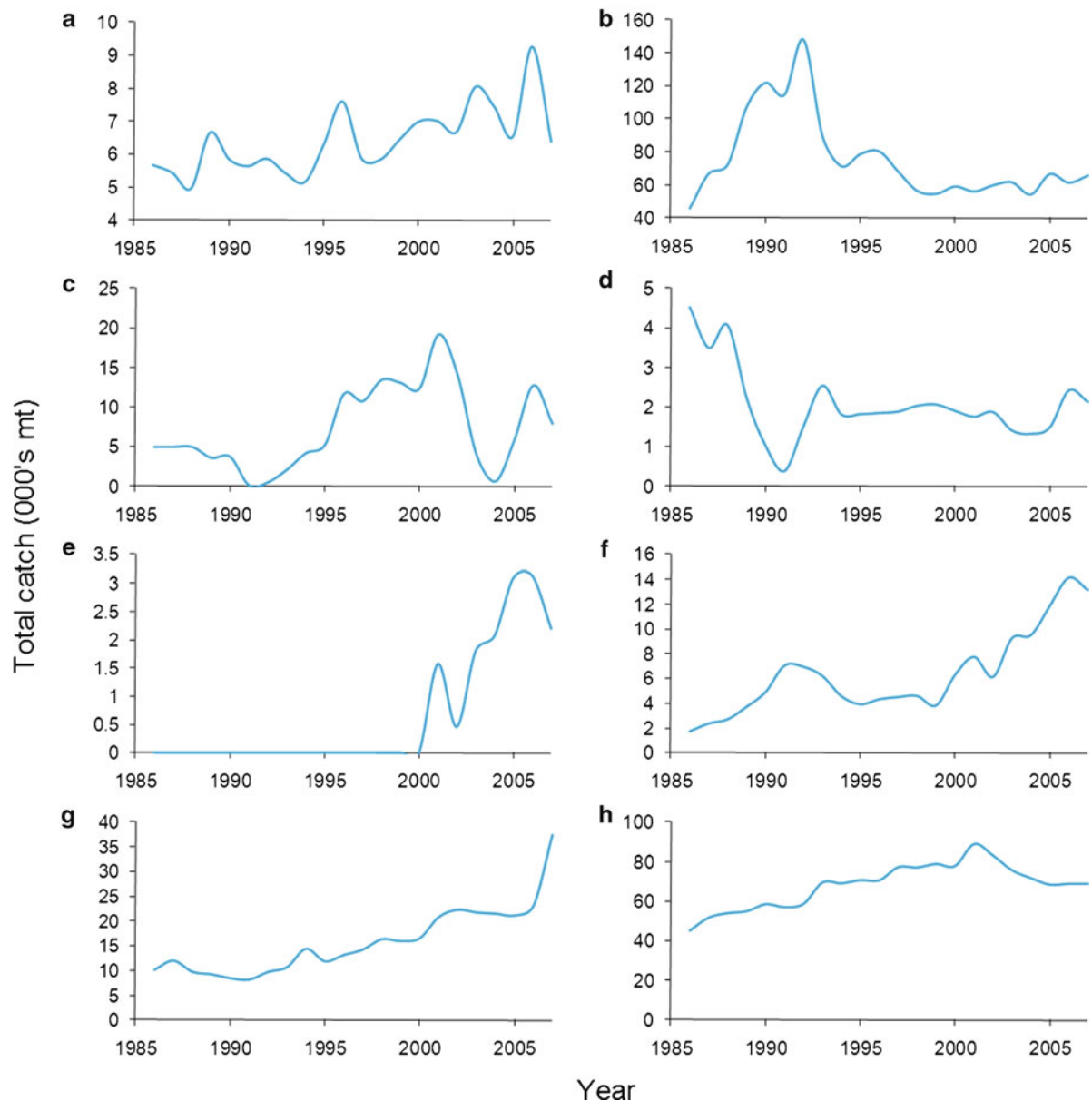


Fig. 8.11 Total annual landed catch of reef fish in the Gulf by country between 1986 and 2007. (a) Bahrain, (b) Iran, (c) Iraq, (d) Kuwait, (e) Oman, (f) Qatar, (g) Saudi Arabia, (h) United Arab Emirates (Data source: FAO 2009)

Gulf of Oman eg. Field (2005). Many of the misidentifications in these publications, name changes due to revisions and new records have been addressed in a review of the systematic literature of the Gulf (Randall et al. 1994). Still, a critical problem in constructing a checklist of reef fish for the Gulf is that many listed species are from literature records with comparatively few being based on actual specimens, consequently, the distribution of many species remains poorly known (Bishop 2003). Furthermore, where publications relate to both the Gulf and Gulf of Oman, the localities are often not specified so it is uncertain in which area species have been recorded.

Nevertheless, a list of reef associated fish, sharks and rays compiled from a wide variety of sources indicates that there are 302 species recorded for the Gulf from 70 families (Table 8.1). The best represented families are the; Carangidae (30 species), Gobiidae (28 species), Apogonidae (20 species), Pomacentridae (16 species), Labridae (12 species), Blenniidae (11 species) and Lutjanidae (11 species). The check list presented here also includes species that have been observed on coral reefs in the Gulf but are not typically associated with this habitat type, or only occur on coral reefs during part of their life cycle such as an early juvenile or sub-adult phase. It also includes representatives of roving

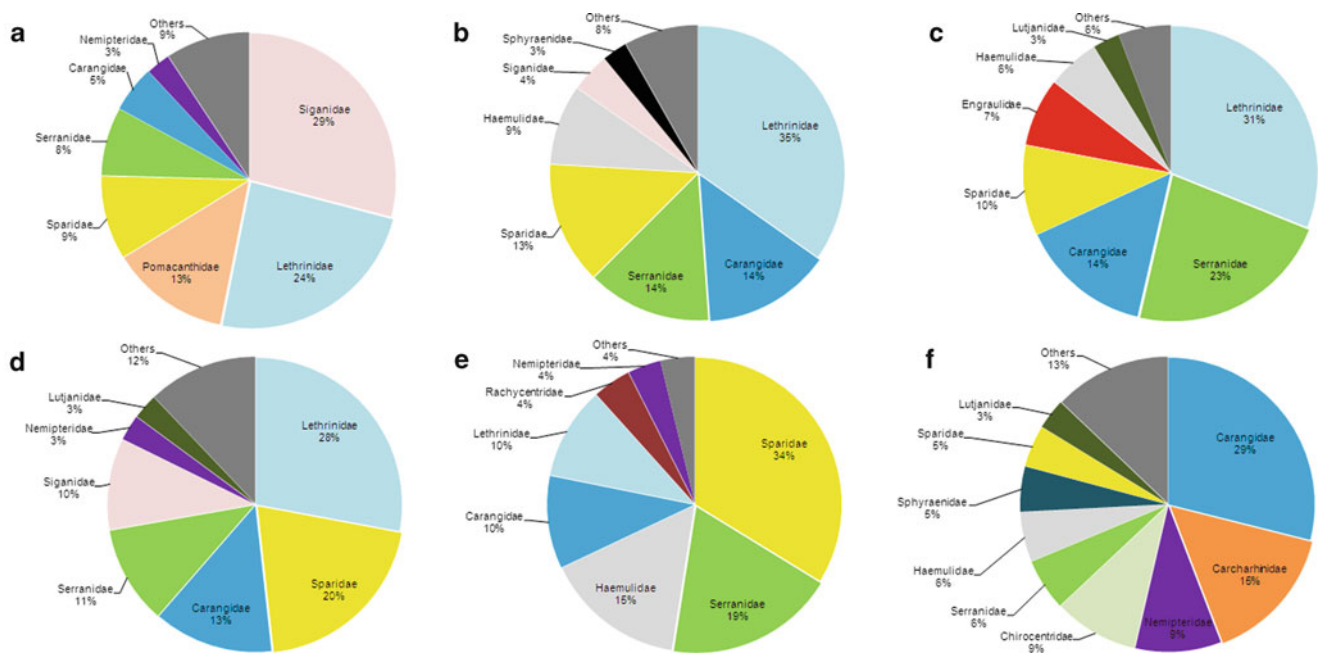


Fig. 8.12 Species composition of reef fish landings by country in the Gulf during 2007 (a) Bahrain, (b) Qatar, (c) United Arab Emirates, (d) Saudi Arabia, (e) Kuwait, (f) Iran (Data source: FAO 2009)

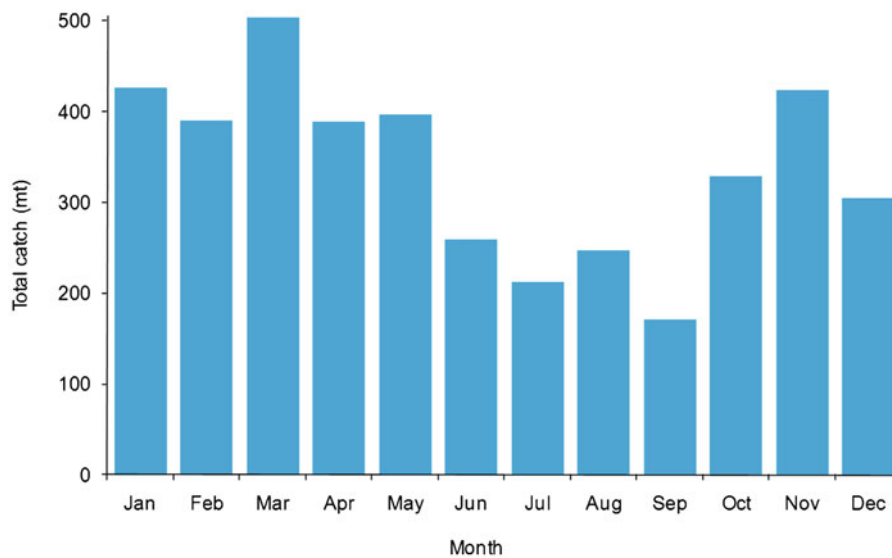


Fig. 8.13 Landings of reef associated fish by month in the southern Gulf showing the seasonal pattern in yields (Data source: Hartmann et al. 2009)

and transient species such as many representatives of the family Carangidae.

A comparison of the number of reef associated species occurring in the Gulf with that for Oman alone (579) emphasizes how limited diversity is within the area. Counts of reef fishes from underwater visual census surveys range from 71 species in Bahrain (Smith et al. 1987) to 106 species on reefs off the coast of Saudi Arabia (McCain et al. 1984). A total of

103 species have been recorded off the coast of Dubai (Riegl 2002) and 85 species on the reefs of Kuwait (Downing 1985). A compilation of records by country indicates that Iraq has the lowest number of reef associated species (68), with Saudi Arabia having the highest number of records (309) (Fig. 8.14). It must be stressed however, that the value for Saudi Arabia also includes species recorded from its Red Sea coastline. Similarly, the value for Iran (177) includes species recorded

Table 8.1 Checklist of reef associated fishes, sharks and rays of the Gulf

Order	Family	Genus and species	Common name
Anguilliformes	Muraenidae	<i>Echidna nebulosa</i> (Ahl, 1789)	Starry moray
Anguilliformes	Muraenidae	<i>Gymnomuraena zebra</i> (Shaw, 1797)	Zebra moray
Anguilliformes	Muraenidae	<i>Gymnothorax phasmatodes</i> (Smith, 1962)	Phantom moray
Anguilliformes	Muraenidae	<i>Gymnothorax undulatus</i> (Lacepède, 1803)	Undulated moray
Atheriniformes	Atherinidae	<i>Atherinomorus lacunosus</i> (Forster, 1801)	Hardyhead silverside
Atheriniformes	Atherinidae	<i>Hypoatherina temminckii</i> (Bleeker, 1853)	Samoa silverside
Aulopiformes	Synodontidae	<i>Saurida tumbil</i> (Bloch, 1795)	Greater lizardfish
Aulopiformes	Synodontidae	<i>Saurida undosquamis</i> (Richardson, 1848)	Brushtooth lizardfish
Aulopiformes	Synodontidae	<i>Synodus engelmani</i> (Schultz, 1953)	Engleman's lizardfish
Aulopiformes	Synodontidae	<i>Synodus variegatus</i> (Lacepède, 1803)	Variiegated lizardfish
Aulopiformes	Synodontidae	<i>Trachinocephalus myops</i> (Forster, 1801)	Bluntnose lizardfish
Batrachoidiformes	Batrachoididae	<i>Austrobatrachus dussumieri</i> (Valenciennes, 1837)	Flat toadfish
Beloniformes	Belonidae	<i>Ablennes hians</i> (Valenciennes, 1846)	Flat needlefish
Beloniformes	Belonidae	<i>Strongylura leiura</i> (Bleeker, 1850)	Banded needlefish
Beloniformes	Belonidae	<i>Tylosurus crocodilus crocodilus</i> (Péron & Lesueur, 1821)	Houndfish
Beloniformes	Hemiramphidae	<i>Hemiramphus marginatus</i> (Forsskål, 1775)	Yellowtip halfbeak
Beloniformes	Hemiramphidae	<i>Hyporhamphus sindensis</i> (Regan, 1905)	Sind halfbeak
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus albimarginatus</i> (Rüppell, 1837)	Silvertip shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus amboinensis</i> (Müller & Henle, 1839)	Pigeye shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus brevipinna</i> (Müller & Henle, 1839)	Spinner shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus dussumieri</i> (Valenciennes, 1839)	Whitecheek shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus leucas</i> (Valenciennes, 1839)	Bull shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus limbatus</i> (Valenciennes, 1839)	Blacktip shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus melanopterus</i> (Quoy & Gaimard, 1824)	Blacktip reef shark
Carcharhiniformes	Carcharhinidae	<i>Carcharhinus sorrah</i> (Valenciennes, 1839)	Spot-tail Shark
Carcharhiniformes	Carcharhinidae	<i>Rhizoprionodon oliginx</i> (Springer, 1964)	Grey sharpnose shark
Clupeiformes	Chirocentridae	<i>Chirocentrus dorab</i> (Forsskål, 1775)	Dorab wolf-herring
Clupeiformes	Clupeidae	<i>Herklotsichthys quadrimaculatus</i> (Rüppell, 1837)	Bluestripe herring
Clupeiformes	Clupeidae	<i>Nematalosus nasus</i> (Bloch, 1795)	Bloch's gizzard shad
Clupeiformes	Clupeidae	<i>Sardinella albella</i> (Valenciennes, 1847)	White sardinella
Clupeiformes	Clupeidae	<i>Sardinella gibbosa</i> (Bleeker, 1849)	Goldstripe sardinella
Clupeiformes	Engraulidae	<i>Encrasicholina devisi</i> (Whitley, 1940)	Devis' anchovy
Clupeiformes	Engraulidae	<i>Encrasicholina punctifer</i> (Fowler, 1938)	Bucaneer anchovy
Lamniformes	Odontaspidae	<i>Carcharias taurus</i> (Rafinesque, 1810)	Sand tiger shark
Lophiiformes	Antennariidae	<i>Antennarius nummifer</i> (Cuvier, 1817)	Spotfin frogfish
Ophidiiformes	Ophidiidae	<i>Brotula multibarbata</i> (Temminck & Schlegel, 1846)	Goatsbeard brotula
Orectolobiformes	Ginglymostomatidae	<i>Nebrius ferrugineus</i> (Lesson, 1830)	Tawny nurse shark
Orectolobiformes	Hemiscyllidae	<i>Chiloscyllium arabicum</i> (Gubanov, 1980)	Arabian carpet shark
Orectolobiformes	Hemiscyllidae	<i>Chiloscyllium griseum</i> (Müller & Henle, 1838)	Grey bambooshark
Orectolobiformes	Stegostomatidae	<i>Stegostoma fasciatum</i> (Hermann, 1783)	Zebra shark
Perciformes	Acanthuridae	<i>Acanthurus sohal</i> (Forsskål, 1775)	Sohal
Perciformes	Acanthuridae	<i>Zebrasoma xanthurum</i> (Blyth, 1852)	Yellowtail surgeonfish
Perciformes	Apogonidae	<i>Apogon coccineus</i> (Rüppell, 1838)	Ruby cardinalfish
Perciformes	Apogonidae	<i>Apogon cookii</i> (Macleay, 1881)	Cook's cardinalfish
Perciformes	Apogonidae	<i>Apogon cyanosoma</i> (Bleeker, 1853)	Yellowstriped cardinalfish
Perciformes	Apogonidae	<i>Apogon fasciatus</i> (Shaw, 1790)	Twostripe cardinalfish
Perciformes	Apogonidae	<i>Apogon fleurieu</i> (Lacepède, 1801)	Cardinalfish
Perciformes	Apogonidae	<i>Apogon nigripinnus</i> (Cuvier, 1828)	Bullseye cardinal fish
Perciformes	Apogonidae	<i>Apogon pharaonis</i> (Bellotti, 1874)	
Perciformes	Apogonidae	<i>Apogon pseudotaeniatus</i> (Gon, 1986)	Doublebar cardinalfish
Perciformes	Apogonidae	<i>Apogon taeniatus</i> (Cuvier, 1828)	Striped cardinalfish
Perciformes	Apogonidae	<i>Apogon uninotatus</i> (Smith & Radcliffe, 1912)	Brunpletet cardinalfish

(continued)

Table 8.1 (continued)

Order	Family	Genus and species	Common name
Perciformes	Apogonidae	<i>Archamia fucata</i> (Cantor, 1849)	Orangelined cardinalfish
Perciformes	Apogonidae	<i>Cheilodipterus arabicus</i> (Gmelin, 1789)	Tiger cardinal
Perciformes	Apogonidae	<i>Cheilodipterus novemstriatus</i> (Rüppell, 1838)	Twospot cardinalfish
Perciformes	Apogonidae	<i>Cheilodipterus persicus</i> (Gon, 1993)	Persian cardinalfish
Perciformes	Apogonidae	<i>Cheilodipterus quinquelineata</i> (Cuvier, 1828)	Five-lined cardinalfish
Perciformes	Apogonidae	<i>Fowleria abocellata</i> (Goren & Karplus, 1980)	Mottled cardinalfish
Perciformes	Apogonidae	<i>Fowleria variegata</i> (Valenciennes, 1832)	Variegated cardinalfish
Perciformes	Apogonidae	<i>Pseudamia tarri</i> (Randall, Lachner and Fraser, 1885)	Tarr's cardinalfish
Perciformes	Apogonidae	<i>Rhabdamia cypselura</i> (Weber, 1909)	Swallowtail cardinalfish
Perciformes	Blenniidae	<i>Antennablennius adenensis</i> (Fraser-Brunner, 1951)	Aden blenny
Perciformes	Blenniidae	<i>Antennablennius hypenetes</i> (Klungzinger, 1871)	Arabian blenny
Perciformes	Blenniidae	<i>Antennablennius variopunctatus</i> (Jatzow & Lenz, 1898)	Orangespotted blenny
Perciformes	Blenniidae	<i>Blenniella periophthalmus</i> (Valenciennes, 1836)	Blue-dashed rockskipper
Perciformes	Blenniidae	<i>Cirripectes filamentosus</i> (Alleyne & Macleay, 1877)	Filamentous blenny
Perciformes	Blenniidae	<i>Escenius pulcher</i> (Murray, 1887)	Gulf blenny
Perciformes	Blenniidae	<i>Hirculops cornifer</i> (Rüppell, 1830)	Highbrowblenny
Perciformes	Blenniidae	<i>Mimoblennius cirrosus</i> (Smith-Vaniz & Springer, 1971)	Fringed blenny
Perciformes	Blenniidae	<i>Omobranchus punctatus</i> (Valenciennes, 1836)	Muzzled blenny
Perciformes	Blenniidae	<i>Parablennius opercularis</i> (Murray, 1887)	Cheekspot blenny
Perciformes	Blenniidae	<i>Petroscirtes variabilis</i> (Cantor, 1849)	Variable sabretooth blenny
Perciformes	Caesionidae	<i>Caesio lunaris</i> (Cuvier, 1830)	Lunar fusilier
Perciformes	Caesionidae	<i>Caesio varilineata</i> (Carpenter, 1987)	Variablelined fusilier
Perciformes	Callionymidae	<i>Diplogrammus pygmaeus</i> (Fricke, 1981)	Pigmy dragonet
Perciformes	Carangidae	<i>Alectis indicus</i> (Rüppell, 1830)	Indian threadfish
Perciformes	Carangidae	<i>Alepes djedaba</i> (Forsskål, 1775)	Shrimp scad
Perciformes	Carangidae	<i>Alepes Kleinii</i> (Bloch, 1793)	Sharpbelly scad
Perciformes	Carangidae	<i>Alepes vari</i> (Cuvier, 1833)	Herring scad
Perciformes	Carangidae	<i>Atule mate</i> (Cuvier, 1833)	Yellowtail scad
Perciformes	Carangidae	<i>Carangoides bajad</i> (Forsskål, 1775)	Orangespotted trevally
Perciformes	Carangidae	<i>Carangoides caeruleopinnatus</i> (Rüppell, 1830)	Coastal trevally
Perciformes	Carangidae	<i>Carangoides chrysophrys</i> (Cuvier, 1833)	Longnose trevally
Perciformes	Carangidae	<i>Carangoides ferdau</i> (Forsskål, 1775)	Blue trevally
Perciformes	Carangidae	<i>Carangoides fulvoguttatus</i> (Forsskål, 1775)	Yellowspotted trevally
Perciformes	Carangidae	<i>Carangoides gymnostethus</i> (Cuvier, 1833)	Bludger
Perciformes	Carangidae	<i>Carangoides malabaricus</i> (Bloch & Schneider, 1801)	Malabar trevally
Perciformes	Carangidae	<i>Caranx heberi</i> (Bennett, 1828)	Blacktip trevally
Perciformes	Carangidae	<i>Caranx ignobilis</i> (Forsskål, 1775)	Giant trevally
Perciformes	Carangidae	<i>Caranx sexfasciatus</i> (Quoy & Gaimard, 1825)	Bigeye trevally
Perciformes	Carangidae	<i>Gnathanodon speciosus</i> (Forsskål, 1775)	Golden trevally
Perciformes	Carangidae	<i>Megalaspis cordyla</i> (Linnaeus, 1758)	Torpedo scad
Perciformes	Carangidae	<i>Naucrates ductor</i> (Linnaeus, 1758)	Pilotfish
Perciformes	Carangidae	<i>Parastromateus niger</i> (Bloch, 1795)	Black pomfret
Perciformes	Carangidae	<i>Scomberoides commersonnianus</i> (Lacepède, 18016)	Talang queenfish
Perciformes	Carangidae	<i>Scomberoides lysan</i> (Forsskål, 1775)	Doublespotted queenfish
Perciformes	Carangidae	<i>Scomberoides tol</i> (Cuvier, 1832)	Needlescaled queenfish
Perciformes	Carangidae	<i>Selar crumenophthalmus</i> (Bloch, 1793)	Bige eye scad
Perciformes	Carangidae	<i>Selaroides leptolepis</i> (Cuvier, 1833)	Yellowstripe scad
Perciformes	Carangidae	<i>Seriola dumerili</i> (Risso, 1810)	Greater amberjack
Perciformes	Carangidae	<i>Seriolina nigrofasciata</i> (Rüppell, 1829)	Blackbanded trevally
Perciformes	Carangidae	<i>Trachinothus blochii</i> (Lacepède, 1801)	Snubnose pompano
Perciformes	Carangidae	<i>Trachurus indicus</i> (Nekrasov, 1966)	Arabian scad

(continued)

Table 8.1 (continued)

Order	Family	Genus and species	Common name
Perciformes	Carangidae	<i>Ulua mentalis</i> (Cuvier, 1833)	Longrakered trevally
Perciformes	Carangidae	<i>Uraspis helvola</i> (Foster, 1801)	Whitetongue jack
Perciformes	Chaetodontidae	<i>Chaetodon gardineri</i> (Norman, 1939)	Gardiner's butterflyfish
Perciformes	Chaetodontidae	<i>Chaetodon melapterus</i> (Guichenot, 1862)	Arabian butterflyfish
Perciformes	Chaetodontidae	<i>Chaetodon nigropunctatus</i> (Sauvage, 1880)	Dark butterflyfish
Perciformes	Chaetodontidae	<i>Heniochus acuminatus</i> (Linnaeus, 1758)	Longfin bannerfish
Perciformes	Drepaneidae	<i>Drepane longimana</i> (Bloch & Schneider, 1801)	Concertina fish
Perciformes	Drepanidae	<i>Drepane punctata</i> (Linnaeus, 1758)	Spotted sicklefish
Perciformes	Echeneidae	<i>Echeneis naucrates</i> (Linnaeus, 1758)	Live sharksucker
Perciformes	Ephippidae	<i>Ephippus orbis</i> (Bloch, 1787)	Spadefish
Perciformes	Ephippidae	<i>Platax obicularis</i> (Forsskål, 1775)	Obicularis batfish
Perciformes	Ephippidae	<i>Platax teira</i> (Forsskål, 1775)	Teira
Perciformes	Gerreidae	<i>Gerres filamentosus</i> (Cuvier, 1829)	Whipfin silver-biddy
Perciformes	Gerreidae	<i>Gerres longirostris</i> (Bleeker, 1854)	Longtail silver-biddy
Perciformes	Gerreidae	<i>Gerres oyena</i> (Forsskål, 1775)	Common silver-biddy
Perciformes	Gobiidae	<i>Amblyeleotris diagonalis</i> (Polunin & Lubbock, 1979)	Slantbar shrimpgoby
Perciformes	Gobiidae	<i>Amblyeleotris periophthalma</i> (Bleeker, 1853)	Blotchy shrimpgoby
Perciformes	Gobiidae	<i>Amblygobius albimaculatus</i> (Rüppell, 1830)	Tailspot goby
Perciformes	Gobiidae	<i>Amblygobius nocturnus</i> (Herre, 1945)	Orangestriped goby
Perciformes	Gobiidae	<i>Asterropteryx semipunctatus</i> (Rüppell, 1830)	Halfspotted goby
Perciformes	Gobiidae	<i>Callogobius bifasciatus</i> (Smith, 1958)	Doublebar goby
Perciformes	Gobiidae	<i>Callogobius plumatus</i> (Smith, 1959)	Feather goby
Perciformes	Gobiidae	<i>Coryogalops adamsoni</i> (Goren, 1985)	Adamson's goby
Perciformes	Gobiidae	<i>Coryogalops anomolus</i> (Smith, 1958)	Anomalous goby
Perciformes	Gobiidae	<i>Cryptocentroides arabicus</i> (Gmelin, 1789)	Arabian goby
Perciformes	Gobiidae	<i>Cryptocentrus caeruleopunctatus</i> (Rüppell, 1830)	Harlequin prawn-goby
Perciformes	Gobiidae	<i>Cryptocentrus fasciatus</i> (Playfair & Günther, 1867)	Y-bar shrimpgoby
Perciformes	Gobiidae	<i>Cryptocentrus lutheri</i> (Klausewitz, 1960)	Luther's prawn-goby
Perciformes	Gobiidae	<i>Eviota guttata</i> (Lacher & Karnella, 1978)	Spotted dwarfgoby
Perciformes	Gobiidae	<i>Eviota pardalota</i> (Lachner & Karnella, 1978)	Leopard dwarfgoby
Perciformes	Gobiidae	<i>Eviota sebreei</i> (Jordan & Seale, 1906)	Redstripe dwarfgoby
Perciformes	Gobiidae	<i>Flabelligobius latruncularius</i> (Klausewitz, 1974)	Fan shrimpgoby
Perciformes	Gobiidae	<i>Gnatholepis anjerensis</i> (Bleeker, 1850)	Anjer goby
Perciformes	Gobiidae	<i>Gobiodon reticulatus</i> (Playfair & Günther, 1867)	Reticulated coral goby
Perciformes	Gobiidae	<i>Heteroleotris vulgare</i> (Kluzinger, 1871)	Common goby
Perciformes	Gobiidae	<i>Istigobius decoratus</i> (Herre, 1927)	Decorated goby
Perciformes	Gobiidae	<i>Istigobius ornatus</i> (Rüppell, 1830)	Ornate goby
Perciformes	Gobiidae	<i>Papillogobius melanobranchus</i> (Fowler, 1934)	Blackthroat goby
Perciformes	Gobiidae	<i>Parachaeturichthys polynema</i> (Bleeker, 1853)	Ocellus-tail goby
Perciformes	Gobiidae	<i>Priolepis cincta</i> (Regan, 1908)	Girdled goby
Perciformes	Gobiidae	<i>Trimma winterbottomi</i> (Randall & Downing, 1994)	Winterbottom's goby
Perciformes	Gobiidae	<i>Valenciennea persica</i> (Hoese & Larson, 1994)	Gulf goby
Perciformes	Gobiidae	<i>Valenciennea sexguttata</i> (Valenciennes, 1837)	Sixspot goby
Perciformes	Haemulidae	<i>Diagramma pictum</i> (Thunberg, 1792)	Painted sweetlips
Perciformes	Haemulidae	<i>Plectorhinchus gaterinus</i> (Forsskål, 1775)	Blackspotted rubberlip
Perciformes	Haemulidae	<i>Plectorhinchus pictus</i> (Tortonese, 1935)	Trout sweetlips
Perciformes	Haemulidae	<i>Plectorhinchus sordidus</i> (Klunzinger, 1870)	Sordid sweetlip
Perciformes	Haemulidae	<i>Pomadasys kaakan</i> (Cuvier, 1830)	Javelin grunter
Perciformes	Haemulidae	<i>Pomadasys maculatum</i> (Bloch, 1797)	Saddle grunt
Perciformes	Haemulidae	<i>Pomadasys stridens</i> (Forsskål, 1775)	Striped grunt
Perciformes	Labridae	<i>Cheilinus lunulatus</i> (Forsskål, 1775)	Broomtail wrasse

(continued)

Table 8.1 (continued)

Order	Family	Genus and species	Common name
Perciformes	Labridae	<i>Choerodon robustus</i> (Günther, 1862)	Robust tuskfish
Perciformes	Labridae	<i>Halichoeres marginatus</i> (Rüppell, 1835)	Dusky wrasse
Perciformes	Labridae	<i>Halichoeres stigmaticus</i> (Randall & Smith, 1982)	U-Spot wrasse
Perciformes	Labridae	<i>Halichoeres zeylonicus</i> (Bennett, 1832)	Goldstripe wrasse
Perciformes	Labridae	<i>Labroides dimidiatus</i> (Valenciennes, 1839)	Black-and-blue cleaner wrasse
Perciformes	Labridae	<i>Leptojulius cyanopleura</i> (Bleeker, 1853)	Shoulderspot wrasse
Perciformes	Labridae	<i>Paracheilinus mccoskeri</i> (Randall & Harmelin-Vivien, 1977)	McCosker's wrasse
Perciformes	Labridae	<i>Pteragogus flagellifer</i> (Valenciennes, 1839)	Cocktail wrasse
Perciformes	Labridae	<i>Stethojulis interrupta</i> (Bleeker, 1851)	Cutribbon wrasse
Perciformes	Labridae	<i>Suezichthys gracilis</i> (Steindachner & Döderlein, 1887)	Slender wrasse
Perciformes	Labridae	<i>Thalassoma lunare</i> (Linnaeus, 1758)	Moon wrasse
Perciformes	Lethrinidae	<i>Lethrinus borbonicus</i> (Valenciennes, 1830)	Snubnose emperor
Perciformes	Lethrinidae	<i>Lethrinus lentjan</i> (Lacepède, 1802)	Pinkear emperor
Perciformes	Lethrinidae	<i>Lethrinus microdon</i> (Valenciennes, 1830)	Smalltooth emperor
Perciformes	Lethrinidae	<i>Lethrinus nebulosus</i> (Forsskål, 1775)	Spangled emperor
Perciformes	Lutjanidae	<i>Lutjanus argentimaculatus</i> (Forsskål, 1775)	Mangrove red snapper
Perciformes	Lutjanidae	<i>Lutjanus coeruleolineatus</i> (Rüppell, 1830)	Bluelined snapper
Perciformes	Lutjanidae	<i>Lutjanus ehrenbergii</i> (Peters, 1869)	Ehrenberg's snapper
Perciformes	Lutjanidae	<i>Lutjanus fulviflamma</i> (Forsskål, 1775)	Blackspot snapper
Perciformes	Lutjanidae	<i>Lutjanus johnii</i> (Bloch, 1792)	John's snapper
Perciformes	Lutjanidae	<i>Lutjanus lutjanus</i> (Bloch, 1790)	Bigeye snapper
Perciformes	Lutjanidae	<i>Lutjanus malabaricus</i> (Bloch & Schneider, 1801)	Malabar blood snapper
Perciformes	Lutjanidae	<i>Lutjanus quinquelineatus</i> (Bloch, 1790)	Fivelined snapper
Perciformes	Lutjanidae	<i>Lutjanus russelli</i> (Bleeker, 1849)	Russell's snapper
Perciformes	Lutjanidae	<i>Lutjanus sanguineus</i> (Cuvier, 1828)	Humphead snapper
Perciformes	Lutjanidae	<i>Pinjalo pinjalo</i> (Bleeker, 1850)	Pinjalo
Perciformes	Menidae	<i>Mene maculata</i> (Bloch & Schneider, 1801)	Moonfish
Perciformes	Monodactylidae	<i>Monodactylus argenteus</i> (Linnaeus, 1758)	Silver mono
Perciformes	Mugilidae	<i>Liza subviridis</i> (Valenciennes, 1836)	Greenback mullet
Perciformes	Mullidae	<i>Mulloidichthys flavolineatus</i> (Lacepède, 1802)	Yellowstripe goatfish
Perciformes	Mullidae	<i>Parupeneus heptacanthus</i> (Lacepède, 1801)	Cinnabar goatfish
Perciformes	Mullidae	<i>Parupeneus margaritatus</i> (Randall & Guézé, 1984)	Pearly goatfish
Perciformes	Mullidae	<i>Parupeneus rubescens</i> (Lacepède, 1801)	Rosy goatfish
Perciformes	Mullidae	<i>Upeneus tragula</i> (Richardson, 1845)	Freckled goatfish
Perciformes	Mullidae	<i>Upeneus vittatus</i> (Forsskål, 1775)	Striped goatfish
Perciformes	Nemipteridae	<i>Nemipterus peronii</i> (Valenciennes, 1830)	Notched threadfin bream
Perciformes	Nemipteridae	<i>Scolopsis bimaculatus</i> (Rüppell, 1828)	Thumbprint monocle
Perciformes	Nemipteridae	<i>Scolopsis ghanam</i> (Forsskål, 1775)	Arabian monocle bream
Perciformes	Nemipteridae	<i>Scolopsis taeniatus</i> (Cuvier, 1830)	Blackstreaked monocle bream
Perciformes	Nemipteridae	<i>Scolopsis vosmeri</i> (Bloch, 1792)	Whitecheek monocle bream
Perciformes	Pinguipedidae	<i>Parapercis nebulosa</i> (Quoy & Gaimard, 1825)	Barred sandperch
Perciformes	Platycephalidae	<i>Platycephalus indicus</i> (Linnaeus, 1758)	Bartail flathead
Perciformes	Platycephalidae	<i>Thysanophrys celebicus</i> (Bleeker, 1854)	Sulawesi flathead
Perciformes	Pomacanthidae	<i>Pomacanthus maculosus</i> (Forsskål, 1775)	Yellowbar angelfish
Perciformes	Pomacentridae	<i>Abudefduf saxatilis</i> (Linnaeus, 1758)	Sergeant major
Perciformes	Pomacentridae	<i>Abudefduf sordidus</i> (Forsskål, 1775)	Blackspot sergeant
Perciformes	Pomacentridae	<i>Abudefduf vaigiensis</i> (Quoy & Gaimard, 1825)	Indo-Pacific sergeant
Perciformes	Pomacentridae	<i>Amphiprion clarkii</i> (Bennett, 1830)	Clark's anemonefish
Perciformes	Pomacentridae	<i>Chromis flavaxilla</i> (Randall, 1994)	Arabian chromis
Perciformes	Pomacentridae	<i>Chromis ternatensis</i> (Bleeker, 1856)	Ternate chromis

(continued)

Table 8.1 (continued)

Order	Family	Genus and species	Common name
Perciformes	Pomacentridae	<i>Chromis weberi</i> (Fowler & Bean, 1928)	Weber's chromis
Perciformes	Pomacentridae	<i>Chromis xanthopterygia</i> (Randall & McCarthy, 1988)	Yellowfin chromis
Perciformes	Pomacentridae	<i>Dascyllus trimaculatus</i> (Rüppell, 1829)	Threespot dascyllus
Perciformes	Pomacentridae	<i>Neopomacentrus cyanomos</i> (Bleeker, 1856)	Regal damselfish
Perciformes	Pomacentridae	<i>Neopomacentrus sindensis</i> (Day, 1873)	Arabian demoiselle
Perciformes	Pomacentridae	<i>Pomacentrus aquilus</i> (Allen & Randall, 1980)	Dark damselfish
Perciformes	Pomacentridae	<i>Pomacentrus leptus</i> (Allen & Randall, 1980)	Slender damselfish
Perciformes	Pomacentridae	<i>Pomacentrus trichourus</i> (Playfair & Günther, 1867)	Paletail damselfish
Perciformes	Pomacentridae	<i>Pomacentrus trilineatus</i> (Cuvier, 1830)	Threeline damselfish
Perciformes	Priacanthidae	<i>Priacanthus blochii</i> (Bleeker, 1853)	Paeony bulleye
Perciformes	Priacanthidae	<i>Priacanthus tayenus</i> (Richardson, 1846)	Purple spotted bigeye
Perciformes	Pseudochromidae	<i>Pseudochromis aldabraensis</i> (Bauchot & Boutin, 1958)	Orange dottyback
Perciformes	Pseudochromidae	<i>Pseudochromis dutoiti</i> (Smith, 1955)	Dutoiti
Perciformes	Pseudochromidae	<i>Pseudochromis persicus</i> (Murry, 1887)	Persian dottyback
Perciformes	Rachycentridae	<i>Rachycentron canadum</i> (Linnaeus, 1766)	Cobia
Perciformes	Scaridae	<i>Chlorurus sordidus</i> (Forsskål, 1775)	Daisy parrotfish
Perciformes	Scaridae	<i>Scarus ferrugineus</i> (Forsskål, 1775)	Rusty parrotfish
Perciformes	Scaridae	<i>Scarus fuscopurpureus</i> (Kluzinger, 1871)	Purplebrown parrotfish
Perciformes	Scaridae	<i>Scarus ghobban</i> (Forsskål, 1775)	Bluebarred parrotfish
Perciformes	Scaridae	<i>Scarus persicus</i> (Randall & Bruce, 1983)	Gulf parrotfish
Perciformes	Scaridae	<i>Scarus psittacus</i> (Forsskål, 1775)	Common parrotfish
Perciformes	Scatophagidae	<i>Scatophagus argus</i> (Bloch, 1788)	Spotted scat
Perciformes	Serranidae	<i>Aethaloperca rogaea</i> (Forsskål, 1775)	Redmouth grouper
Perciformes	Serranidae	<i>Cephalopholis hemistiktos</i> (Rüppell, 1830)	Yellowfin hind
Perciformes	Serranidae	<i>Epinephelus areolatus</i> (Forsskål, 1775)	Areolate grouper
Perciformes	Serranidae	<i>Epinephelus bleekeri</i> (Vaillant, 1877)	Bleeker's grouper
Perciformes	Serranidae	<i>Epinephelus caeruleopunctatus</i> (Bloch, 1790)	Whitespotted grouper
Perciformes	Serranidae	<i>Epinephelus coioides</i> (Hamilton, 1822)	Orangespotted grouper
Perciformes	Serranidae	<i>Epinephelus latifasciatus</i> (Temminck & Schlegel, 1842)	Banded grouper
Perciformes	Serranidae	<i>Epinephelus malabaricus</i> (Bloch & Schneider, 1801)	Malabar grouper
Perciformes	Serranidae	<i>Epinephelus multinotatus</i> (Peters, 1876)	Whiteblotched grouper
Perciformes	Serranidae	<i>Epinephelus polylepis</i> (Randall & Heemstra, 1991)	Smallscale grouper
Perciformes	Siganidae	<i>Siganus canaliculatus</i> (Park, 1797)	White-spotted spinefoot
Perciformes	Siganidae	<i>Siganus javus</i> (Linnaeus, 1766)	Streaked spinefoot
Perciformes	Siganidae	<i>Siganus luridus</i> (Rüppell, 1829)	Dusky spinefoot
Perciformes	Siganidae	<i>Siganus rivulatus</i> (Forsskål, 1775)	Marbled spinefoot
Perciformes	Sillaginidae	<i>Sillago sihama</i> (Forsskål, 1775)	Silver sillago
Perciformes	Scombridae	<i>Rastrelliger kanagurta</i> (Cuvier, 1817)	Indian mackerel
Perciformes	Sparidae	<i>Acanthopagrus berda</i> (Forsskål, 1775)	Picnic seabream
Perciformes	Sparidae	<i>Acanthopagrus bifasciatus</i> (Forsskål, 1775)	Two-bar seabream
Perciformes	Sparidae	<i>Cheimerius nufar</i> (Valenciennes, 1830)	Santer seabream
Perciformes	Sparidae	<i>Crenidens crenidens</i> (Forsskål, 1775)	Karanteen seabream
Perciformes	Sparidae	<i>Diplodus sargus kotschy</i> (Steindachner, 1876)	Onespot seabream
Perciformes	Sparidae	<i>Rhabdosargus haffara</i> (Forsskål, 1775)	Haffara seabream
Perciformes	Sparidae	<i>Rhabdosargus sarba</i> (Forsskål, 1775)	Goldlined seabream
Perciformes	Sparidae	<i>Sparidentex hasta</i> (Valenciennes, 1830)	Sobaity seabream
Perciformes	Sphyraenidae	<i>Sphyraena barracuda</i> (Walbaum, 1792)	Great barracuda
Perciformes	Sphyraenidae	<i>Sphyraena flavicauda</i> (Rüppell, 1838)	Yellowtail barracuda
Perciformes	Sphyraenidae	<i>Sphyraena fosteri</i> (Cuvier, 1829)	Bigeye barracuda
Perciformes	Sphyraenidae	<i>Sphyraena jello</i> (Cuvier, 1829)	Pickhandle barracuda
Perciformes	Sphyraenidae	<i>Sphyraena obtusata</i> (Cuvier, 1829)	Obtuse barracuda

(continued)

Table 8.1 (continued)

Order	Family	Genus and species	Common name
Perciformes	Sphyraenidae	<i>Sphyraena putnamiae</i> (Jordan & Seale, 1905)	Sawtooth barracuda
Perciformes	Sphyraenidae	<i>Sphyraena qenie</i> (Klunzinger, 1870)	Blacktail barracuda
Perciformes	Teraponidae	<i>Pelates quadrilineatus</i> (Bloch, 1790)	Fourlined terapon
Perciformes	Teraponidae	<i>Terapon puta</i> (Cuvier & Valenciennes, 1829)	Smallscaled terapon
Perciformes	Teraponidae	<i>Terapon theraps</i> (Cuvier & Valenciennes, 1829)	Largescaled terapon
Perciformes	Tripterygiidae	<i>Enneapterygius pusillus</i> (Rüppell, 1835)	Pixie tripplefin
Pleuronectiformes	Bothidae	<i>Bothus pantherinus</i> (Rüppell, 1828)	Leopard flounder
Pleuronectiformes	Soleidae	<i>Pardachirus marmoratus</i> (Lacepède, 1802)	Finless sole
Rajiformes	Dasyatidae	<i>Himantura uarnak</i> (Forsskål, 1775)	Reticulated whipray
Rajiformes	Dasyatidae	<i>Pastinachus sephen</i> (Forsskål, 1775)	Cowtail stingray
Rajiformes	Dasyatidae	<i>Taeniura lymma</i> (Forsskål, 1775)	Bluespotted ribbontail ray
Rajiformes	Myliobatidae	<i>Aetobatus narinari</i> (Euphrasen, 1790)	Spotted eagle ray
Rajiformes	Myliobatidae	<i>Aetomyleus nichofi</i> (Bloch & Schneider, 1801)	Banded eagle ray
Rajiformes	Myliobatidae	<i>Rhinoptera javanica</i> (Müller & Henle, 1841)	Javanese cownose ray
Rajiformes	Rhinobatidae	<i>Rhina ancylostoma</i> (Bloch & Schneider, 1801)	Bowmouth guitarfish
Rajiformes	Rhinobatidae	<i>Rhynchobatus djiddensis</i> (Forsskål, 1775)	Giant guitarfish
Scorpaeniformes	Scorpaenidae	<i>Pterois miles</i> (Bennett, 1828)	Military turkeyfish
Scorpaeniformes	Scorpaenidae	<i>Pterois russellii</i> (Bennett, 1831)	Plaintail turkeyfish
Scorpaeniformes	Scorpaenidae	<i>Pterois volitans</i> (Linnaeus, 1758)	Common lionfish
Scorpaeniformes	Scorpaenidae	<i>Scorpaenopsis barbatus</i> (Rüppell, 1838)	Bearded scorpionfish
Siluriformes	Plotosidae	<i>Plotosus lineatus</i> (Thunberg, 1787)	Striped eel catfish
Syngnathiformes	Centriscidae	<i>Centriscus scutatus</i> (Linnaeus, 1758)	Grooved shrimpfish
Syngnathiformes	Fistulariidae	<i>Fistularia petimba</i> (Lacepède, 1803)	Red cornetfish
Syngnathiformes	Sygnathidae	<i>Acentronura tentaculata</i> (Günther, 1870)	Pipehorse
Syngnathiformes	Sygnathidae	<i>Bryx analicarens</i> (Duncker, 1915)	Pink pipefish
Syngnathiformes	Sygnathidae	<i>Choeroichthys brachysoma</i> (Bleeker, 1855)	Shortbodied pipefish
Syngnathiformes	Sygnathidae	<i>Cosmocampus investigatorius</i> (Hora, 1925)	Investigator pipefish
Syngnathiformes	Sygnathidae	<i>Hippocampus histrix</i> (Kaup, 1853)	Thorny seahorse
Syngnathiformes	Sygnathidae	<i>Doryrhamphus excisus excisus</i> (Kaup, 1856)	Bluestripe pipefish
Syngnathiformes	Sygnathidae	<i>Hippichthys cyanospilus</i> (Bleeker, 1854)	Bluespeckled pipefish
Syngnathiformes	Sygnathidae	<i>Hippichthys penicillus</i> (Cantor, 1849)	Beady pipefish
Syngnathiformes	Sygnathidae	<i>Hippocampus kuda</i> (Bleeker, 1852)	Spotted seahorse
Tetraodontiformes	Balistidae	<i>Abalistes stellatus</i> (Lacepède, 1798)	Starry triggerfish
Tetraodontiformes	Balistidae	<i>Rhinecanthus assasi</i> (Forsskål, 1775)	Picasso triggerfish
Tetraodontiformes	Balistidae	<i>Sufflamen chrysopterus</i> (Bloch & Schneider, 1801)	Flagtail triggerfish
Tetraodontiformes	Diodontidae	<i>Cylichthys orbicularis</i> (Bloch, 1785)	Orbicular burrfish
Tetraodontiformes	Monacanthidae	<i>Aluterus monoceros</i> (Linnaeus, 1758)	Unicorn leatherjacket
Tetraodontiformes	Monacanthidae	<i>Stephanolepis diaspros</i> (Fraser-Brunner, 1940)	Reticulated filefish
Tetraodontiformes	Ostraciidae	<i>Ostracion cubicus</i> (Linnaeus, 1758)	Yellow trunkfish
Tetraodontiformes	Ostraciidae	<i>Ostracion cyanurus</i> (Rüppell, 1828)	Bluetail trunkfish
Tetraodontiformes	Tetraodontidae	<i>Arothron stellatus</i> (Bloch & Schneider, 1801)	Stellate puffer
Tetraodontiformes	Tetraodontidae	<i>Chelonodon patoca</i> (Hamilton, 1822)	Milkspotted puffer
Tetraodontiformes	Tetraodontidae	<i>Lagocephalus sceleratus</i> (Gmelin, 1788)	Elongate puffer
Tetraodontiformes	Triacanthidae	<i>Triacanthus biaculeatus</i> (Bloch, 1786)	Shortnose tripodfish
Torpediniformes	Torpedinidae	<i>Torpedo panthera</i> (Olfers, 1831)	Panther electric ray
Torpediniformes	Torpedinidae	<i>Torpedo sinuspersici</i> (Olfers, 1831)	Marbled electric ray

Data source: Randall and Smith 1982; Sivasubramaniam and Ibrahim 1982; McCain et al. 1984; Dawson 1985; Downing 1985; Randall et al. 1985, 1994; Al-Baharna 1986; Smith et al. 1987; Williams 1988; Coles and Tarr 1990; Randall and Heemstra 1991; Randall 1994; Bishop 2003; Froese and Pauly 2009; Burt et al. 2009

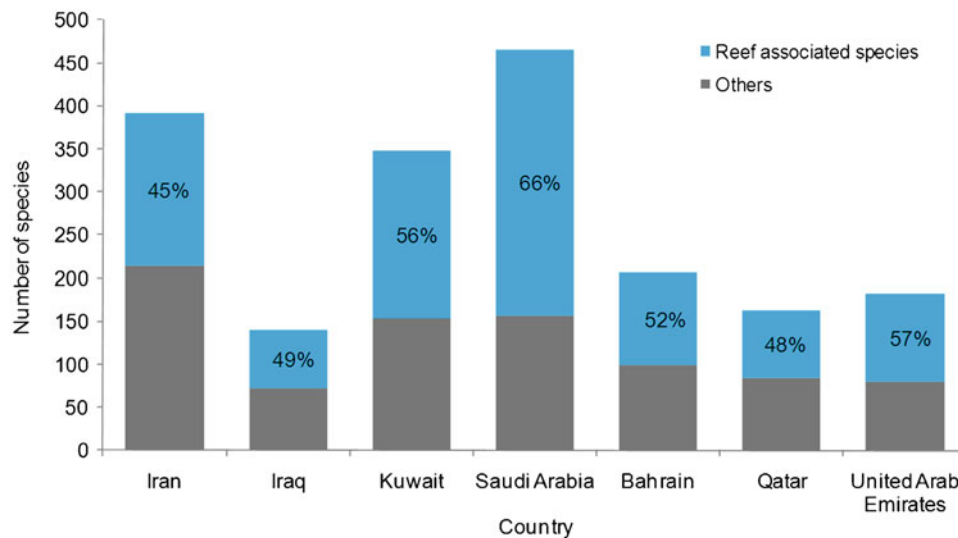


Fig. 8.14 Total number of marine fish species by country in the Gulf showing the proportion that are reef associated (data labels) (Data source: Froese and Pauly 2009; Bishop 2003; Riegl 2002)

from the Gulf of Oman. The numbers for Oman (982 species of which 579 are reef associated) were excluded from the synopsis as Oman has such a comparatively small coastline inside the Gulf by comparison with that along the Gulf of Oman and Arabian Sea.

Analyses of reef fish distributions support the contention that a major zoogeographic discontinuity exists within the region and that the Gulf reef fish fauna cannot be relegated to either the western Indian Ocean province or the Indo-Polynesian province, rather, it is a transitional fauna with elements belonging to each (Smith et al. 1987). Peak diversity in the western Gulf is attained on the best developed off-shore reefs of Saudi Arabia (McCain et al. 1984; Downing 1985; Smith et al. 1987; Coles and Tarr 1990). Diversity declined moving northwards and southwards as environmental conditions become more extreme. Whilst there are no survey data available, the richest reef fish fauna is considered to be located on the Iranian reefs of the eastern Gulf, near the Strait of Hormuz. These reefs lie in deeper water than those of the western Gulf and are supplied with oceanic water inflowing through the Strait (Price et al. 1993). Species richness has been observed to increase with depth on the reefs of Bahrain (Smith and Saleh 1987) and Saudi Arabia (Coles and Tarr 1990). A cursory analysis of data held in Fishbase (Froese and Pauly 2009), indicates that about half of the marine fishes present in the region are associated with coral reefs (Fig. 8.14), which is an attestation of the importance of these habitats from both a fisheries management and marine biodiversity conservation point of view.

Demersal reef fish are traditionally considered to undergo little or no seasonal change in abundance because of the relatively constant environmental regimes that typically

characterize tropical waters. However, the distribution and abundance of Gulf reef fish is known to vary seasonally and among habitat types (McCain et al. 1984; Downing 1985; Smith et al. 1987; Basson et al. 1977). A comprehensive survey of the demersal fisheries resources of the southern Gulf (Shallard and Associates 2003a) defined three patterns of seasonal abundance; (i) species that were more abundant in the winter months (ii) those that were more abundant in the summer and (iii) species whose abundance did not change between seasons (Table 8.2 and Fig. 8.15). The overall biomass of demersal (primarily reef associated) species declines dramatically with increasing seawater temperature and vice versa (Fig. 8.16). As there is no direct evidence from tagging, it is assumed that the large scale reduction in abundance is a result of the movement of fish to deeper and cooler waters during the summer.

A survey of coral reefs off the Gulf coast of Saudi Arabia (Coles and Tarr 1990) indicated seasonal patterns of abundance, with fish apparently moving from shallow near shore reefs in the summer to deeper offshore reefs in the winter. Seasonal changes in abundance have also been attributed to an increase in herbivorous fish numbers in association with algal blooms (McCain et al. 1984). A comparison of artificial and natural reefs off the coast of Dubai indicated that fish communities differed significantly among habitat types in the summer and fall but converged in the winter and spring. This was shown to be a result of species richness and abundance remaining stable throughout the year on natural coral patches but increasing significantly on artificial reefs in the summer due to adult immigration (Burt et al. 2009).

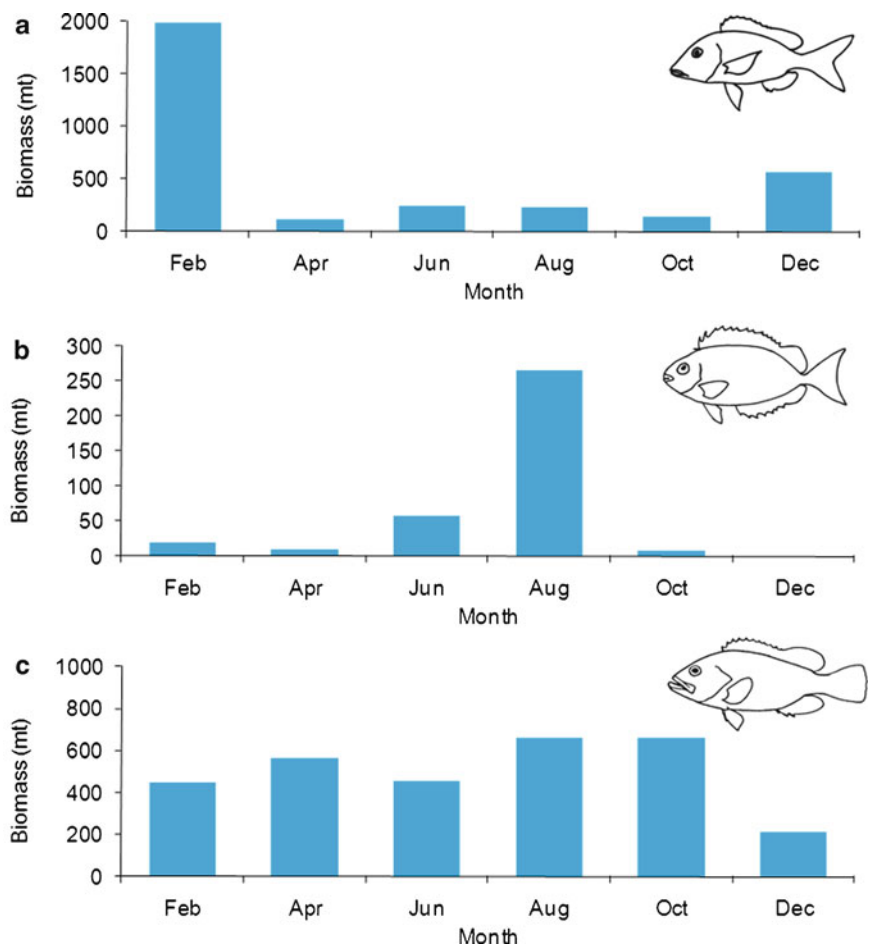
Another notable characteristic of the distribution of Gulf reef fish is their utilization of multiple habitat types, hence the

Table 8.2 Seasonal abundance characteristics of common demersal fishes in the southern Gulf

Greater abundance in winter (Nov–Feb)	Greater abundance in summer (May–Sept)	No seasonal abundance change
<i>Acanthopagrus latus</i>	<i>Argyrops spinifer</i>	<i>Lethrinus lentjan</i>
<i>Acanthopagrus bifasciatus</i>	<i>Siganus canaliculatus</i>	<i>Lethrinus nebulosus</i>
<i>Carangoides bajad</i>	<i>Lutjanus lutjanus</i>	<i>Epinephelus coioides</i>
<i>Plectorhinchus pictus</i>	<i>Scolopsis taeniatus</i>	<i>Gerres longirostris</i>
<i>Rhabdosargus sarba</i>		<i>Plectorhinchus sordidus</i>
<i>Lethrinus borbonicus</i>		<i>Gnathanodon speciosus</i>
<i>Sphyraena qenie</i>		
<i>Saurida undosquamis</i>		
<i>Saurida tumbil</i>		
<i>Epinephelus areolatus</i>		

Data source: Shallard and Associates 2003b

Fig. 8.15 Seasonal changes in the abundance of representative reef fish from the southern Gulf showing (a) increased abundance in winter (*Lethrinus borbonicus*), (b) increased abundance in the summer (*Siganus canaliculatus*), and (c) relatively constant abundance throughout the year (*Epinephelus coioides*) (Data source: Shallard and Associates 2003b)



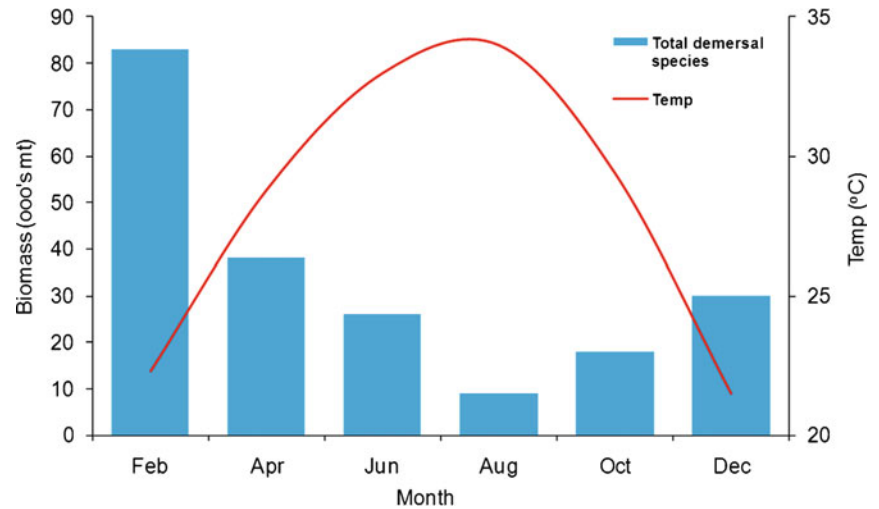
appearance of many reef associated taxa in catches (such as those made by trawlers) that are derived from sandy and soft sediment substrates. Beech (2004) produced a checklist of the major fish species of Abu Dhabi Emirate in the southern part of the Gulf. This summarized the general habitat preferences of 121 fish taxa in the region. Of the 69 species listed as being reef associated, 52 of these also occurred in different habitats and only 17 were uniquely associated with coral reefs.

8.4 Reef Fish Ecology, Population Dynamics and Reproduction

8.4.1 Reef Fish Ecology

Underwater visual census surveys (UVC) have many advantages for assessing reef fish communities and fisheries resources; they are relatively cost effective, rapid and are not

Fig. 8.16 Seasonal variability in the total biomass of demersal species showing the relationship with changes in seawater temperature in the southern Gulf (Data source: Shallard and Associates 2003b)



subject to the sampling bias associated with gear selectivity common in fishery-dependent methods of assessment. The techniques have limitations though and are usually restricted to a maximum depth of 20 m, although this is not so relevant in the context of the Gulf given its shallow nature. It is surprising then that there are so few applications of UVC in the region, particularly by comparison with other methods such as trawl surveys and age and length based demographic assessments. UVC surveys in the United Arab Emirates (Riegl 2002; Burt et al. 2009), Bahrain (Smith et al. 1987), Saudi Arabia (McCain et al. 1984; Coles and Tarr 1990) and Kuwait (Downing 1985) have helped to elucidate a variety of ecological aspects of the reef ichthyofauna in the Gulf. These include; diversity, abundance and seasonality (discussed in the previous section), species composition, community/trophic structure, biomass density, habitat utilization, and the impacts of sea-surface temperature anomalies and associated habitat modifications.

Time series data from Saudi Arabia (McCain et al. 1984) have characterized patterns of recruitment and growth for a suite of commonly encountered reef fish. *Sardinella* species (which are not traditionally considered to be reef associated) were found to use inshore reefs as nursery grounds before moving to a more pelagic habitat. The species composition of nearshore reefs was also found to be controlled by differences in habitat type and thermal seasonality. The combination of these two characteristics imposed a succession regime in the recruitment and growth of reef fishes and changes in the utilization of the reef habitat by transient species (McCain et al. 1984). Other studies from Saudi Arabia have demonstrated that there is no significant relationship between fish abundance and live coral cover and a significant negative relationship between the abundance of reef fish and macroalgae cover (Coles and Tarr 1990).

Habitat changes due to mass coral mortalities occurring as a result of the 1996 and 1998 positive sea-surface

temperature anomalies and the associated impacts on the reef fish communities of Dubai were investigated by Riegl (2002). Overall, reef fish diversity was found to decrease from 95 to 64 species. Despite the mass coral mortality, the maintenance of structural complexity allowed the fish assemblages to avoid the catastrophic change experienced by the coral community. Reef fish assemblages on the natural reefs of Dubai have also been compared to those on artificial structures. Whilst large artificial reefs were found to support diverse and abundant fish communities, they differed both structurally and functionally from those occurring in natural habitats (Burt et al. 2009). Other UVC surveys of reef fish in the United Arab Emirates have demonstrated that even within seasons, there is a high degree of variability in abundance between reefs, with biomass densities of reef fish ranging from 39 to 290 mt/km². These data have also demonstrated that the marine protected areas in the southern Gulf have greater biomass densities and mean sizes of some commercially exploited species by comparison with reefs open to exploitation (Grandcourt, unpublished data).

Aspects of the fisheries ecology of the southern Gulf have also been established using a combination of data derived from biological studies and abundance surveys which used trapping, acoustics and the swept area method (Shallard and Associates 2003a, b, c). This provided information on the way in which fish use the marine environment, the apparent movement pattern of many species was represented by an increase in abundance during the cooler winter months and a decrease in abundance during the extreme summer months. Of the species that moved into the southern Gulf during the winter, all except one (*Plectorhinchus pictus*) spawned during the winter period when their abundance was highest. Hence, it was concluded that these species were using the shallow waters as spawning and nursery areas. The timing of spawning and subsequent recruitment also coincided with peaks in the abundance of phytoplankton and zooplankton

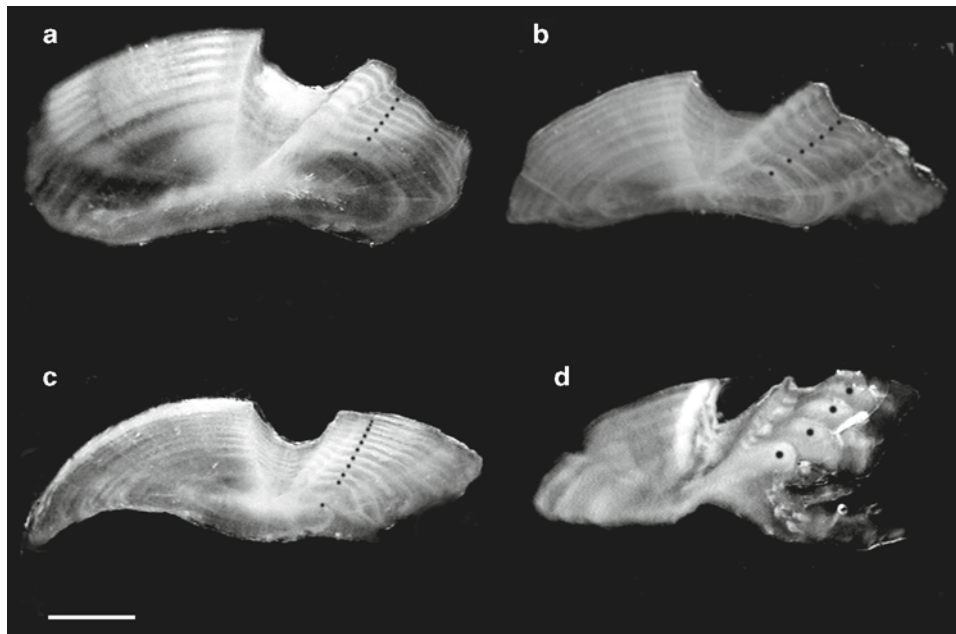


Fig. 8.17 Photomicrographs of transverse sections through the sagittal otoliths of (a) *Lethrinus borbonicus* (210 mm LF), (b) *Lethrinus microdon* (390 mm LF), (c) *Pomacanthus maculosus* (276 mm LT), and

(d) *Scolopsis taeniatus* (224 mm LF). Dots mark opaque bands within annuli and the axes along which age readings were made (scale bar = 1 mm) (Source: Grandcourt et al. 2009a by permission of Blackwell)

during the winter. The non-migratory or resident species that had a constant year round abundance showed a summer peak in spawning activity. The patterns of abundance, timing of spawning and subsequent recruitment of many of the most important commercially exploited reef associated species makes it likely that the southern Gulf is providing an important regional function as a spawning and nursery area. This is in accordance with the extensive areas of shallow water habitat, sea grass beds and mangrove areas along the coast, particularly in the western areas of the United Arab Emirates (Shallard and Associates 2003a, b, c).

8.4.2 Reef Fish Population Dynamics

Progress in understanding the demographics, biology and population dynamics of reef fish in the Gulf has been hampered by the limited research capability of many of the littoral states. To a certain extent, this is due to a lack of specialized scientific capacity and a general absence of long time series catch, effort, size and age composition data. The problem has been exacerbated by the misconception that annuli do not form in the otoliths of reef fish due to protracted spawning and a lack of seasonality in the tropics (see Green et al. 2009 for review).

One of the benefits of the extreme seasonality in the Gulf is its association with the formation of banding patterns in

the sagittal otoliths of reef fish which can be used for ageing (Fig. 8.17). These structures were initially identified by Bedford (1982) who applied routine ageing methods to reef fish otoliths from Kuwait. The potential for ageing of many other reef associated species was later demonstrated by Samuel et al. (1987b) who also validated the annual periodicity of banding patterns for the orangespotted grouper (*Epinephelus coioides*) and the malabar blood snapper (*Lutjanus malabaricus*). The age based demographic and life history parameters for many of Kuwait's commercially important reef fish were subsequently established and applied to fisheries resource assessments (Table 8.3).

A spate of similar studies on the age based population dynamics, life history characteristics and status of reef fish in the southern Gulf started in 2002. These validated the annual periodicity of increments in the sagittae of 15 commercially important species (Grandcourt et al. 2004a, 2005, 2006a, b, c, d, 2009a, 2011a). The sagittae of representatives of the family Carangidae (*Carangoides bajad* and *Gnathanodon speciosus*), however, could not be used for ageing (Grandcourt et al. 2004b) and in these cases, length based methods of assessment were applied (Pauly 1987). Opaque zone formation in the southern Gulf occurs during the summer months (Fig. 8.18), which coincides with the period of opaque zone formation in the waters of Kuwait.

Growth characteristics and longevity vary widely among species. The short lived species such as the blackstreaked

Table 8.3 Biological research on reef fish by family and location in the Gulf

Family	Location	Source
Carangidae	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2004a)
Gerreidae	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2006c)
Haemulidae	Kuwait	Hussain and Abdullah (1977)
	Kuwait	Al-Husaini et al. (2001)
	Kuwait	Lee and Al-Baz (1989)
	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2006b)
	United Arab Emirates	Grandcourt et al. (2011a, b)
Lethrinidae	Kuwait	Baddar (1987)
	Kuwait	Lee and Al-Baz (1989)
	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2006b)
	United Arab Emirates	Grandcourt et al. (2009a, 2011a, b)
Lutjanidae	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2006a)
	United Arab Emirates	Grandcourt et al. (2011a)
	Kuwait	Samuel et al. (1987a)
	Kuwait	Lee and Al-Baz (1989)
Mullidae	Kuwait	Ismail et al. (1998)
Nemipteridae	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2009a)
Pomacanthidae	United Arab Emirates	Grandcourt et al. (2009a)
Serranidae	Kuwait	Hussain and Abdullah (1977)
	Kuwait	Samuel and Mathews (1985)
	Kuwait	Mathews and Samuel (1985, 1987)
	Kuwait	Abu-Hakima (1987)
	Kuwait	Samuel et al. (1987a, b)
	Kuwait	Lee and Al-Baz (1989)
	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2005)
	United Arab Emirates	Grandcourt et al. (2009c, 2011b)

Siganidae	Saudi Arabia	Wassef and Abdul Hady (1997)
	United Arab Emirates	Shallard & Associates (2003a, b)
Sparidae	United Arab Emirates	Grandcourt et al. (2006d)
	Kuwait	Hussain and Abdullah (1977)
	Kuwait	Morgan (1985)
	Kuwait	Samuel and Bawazeer (1985)
	Kuwait	Samuel and Mathews (1987)
	Kuwait	Lee and Al-Baz (1989)
	United Arab Emirates	Shallard and Associates (2003a, b)
	United Arab Emirates	Grandcourt et al. (2004b)

monocle bream (*Scolopsis taeniatus*) grow up to their asymptotic (mean maximum) size very rapidly whereas growth of the longer lived species such as the two-bar sea-bream (*Acanthopagrus bifasciatus*) is more protracted. Another consistent feature of the growth characteristics is the reduction in somatic growth associated with the size and age at which maturity occurs, probably as a result of the allocation of energy to sexual development. The oranges-potted grouper (*Epinephelus coioides*) has an indeterminate growth curve, perhaps due to the absence of individuals at the upper end of the age range (Fig. 8.19). Growth and longevity are also linked to natural mortality with the shorter lived and faster growing species having higher natural mortality rates (Table 8.4).

In addition to estimating demographic parameters, size-at-age data are also used to establish population age structures. These have been found to be highly truncated for the larger commercially important species such as *Diagramma pictum*, *Lethrinus nebulosus* and *Epinephelus coioides* (Grandcourt et al. 2011b). The maximum observed ages in the Gulf are often considerably lower than in other populations that are not as intensively exploited. For *Diagramma pictum* the maximum observed age of 13 years in the southern Gulf is considerably less than that (31 years) recorded for this species in New Caledonia (Loubens 1980). The maximum age recorded in the southern Gulf for *Lethrinus nebulosus* (14 years) is also much lower than that (20 years) recorded for this species in the northern Gulf by Mathews and Samuel (1991). The consistent disparity in longevities for the larger, typically longer lived species is likely to be a direct impact of the intensive demersal trap fishery.

Demographic studies have also revealed aspects of the seasonal growth characteristics of some reef fish. For species with seasonally oscillating growth rates, normally growth is faster during the summer months and slower during the

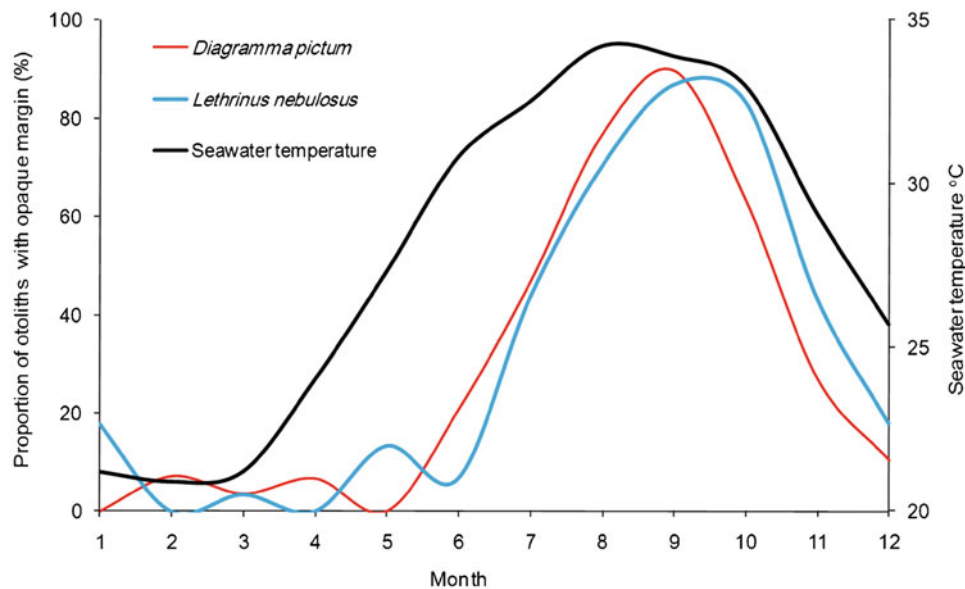


Fig. 8.18 The proportion of otoliths with opaque margins for *Diagramma pictum* and *Lethrinus nebulosus* showing the relationship with monthly seawater temperatures in the southern Gulf (Source: Grandcourt et al. 2006b by permission of Elsevier)

winter when some species may even stop growing entirely (Longhurst and Pauly 1987). In contrast to this pattern, the growth rate for *Carangoides bajad* was fastest during the winter months (November to April) and slowest during the summer (May to September) in the southern Gulf. It was suggested that the faster growth in the winter could be attributed to the substantial increase in nekton and consequently food availability during this period. As the summer months are the main spawning season for this species, the cessation of growth may have been associated with the allocation of energy to gonad development. Furthermore, the extreme temperatures during the summer may act as a stressor and retarded growth. Conversely, the growth rate of *Gnathanodon speciosus*, was fastest during the summer months (April to August) and slowest during the winter (September to March). Unlike *Carangoides bajad*, it is a bottom feeder that uses its protractile mouth to root for crustaceans, molluscs and fishes in the sand (Randall et al. 1997). The growth rate oscillation may have varied less throughout the year because of the dependence on a benthic food source that does not display such wide seasonal fluctuations in abundance. Furthermore, spawning occurs in April and May so growth over the summer may not be inhibited by the allocation of energy to gamete production during this period (Grandcourt et al. 2004a).

8.4.3 Reef Fish Reproduction

Patterns in the relative weight of testes and ovaries to the gonad free body weight (gonadosomatic indices) have enabled the definition of spawning seasons for many of the

commercially important species of reef fish in the southern Gulf. The majority spawn during April and May in association with increasing seawater temperatures. However, some start spawning in the winter months (e.g. *Acanthopagrus bifasciatus* and *Rhabdosargus sarba*), others extend spawning from the spring to the summer months (e.g. *Carangoides bajad* and *Gerres longirostris*) and some only spawn at the end of the summer (e.g. *Pomacanthus maculosus*). The general pattern is for a single well defined spawning season although for *Scolopsis taeniatus* two spawning periods have been identified during the spring and summer (Table 8.5).

The duration of the spawning season is also highly variable among species ranging from only 1 month (*Epinephelus coioides*) to 6 months (*Lethrinus microdon* and *Rhabdosargus sarba*). Where time series data are available, patterns in gonadosomatic indices also reveal consistency in the timing of the spawning season from year to year (Fig. 8.20). Fisheries may be disruptive to spawning behavior, particularly for species that form spawning aggregations. Given the associated utility of closed seasons as management tools, fine scale sampling has been conducted to establish the relationship of spawning activity with the lunar phase for *Epinephelus coioides*. Peaks were found to occur after the full and new moons and spawning was completed within a single lunar cycle (Fig. 8.21).

Because stock assessment and management techniques are predominantly geared towards gonochoristic species with equivalent numbers of males and females, it is particularly important that populations that do not share these characteristics be carefully assessed (Sadovy 1996). Simulations indicate that a failure to account for the selectivity characteristics

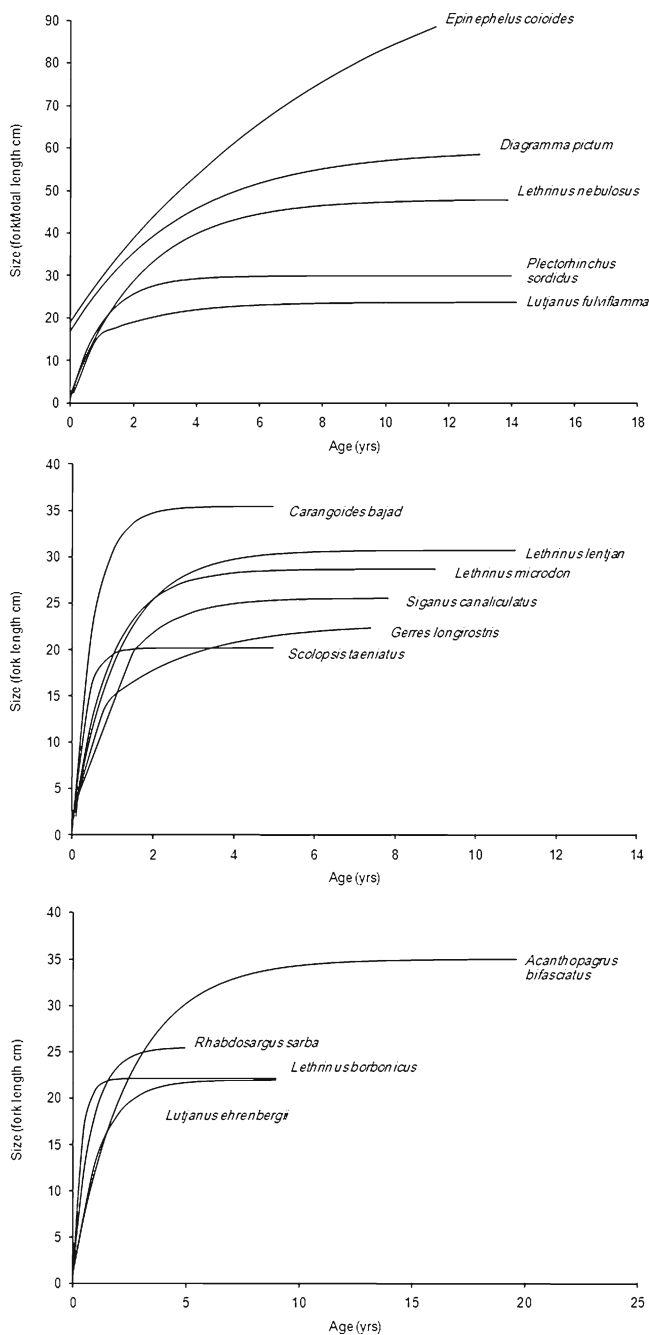


Fig. 8.19 Relationships between size and age for some commonly exploited reef fish in the southern Gulf (Data source: Grandcourt et al. 2004a, b, 2005, 2006a, b, c, d, 2009a, 2011a, by permission of Elsevier)

of the fishing pattern in relation to size at maturity and the size at sex change, can lead to a sudden and unexpected collapse of populations that have a protogynous (female to male sex change) sexual pattern (Alonzo and Mangel 2004). This can occur as a result of the differential removal of larger older males and the associated phenomena of sperm limitation, whereby there are insufficient males to fertilize the eggs from all females.

Most of the commercially exploited reef fish in the Gulf have female-biased sex ratios (Table 8.4) which is indicative (though not diagnostic) of a protogynous sexual pattern (Sadovy de Mitcheson and Liu 2008). Because protogynous reef fish are more vulnerable to exploitation than comparable gonochoristic species, a detailed reproductive study has been carried out on the orangespotted grouper (*Epinephelus coioides*). This revealed a diandric protogynous sexual pattern where males may develop from the sex change of mature females or directly from the juvenile phase. The population was not considered to be threatened by sperm limitation as mature males were present over the entire size and age range and there were no inactive females recorded during the spawning season (Grandcourt et al. 2009c). Whilst specimens undergoing sexual transition (Fig. 8.22) were only observed in size and age ranges of 33.5–68.5 cm L_T and 5–6 years, patterns in the proportion of males in age classes suggested that sex change occurred at a relatively constant rate after female maturation (Fig. 8.23). Other important findings derived from relationships between reproductive output and size (Fig. 8.24) indicated that conventional regulations that equate the mean size at first capture to sexual maturation are unsuitable for the management of this species. The size at which all fish were mature was found to be associated with a much more substantial increase in reproductive output and yields.

8.5 Resource Assessments and Status

Whilst contemporary stock assessments and detailed catch and effort data are lacking for many of the Gulf's reef associated fisheries (Morgan 2006), those of the United Arab Emirates (in particular the Emirate of Abu Dhabi) have been assessed using both fisheries dependant and independent methods. Age-based demographic data have been used for the assessment of 15 reef associated species using yield and spawner biomass per recruit models (Grandcourt et al. 2004a, b, 2005, 2006a, b, c, d, 2009a, 2011a). Where ageing using sagittal otoliths has not been possible, for example for *Carangoides bajad* and *Gnathanodon speciosus*, length based methods have been employed. These have provided a valuable insight into the population dynamics and status of the most important commercially exploited species which collectively represented 84% of the weight of all reef fish landings during 2008. Of this, a total of 13.2% consisted of species that were under exploited, 5.3% that were optimally exploited and 65.5% that were over exploited (Table 8.6). Other species for which assessments have yet to be conducted represent 16% of the total landed catch weight of all reef associated species.

The results of these studies demonstrate that whilst the majority of species that are targeted by the off-shore demersal trap fishery are over exploited (e.g. *Epinephelus coioides*,

Table 8.4 Population parameters of reef fish in the southern Gulf

Species	Growth			Reproduction		Sex ratio ♂:♀	Mortality		
	k	L_{∞} (cm)	t_0 (years)	L_{m50} (cm)	t_m (years)		Z	F	M
<i>Acanthopagrus bifasciatus</i>	0.23	32.5 L_F	-2.20	26.4 L_F	4.6	1:1.9	0.74	0.07	0.67
<i>Carangoides bajad</i>	0.59	40.4 L_F	-0.35	24.7 L_F	-	1:1.0	1.16	0.04	1.12
<i>Diagramma pictum</i>	0.24	63.0 L_F	-1.40	31.8 L_F	-	1:2.8	0.63	0.50	0.13
<i>Epinephelus coioides</i>	0.14	97.9 L_T	-1.50	42.6 L_T	3.5	1:7.9	0.97	0.78	0.19
<i>Gerres longirostris</i>	1.10	20.8 L_F	-0.10	20.6 L_F	1.5	1:2.2	0.59	0.32	0.57
<i>Gnathanodon speciosus</i>	0.51	72.3 L_F	-0.70	32.5 L_F	-	1:1.1	1.83	0.94	0.89
<i>Lethrinus borbonicus</i>	0.84	25.3 L_F	-0.10	21.3 L_F	1.3	1:0.6	1.07	0.61	0.47
<i>Lutjanus ehrenbergii</i>	0.99	24.2 L_F	-0.05	20.4 L_F	1.8	1:3.6	0.51	0.16	0.35
<i>Lutjanus fulviflamma</i>	1.00	23.2 L_F	-0.06	18.7 L_F	1.9	1:1.8	0.46	0.17	0.29
<i>Lethrinus lentjan</i>	0.70	33.9 L_F	-0.04	27.7 L_F	2.4	1:1.9	0.44	0.22	0.22
<i>Lethrinus microdon</i>	0.63	34.0 L_F	-0.10	29.1 L_F	4.8	1:1.6	0.74	0.27	0.47
<i>Lethrinus nebulosus</i>	0.11	66.2 L_F	-3.00	27.6 L_F	-	1:2.6	0.56	0.36	0.20
<i>Pomacanthus maculosus</i>	0.19	28.8 L_T	-0.40	21.6 L_T	5.5	1:8.9	0.15	0.04	0.12
<i>Plectorhinchus sordidus</i>	1.00	29.6 L_F	-0.04	26.0 L_F	2.1	1:0.9	0.45	0.15	0.30
<i>Rhabdosargus sarba</i>	1.29	25.3 L_F	-0.03	23.7 L_F	2.1	1:1.4	1.04	0.77	0.26
<i>Siganus canaliculatus</i>	1.00	24.8 L_F	-0.10	25.7 L_F	2.1	1:1.8	1.51	0.84	0.67
<i>Scolopsis taeniatus</i>	1.17	23.4 L_F	-0.10	19.8 L_F	1.1	1:44.9	2.01	1.17	0.85

Data source: Grandcourt et al. 2004a, b, 2005, 2006a, b, c, d, 2009a, 2011a

Note: k , L_{∞} and t_0 are parameters of the von Bertalanffy growth equation, which describes the increase in size with age as follows:

$L_t = L_{\infty}(1 - e^{-k(t-t_0)})$ where L_t is length at age t , L_{∞} is the asymptotic length, k is the growth coefficient and t_0 is the hypothetical age at which length is equal to 0. L_F : fork length, L_T : total length, L_{m50} and t_m are the mean size and age at first sexual maturity respectively and Z, F and M are the instantaneous rates of total, fishing and natural mortality respectively

Table 8.5 Spawning seasons of reef fish in the southern Gulf

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>Acanthopagrus bifasciatus</i>												
<i>Carangoides bajad</i>												
<i>Diagramma pictum</i>												
<i>Epinephelus coioides</i>												
<i>Gerres longirostris</i>												
<i>Gnatha odon speciosus</i>												
<i>Lethrinus borbonicus</i>												
<i>Lethrinus lentjan</i>												
<i>Lethrinus microdon</i>												
<i>Lethrinus nebulosus</i>												
<i>Lutjanus ehrenbergii</i>												
<i>Lutjanus fulviflamma</i>												
<i>Plectorhinchus sordidus</i>												
<i>Pomacanthus maculosus</i>												
<i>Rhabdosargus sarba</i>												
<i>Scolopsis taeniatus</i>												
<i>Siganus canaliculatus</i>												

(Data source: Grandcourt et al. 2004a, b, 2005, 2006a, b, c, d, 2009a, 2011a)

Lethrinus nebulosus, *Diagramma pictum*) many of the smaller inshore species that are the mainstay of traditional fisheries are exploited within sustainable limits (e.g. *Lutjanus ehrenbergii*, *Gerres longirostris*, *Lutjanus fulviflamma*). The assessment of the principal by-catch components (*Lethrinus microdon*, *Pomacanthus maculosus* and

Scolopsis taeniatus) also suggest that these species are not adversely affected by the fishery (Grandcourt et al. 2009a) (Figs. 8.25, 8.26 and 8.27).

Age-based demographic assessments provided estimates of the relative spawner biomass per recruit (SBR), which is a proxy for the adult stock size relative to its unexploited or

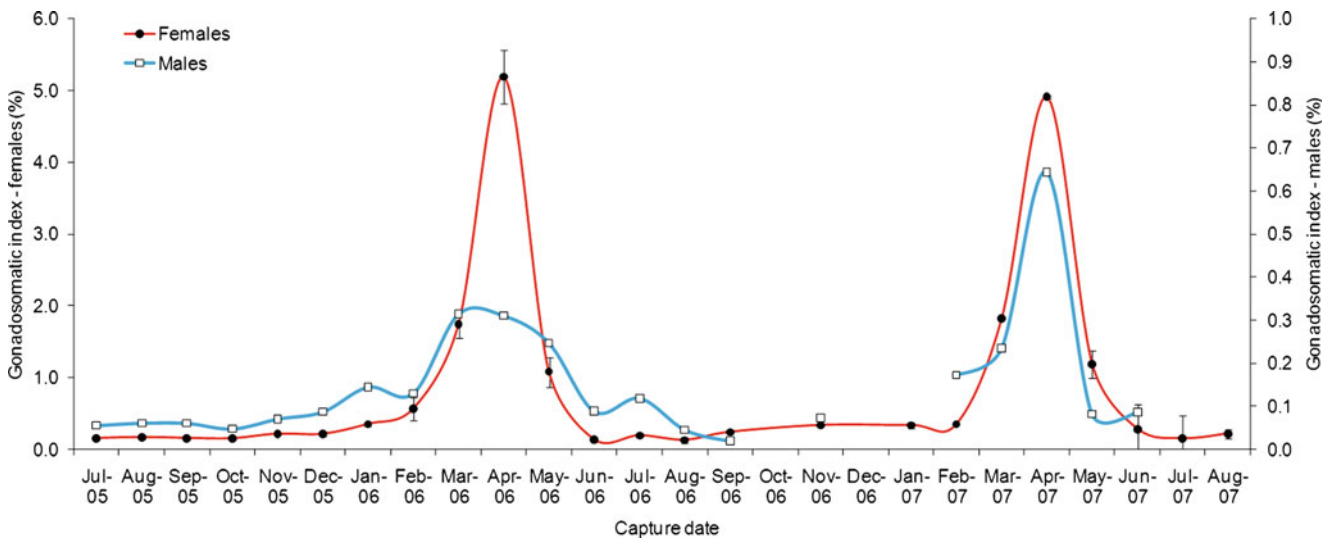


Fig. 8.20 Monthly gonadosomatic indices (\pm SE for females) for *Epinephelus coioides* in the southern Gulf between July 2005 and August 2007 (Source: Grandcourt et al. 2009c by permission of Blackwell)

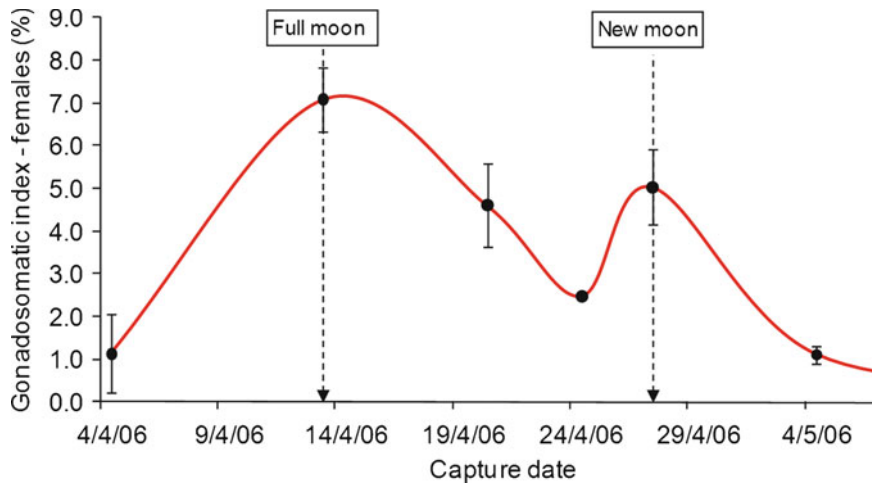


Fig. 8.21 Gonadosomatic indices (\pm SE) for female *Epinephelus coioides* in the southern Gulf showing the timing of spawning in association with the full and new moons (Source: Grandcourt et al. 2009c by permission of Blackwell)

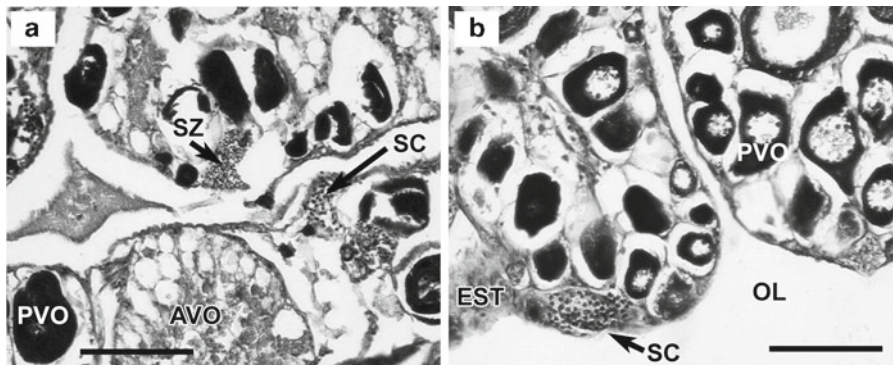


Fig. 8.22 Photomicrographs of transverse sections (6 μ m) through the gonads of *Epinephelus coioides* showing (a) gonad undergoing sexual transitional from female to male (68.5 cm L_T) and (b) a juvenile bisexual gonad (34.3 cm L_T). Scale bar=200 μ m. Previtellogenetic oocytes (PVO),

atretic vitellogenic oocyte (AVO), ovarian lumen (OL), early spermatogenic tissue (EST), spermatocytes (SC), spermatozoa (SZ) (Source: Grandcourt et al. 2009c by permission of Blackwell)

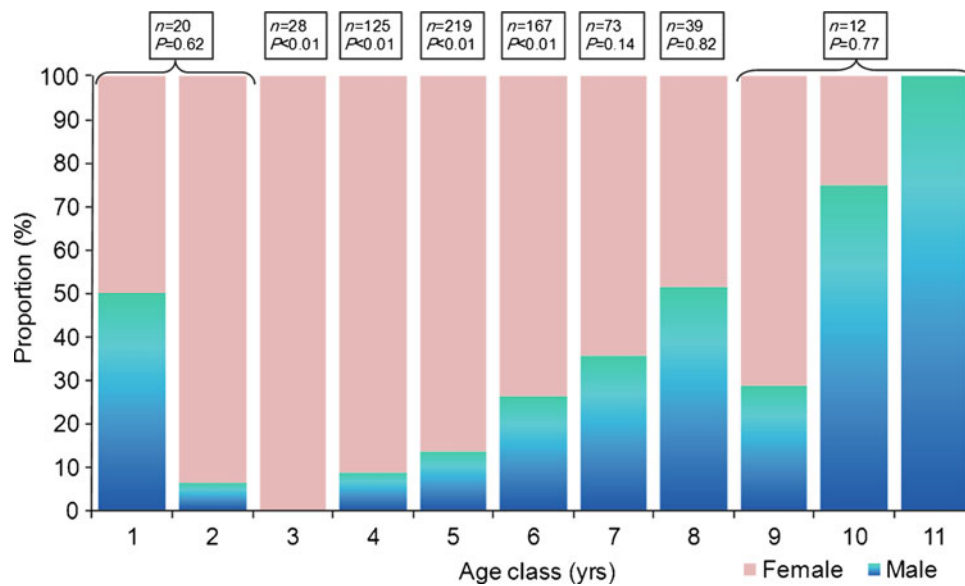


Fig. 8.23 The functional sexual structure of *Epinephelus coioides* in the southern Gulf by age class. Labels show the sample size (*n*) and *P* values from χ^2 goodness of fit tests to determine the difference of the sex ratio from unity. Brackets indicate groups that were pooled because

of small sample sizes. Note: fish undergoing sexual transition were observed in the 5 and 6 year age classes (Source: Grandcourt et al. 2009c by permission of Blackwell)

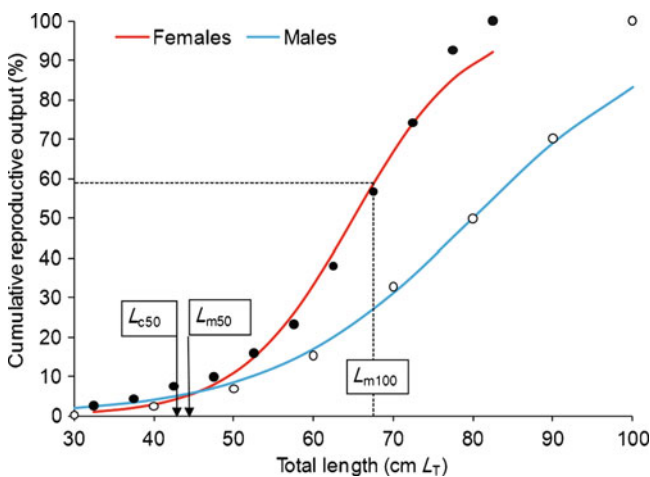


Fig. 8.24 Cumulative reproductive output with size for *Epinephelus coioides* in the southern Gulf showing the mean size at which fish become vulnerable to capture (L_{c50}), the mean size at first sexual maturity (L_{m50}) for females and the size at which all females are mature (L_{m100}). Lines show the logistic function fitted to the data (Source: Grandcourt et al. 2009c by permission of Blackwell)

reproductive capacity. They also suggest that population declines will occur due to recruitment being impaired (recruitment over fishing) when the adult stock is reduced below 30% of its unexploited size.

The fishing mortality rates associated with these population states are termed F_{SB40} and F_{SB30} respectively. A widely accepted international fisheries convention based on these general relationships is that demersal fisheries should have a target biological reference point of F_{SB40} and a limit biological reference point of F_{SB30} which management should try to avoid. Whilst they are generic in nature, these reference points have been used for evaluating the reef fish populations in the southern Gulf and are of particular utility when there is no information available on the relationship between stock size and recruitment.

Values of SBR for the key commercially important reef fish (*Epinephelus coioides*, *Lethrinus nebulosus* and *Diagramma pictum*) during 2002 were 2.5%, 5.9% and 6.6% respectively (Fig. 8.28) (Grandcourt et al. 2011b). This indicates that these populations are heavily over exploited and independently corroborate the findings of abundance surveys (Shallard and Associates 2003a).

‘virgin’ state. The fishing mortality rates (*F*) associated with these SBR values are compared to biological reference points and used to infer population status. Meta analyses of the relationships between parent stock size and recruitment (Mace 1994) indicate that demersal fish populations in general can sustain harvests when the adult component of the stock is reduced to 40% of its unexploited state without jeopardizing

A consistent result of demographic investigations in the southern Gulf is the high level of juvenile retention, particularly for the larger species, 71% of the landings of the golden trevally (*Gnathanodon speciosus*) for example are composed of juvenile fish (Grandcourt et al. 2004a). This is a result of the selectivity characteristics of the main gear type, hemispherical wire traps (gargo), which tend to

Table 8.6 The status of exploited reef fish that have been assessed in the southern Gulf by proportion (%) of the total landed catch weight of all reef associated species

	Total Catch (mt) 2008	%
Under exploited species		
<i>Carangoides bajad</i>	163.6	4.2
<i>Acanthopagrus bifasciatus</i>	42.5	1.1
<i>Scolopsis taeniatus</i>	18.4	0.5
<i>Pomacanthus maculosus</i>	1.2	0.0
<i>Lutjanus ehrenbergii</i>	125.0	3.2
<i>Lethrinus lentjan</i>	132.3	3.4
<i>Plectorhinchus sordidus</i>	32.1	0.8
Total	515.1	13.2
Optimally exploited species		
<i>Gerres longirostris</i>	147.5	3.8
<i>Lethrinus microdon</i>	50.3	1.3
<i>Lutjanus fulviflamma</i>	9.6	0.2
Total	207.4	5.3
Over exploited species		
<i>Epinephelus coioides</i>	922.6	23.6
<i>Lethrinus nebulosus</i>	822.1	21.1
<i>Diagramma pictum</i>	499.7	12.8
<i>Gnathanodon speciosus</i>	140.6	3.6
<i>Lethrinus borbonicus</i>	58.2	1.5
<i>Siganus canaliculatus</i>	14.7	0.4
<i>Rhabdosargus sarba</i>	101.7	2.6
Total	2559.6	65.5

Data source: Grandcourt et al. 2004a, b, 2005, 2006a, b, c, d, 2009a, 2011a; Hartmann et al. 2009



Fig. 8.25 Stock assessment studies of the most important reef associated species in the southern Gulf, the orange spotted grouper (*Epinephelus coioides*), indicate that it is exploited at over six times the sustainable level (Photo: E. Grandcourt)

have very small (about 3.5 cm) hexagonal mesh. This has critical resource management implications as the intensive harvest of immature fish prevents individuals from reaching maturity and contributing to the reproductive output of the stock. It also reduces yields to the fishery as the individuals within the population do not achieve their full growth potential.



Fig. 8.26 Studies of the population dynamics of commercially important reef fish in the southern Gulf indicate that some of the small coastal species such as the longtail silverbiddy (*Gerres longirostris*) are exploited at an optimal rate (Photo: J. Randall)

8.5.1 Application to Fisheries Management

An important component of stock assessment involves management simulations. Following a diagnosis of the status of the resource, models are used to evaluate the impact of various management regimes. Such simulations have been conducted in order to establish appropriate regulations for the offshore demersal trap fishery in the southern Gulf.



Fig. 8.27 Stock assessment studies in the southern Gulf indicate that the off-shore demersal trap fishery is not having a detrimental impact on incidental discarded by-catch species such as this yellowbar angel fish (*Pomacanthus maculosus*) (juvenile inset) (Photo: E. Grandcourt)

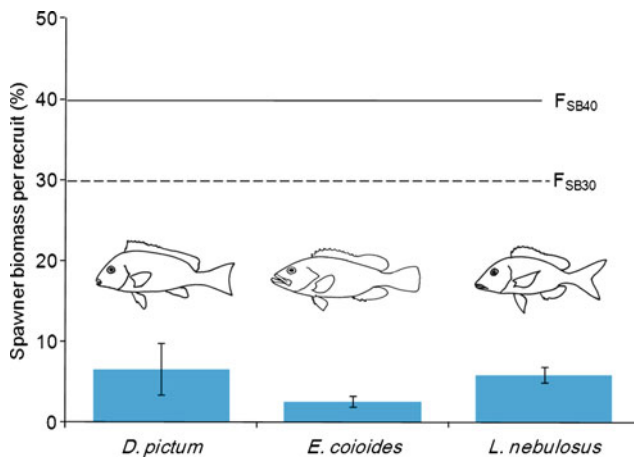


Fig. 8.28 Spawner biomass per recruit (SBR) for the key commercially exploited reef fish in the southern Gulf ($\pm 95\%$ CI) showing the target (F_{SB40}) and limit (F_{SB30}) biological reference points (Source: Grandcourt et al. 2011b by permission of Scientific Research)

The results consistently suggest that large increases in the sizes at which fish become vulnerable to capture are required in order to rebuild stocks and achieve management targets (e.g. Shallard and Associates 2003d, e; Grandcourt et al. 2006b). The importance of the size at which fish are vulnerable to capture from a resource management perspective is illustrated by simulations for the orange spotted grouper (*Epinephelus coioides*) (Grandcourt et al. 2011b). These suggest that the management target of increasing the adult stock size to 40% of its unexploited level, could be exceeded by increasing the mean size at first capture to that at which yields would be maximized. Furthermore, this could be achieved at the same time as increasing yields, without having to reduce fishing effort (Fig. 8.29).

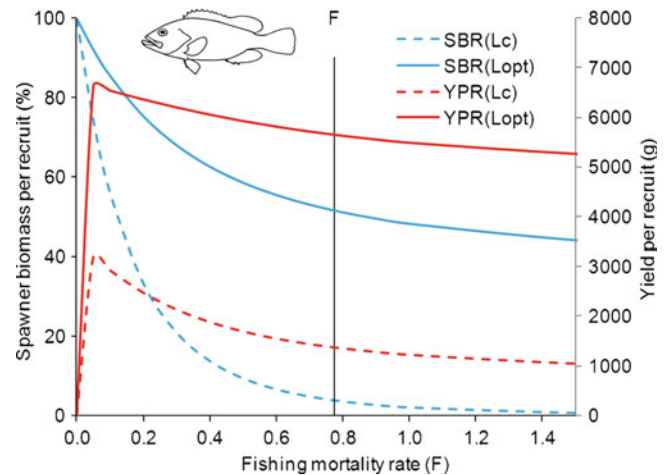


Fig. 8.29 The output of yield (YPR) and spawner biomass per recruit (SBR) simulations for the orange spotted grouper (*Epinephelus coioides*), showing the dramatic increase in yields and spawner biomass associated with increasing the existing mean size at first capture (L_c) to that at which yield per recruit would be maximized (L_{opt}). Critically, this demonstrates the deleterious impact that the existing selectivity characteristics of traps have on the resource base and the potential benefits to the fishery of appropriate gear regulations. Note: F represents the existing fishing mortality rate (Source: Grandcourt et al. 2011b by permission of Scientific Research)

Despite its apparent simplicity, the optimum selectivity characteristics of fishing gears vary by species and a single design will not fulfill the requirements for all in such a multi-species fishery. If mesh sizes are too large, smaller species will not be caught, conversely, the larger species may become vulnerable to capture before they have achieved their full growth potential and sexual maturity if mesh sizes are too small. An experimental fishing program was conducted in the waters off Abu Dhabi in the United Arab Emirates in order to address this problem and evaluate the selectivity characteristics of traps fitted with a variety of juvenile escape panels (Grandcourt et al. 2011c). The results also included an assessment of the different designs on the retention of by-catch species.

The assessment of fisheries resources in the southern Gulf has also been conducted using fishery independent methods. During 2001 and 2002 a combination of trawl, acoustic and trapping surveys were used to evaluate the abundance and distribution demersal and pelagic species (Shallard and Associates 2003a). A comparison of the results with a previous survey (FAO 1981) revealed alarming trends in the abundance of many reef associated species (Fig. 8.30). The overall biomass of commercially exploited demersal species was 19% of that present in 1978. The abundance of the most important reef associated families (Carangidae, Serranidae and Lethrinidae) had been reduced to 2.0%, 13.3% and 17.8% of 1978 levels respectively.

The definitive reasons for these declines are not known and given their magnitude, are unlikely to be a result of the different techniques used in the two surveys. They are,

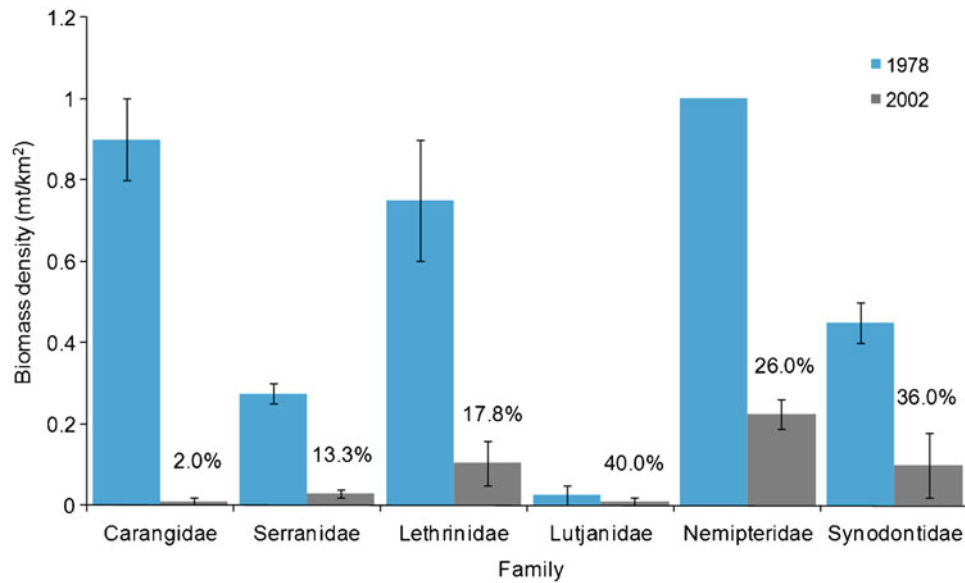


Fig. 8.30 Comparison of the abundance of key commercially important reef fish families between 1978 and 2002 in the southern Gulf. Note: data labels indicate the biomass density in 2002 as a proportion of

1978 levels and error bars indicate maximum and minimum values recorded (Data source: Shallard and Associates 2003b redrawn with permission of EAD)

however, consistent with the patterns in abundance that have been observed in the Gulf in general (Siddeek et al. 1999). It has been suggested that declines in demersal fish stocks within the Gulf were a result of the combination of nursery area degradation, pollution and over-exploitation (Shallard and Associates 2003a). However, analyses of the highly truncated age structures of key species convincingly suggests that the primary reason is the intensive fishing mortality rates which in some cases, such as that for the orange spotted grouper (*Epinephelus coioides*), are up to six times the sustainable level (Grandcourt et al. 2005).

A much less current, though geographically broader understanding of the status of the reef fisheries resources in the Gulf can be gained simply by comparing the carrying capacity with yields. The results of fisheries resource surveys conducted between 1976 and 1979, estimated the potential annual yield of all demersal fin fish in the Gulf at 142,500 mt/year (FAO 1981). As the yields of reef fish alone averaged 181,972 mt each year between 1986 and 2007 (FAO 2009), it appears that the reef fisheries resources of the Gulf in general have been over-exploited in line with the more localized observations for the southern region.

8.6 Conservation Initiatives and Critical Management Issues

The marine environment and associated reef fish resources in the Gulf are managed within a framework of international and regional conventions, national and local policies, laws

and regulations. Some applicable international conventions that relate directly or indirectly to coral reefs and their associated fauna include:

1. Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).
2. Convention on Biological Diversity (CBD).
3. Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution.
4. International Convention for the Prevention of Pollution from Ships (MARPOL).
5. United Nations Framework Convention on Climate Change (UNFCCC).
6. United Nations Convention on the Law of the Sea (UNCLOS).

A number of regional organizations are involved in the assessment and management of reef fisheries resources in the Gulf. These include the Regional Commission for Fisheries (RECOFI), Gulf Cooperative Council (GCC) and the Regional Organization for Protection of the Marine Environment (ROPME). Active international organizations include the World Wildlife Fund for Nature (WWF), United Nations Environment Program (UNEP), the United Nations Development Program (UNDP) and the International Union for the Conservation of Nature (IUCN). Notable environmental strategies and action plans developed for the Gulf are the 'Regional Action Plan for the Conservation of Coral Reefs in the Arabian Seas Region' and the 'Kuwait Action Plan' both developed by the Regional Organization for the Protection of the Marine Environment (ROPME) and member states.

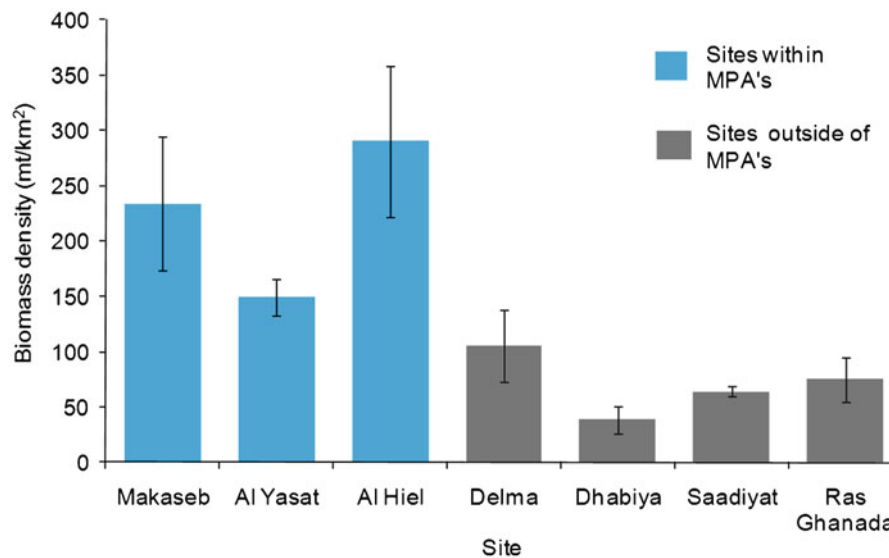


Fig. 8.31 Biomass density (\pm SE) of demersal fishes on coral reefs in the southern Gulf, illustrating differences between reefs located inside and outside of marine protected areas (MPA's) (Source: Grandcourt 2009 unpublished data)

Each littoral state of the Gulf has federal policies, legal instruments and regulations specifically relating to fisheries. In some cases, such as the United Arab Emirates, local government policies, laws and regulations are also in place. Fisheries regulations in the region include outright bans e.g. on trawling in the UAE and Qatar and trammel nets in Kuwait. Other input regulations include fishing gear restrictions such as minimum mesh sizes for gillnets and traps in Bahrain (Siddeek et al. 1999). Destructive fishing gear and materials such as monofilament netting and drift nets have been banned in order to mitigate the impact of fishing on endangered species such as turtles, dugongs and other marine mammals (Beech 2004). Closed areas and seasons are also implemented, sometimes on a species specific basis. Output regulations include size limits e.g. for representatives of the families Siganidae and Serranidae in Bahrain and Serranidae and Lutjanidae in Kuwait (Siddeek et al. 1999).

In a review of the state of marine capture fisheries management, Morgan (2006) highlights some pertinent issues relating to fisheries management in the region. It was found that there was no regional management of any stock although many stocks are undoubtedly shared between states. Of the management tools implemented, those for controlling fishing capacity were the most poorly developed (despite being the most needed). There are very few output controls on the fisheries with virtually all fisheries being managed with input controls and finally, the effectiveness of the enforcement of management regulations in the region was generally weak. Additional constraints to management are the general absence of stock assessment and monitoring programs for the key fisheries resources, thus basic contemporary data on stock status is more often than not unavailable.

The effectiveness of fisheries management has also been evaluated on a more local scale in the southern Gulf where a variety of regulations were introduced in 2003 in order to rebuild depleted reef fish stocks. Stock status indicators for the key species *Diagramma pictum*, *Epinephelus coioides* and *Lethrinus nebulosus* indicated a failure of the regulations to modify gear selectivity, reduce effort and rebuild stocks over a 5 year period after their introduction. The results of the study suggested that more dramatic management measures, such as fishery closures, may be required in order to achieve stock rebuilding targets (Grandcourt et al. 2011b).

Because of their potential to achieve a combination of fisheries, biodiversity conservation and socio-economic objectives, marine protected areas are increasingly being used as marine resource management tools in the Gulf. Extensive marine protected areas have been established in the Emirate of Abu Dhabi in the UAE and contrary to the direct fisheries management regulations, show signs of fulfilling their fisheries resource conservation objectives. A comparison of the biomass density (Fig. 8.31) between protected and un-protected reefs indicates that reef fish are more abundant on reefs in marine protected areas by comparison with reefs open to exploitation. Furthermore, many of the commercially important species are larger in marine protected areas by comparison with reefs open to exploitation (Fig. 8.32).

The critical issues relating to the conservation and management of reef fishes in the Gulf are largely common to all littoral states. In addition to the direct impacts of fisheries, a variety of indirect threats exist such as habitat loss and fragmentation, pollution and loss of nursery areas (Sheppard et al. 1992). Natural threats which can be exacerbated by

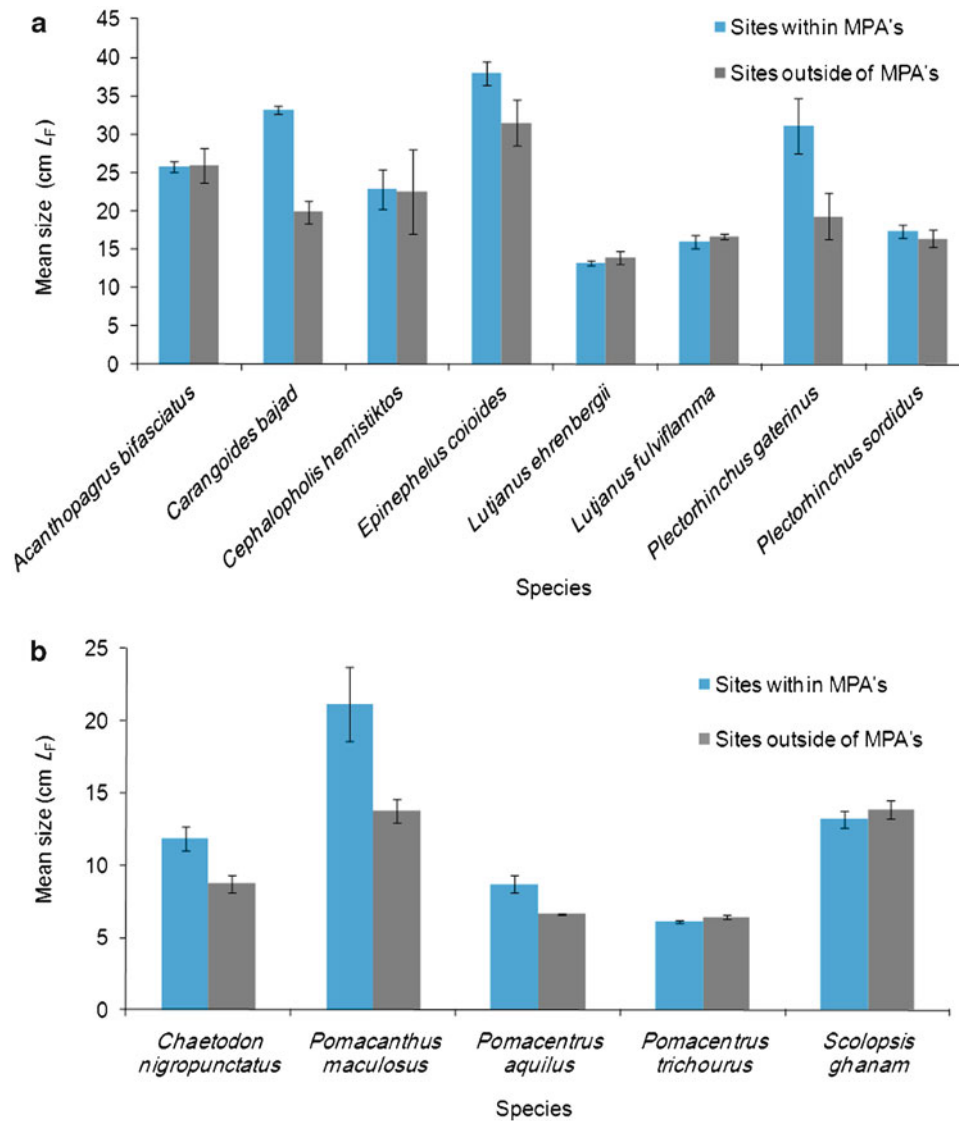


Fig. 8.32 Mean size (\pm SE) of (a) target species and (b) non-target and by-catch species on coral reefs in the southern Gulf, illustrating differences between reefs located inside and outside of marine protected areas (MPA's) (Source: Grandcourt 2009 unpublished data)

anthropogenic activities include the incidence of disease. A particularly challenging management issue is the mortality and associated habitat loss following coral bleaching events. The reefs off Dubai for example, which were previously one of the Gulf's richest marine ecosystems, suffered extensive mortality in the summer of 1996 (Pilcher et al. 2000; Riegl 2002). The increase in the frequency and prolongation in positive seawater temperature anomalies suggests that the future of coral reefs in the Gulf is bleak. It has been predicted that within the next few decades, the once coral dominated reefs will be transformed into ones composed of coralline and turf forming algae seasonally dominated by dense forests of fleshy brown algae (George and John 2002). There have not been any detrimental short term impacts on reef fish communities, due to the maintenance of structural complexity

(Riegl 2002) however, the long term effects of habitat loss associated with mass coral mortality is a critical management issue.

A common problem affecting fisheries in the region is the loss of fish traps which leads to 'ghost fishing' where the gear continues to catch fish indiscriminately. The traps can take anything from 5 to 7 months to corrode so they may continue trapping fish for some time after they are lost. Inshore fishermen may lose 7–12 traps per month, whilst the traditional dhows which generally operate 150–200 traps, may lose 20–25 traps per month (Beech 2004). Measures to counter this problem have been developed and implemented in the southern Gulf. All traps require a juvenile escape panel (Fig. 8.33) which is held closed by a magnesium zinc alloy pin that corrodes after a period of 2 weeks, opening the panel



Fig. 8.33 A typical wire trap used to exploit reef fish in the Gulf. The escape panel is held shut with a magnesium zinc alloy pin which corrodes after 2 weeks, opening the panel so trapped fish can escape. In addition to the prevention of ‘ghost fishing’ the larger mesh on the escape panel was intended to mitigate the retention of juvenile fish (Photo: S. Hartmann)

and allowing trapped fish to escape (Beech 2004). Additional regulations to mitigate damage from fishing gear on coral reef habitats in the southern Gulf include the exclusion of trap fishing within 3 nm of the coastline.

Most heavy industries in the Gulf are located on the coast to make use of sea water for cooling purposes (e.g. electricity generating plants, petro-chemicals, oil refining, aluminium and steel smelting). Concentrated brine and cooling water discharges add to the already high osmotic and thermal stress experienced by marine fauna. Other sources of wastewater pollution include untreated sewage, abattoir waste and effluents from fertilizer plants (Price 1993). The effects of these include increasing biological oxygen demand (BOD) and algal blooms. However, it is still not certain whether the increasing prevalence of off-shore algal blooms, jellyfish and ‘red tides’ in the Gulf are primarily signals of large-scale eutrophication, or more the effects of natural cycles (Lindén 1990).

Landfill, dredging and coastal reclamation are common activities in the coastal zone with intertidal flats and shallow embayments being favored for residential and industrial construction (Price 1993). These activities impact coral reefs by direct habitat loss and various secondary effects such as smothering by sediment and a loss in illumination (Sheppard et al. 2000). Impacts on reef fish communities include the loss of nursery habitats such as sea grass beds, mangroves, shallow sand flats and intertidal areas. The construction of ports and artificial islands through dredging also disrupts water movements and has dramatically affected those reefs near to the shore (Pilcher et al. 2000).

Oil and industrial pollutants pose a threat to reefs in the Gulf, whilst the effects on ecosystem structure and function are generally not well known (Price 1993), it has been suggested that the immediate impact of oil spills and discharges on coral reefs are less than would be expected, suggesting a high resilience among reef communities (Wilson et al. 2002). Socio-economic impacts of oil spills have been reported to include periods when fishing was not possible or reduced in heavily oiled areas following the invasion of Kuwait in 1990 (Ahmed et al. 1998; Carpenter 1992).

As fisheries management initiatives in the Gulf were triggered by the decline in the shrimp fisheries in the early 1980s, they are still relatively poorly developed and hampered by a lack of appropriate regulations, enforcement and data on most stocks (Siddeek et al. 1999). Other constraints include the availability of a cheap migrant labor force and low operating costs which have acted as indirect subsidies and maintained the viability of fishing units despite reduced stock sizes. Policy frameworks are often development orientated, despite many fish stocks being over exploited. Furthermore, management based on principals of ecologically sustainable development (ESD), or some other recognition of the need for long-term sustainable management of exploited fish stocks is rare. There are also limitations with the underlying fisheries legislation, which is often designed as a basis for the administration of fisheries rather than a reflection of an explicitly stated policy framework for the long-term management of the sector (Morgan 2006). Given the multitude of threats to reef fish populations and declining trends in abundance, a paradigm shift in the approach to reef fisheries management in the Gulf is required.

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Extreme Physical Factors and the Structure of Gulf Fish and Reef Communities

David A. Feary, John A. Burt, Georgenes H. Cavalcante,
and Andrew G. Bauman

9.1 Introduction

Coral reefs are one of the most diverse ecosystems on earth, making up <0.5% of the marine environment by area but containing nearly a third of all marine species, most of which are endemic to reefs (Moberg and Folke 1999). Despite their economic and ecological importance, coral reefs are being increasingly degraded by both human and natural stressors. Over-exploitation, destructive fishing methods, eutrophication and sedimentation resulting from land-use changes, among other factors, has resulted in the loss of over 19% of the world's coral reef area in the past several decades (Wilkinson 2008). However, climate change, mainly driven by increases in atmospheric CO₂ from the burning of fossil fuels, represents the greatest threat to the future of coral reefs (Harley et al. 2006; Wilkinson 2008). Atmospheric CO₂ concentrations have increased from ~280 ppm around 1700 AD to >380 ppm today (Brohan et al. 2006), a rate of increase over 100 times faster than experienced in the past 650,000 year (Siegenthaler et al. 2005), and potentially beyond the capacity of reef fauna to adapt and recover (Przeslawski et al. 2008).

D.A. Feary (✉)
School of the Environment, University of Technology,
P.O. Box 123, Broadway, Sydney, NSW 2007, Australia
e-mail: David.Feary@uts.edu.au

J.A. Burt
Department of Biology, New York University-Abu Dhabi,
P.O. Box 129-188, Abu Dhabi, United Arab Emirates
e-mail: John.Burt@nyu.edu

G.H. Cavalcante
Coastal Zone and Waterways Management Section,
Environment Department, Dubai Municipality, P.O. Box 67,
Dubai, United Arab Emirates
e-mail: Georgenes.uff@gmail.com

A.G. Bauman
School of Marine and Tropical Biology, ARC Center
of Excellence for Coral Reef Studies, James Cook University,
Townsville, QLD 4811, Australia
e-mail: Andrew.bauman@my.jcu.edu.au

There is increasing evidence that the impacts of climate change will depend not only on the magnitude of environmental change, but the historical context in which it takes place. Reef faunas with a history of exposure to variable or extreme environmental conditions tend to be more resistant and/or resilient to environmental change compared with those in more benign environments (Thornhill et al. 2006; McClanahan et al. 2007; Middlebrook et al. 2008; Portner and Farrell 2008; Thompson and van Woesik 2009; LaJeunesse et al. 2010), and there is ample evidence that reef fauna can tolerate and even thrive in environments normally considered extreme for reefs (Coles 2003; Przeslawski et al. 2008). As such, it is appropriate to examine organisms on reefs already exposed to physically extreme conditions in order to develop an understanding of how individuals living on these reefs respond to climate-driven stress and to predict its implications for ecology.

9.2 Oceanography of an Extreme Environment

The Gulf is a semi-enclosed marginal sea, separated from the Indian Ocean by the narrow (approximately 42 km) Strait of Hormuz (Chao et al. 1992; Sheppard et al. 1992). Due to its shallow depth and restricted water exchange with the wider Indian Ocean, SSTs vary by over 25°C annually (Sheppard et al. 1992). Typical surface temperatures in the Gulf are approximately 33°C in summer reaching >35°C on reefs in the shallow southern basin (Coles and Fadlallah 1991; Reynolds 1993; Sheppard et al. 2010), though air temperatures in excess of 49°C have frequently been recorded in the region, especially in the northern area (Sheppard et al. 1992). The winter surface temperature is approximately 22°C near the Strait of Hormuz, decreasing northwest to approximately 16°C near the head of the Gulf. The temperature difference between summer and winter is greatest (>20°C) in the north-western part and least within the Gulf of Hormuz (<11°C)

and represents the largest temperature range experienced on reefs worldwide, (Coles 2003; Przeslawski et al. 2008; Munday et al. 2009). Gulf waters are also hyper-saline, with fauna surviving >48 ppt, approximately 10 ppt higher than ambient in tropical oceanic waters and in excess of lethal limits for fauna on Atlantic and Pacific reefs (Coles 2003). For a more detailed review of physical factors see Chap. 2.

9.3 Reef Fish Communities in a Physically Extreme Environment

Reef communities in the Gulf have been variously described as being a relatively depauperate subset of Gulf of Oman or wider Indian Ocean communities due to the physical extremes of salinity and temperature and the limited entry through the narrow straits of Hormuz (Coles 2003; Rezai et al. 2004). Most of this work, however, is based solely on various descriptions of hard substratum associated benthic communities (i.e. coral communities) (Sheppard et al. 1992; Coles 2003; Rezai et al. 2004; Schils and Wilson 2006) and soft sediment assemblages (Price 1981, 1982a, b; Price and Coles 1992; Price et al. 1993). During a broad scale visual survey of reef associated fish communities throughout the SE Gulf (Dubai and Abu Dhabi) and north-eastern Gulf (Musandam Peninsula) the demographic structure of these communities was compared to reef fish communities throughout the Arabian Peninsula (including the Gulf of Oman and the Arabian Sea). The structure of Gulf reef fish communities is similar to that reported for benthic communities; Gulf fish communities are a depauperate subset of those of the Gulf of Oman and Arabian Sea with lower estimated reef fish community diversity. Such lower reef fish diversity had previously been reported by Ghanbarifardi and Malek (2009) for rock-pool fishes. Substantially lower abundance and biomass of fish is found inside the Gulf and functionally, Gulf reefs are dominated by reef fish species with little association to live coral (i.e., a range of herbivorous grazers) while reef fish communities outside of the Gulf are more likely to comprise species more closely associated with the structure of the coral reefs per se (i.e., coral associated planktivorous damselfish).

Quantification of differences in reef fish community structure between the Gulf and the wider Indian Ocean will always be confounded by differences in the available habitat between regions (Sheppard et al. 2010). Although reef fish species vary in the degree to which they are reliant on characteristics of the underlying substratum (Syms and Jones 2000), there is a well-acknowledged and strong relationship between demographic patterns in reef associated fish community structure and habitat availability both within the Gulf (Shokri et al. 2005), and elsewhere (Graham et al. 2006). However, to determine whether the structure and function

of reef fish communities within the Gulf are substantially different from those found outside, it is necessary to discount habitat availability. Feary et al. (2010) attempted to quantify the differences in reef fish structure between the Gulf and the adjacent Gulf of Oman. Survey sites were relatively similar in both cover and composition of coral communities (Feary et al. 2010) but exhibited substantial differences in the structure and composition of associated fish assemblages between regions. Fish assemblages in the southern Gulf held significantly lower abundance, richness, and biomass, with higher relative abundances of smaller-sized individuals than Gulf of Oman assemblages (Feary et al. 2010). Functionally, southern Gulf reefs also held lower abundances of nearly all of the common fish trophic guilds found on Indian Ocean coral reefs, although higher abundances of herbivorous grazers were apparent (Feary et al. 2010). A growing body of work to suggest that fish growth, reproduction and mortality, may be substantially affected by the physical extremes within the Gulf (see also Chap. 8).

In addition to changes in demographic parameters, substantial differences in the structure of reef fish communities between the Gulf and wider Indian Ocean may also be associated with the high seasonal variability in reef fish population structure and abundance that has been documented for Gulf assemblages (Sheppard et al. 1992; Chap. 8). Despite being discussed in the majority of reviews of Gulf reef fish communities (Sheppard et al. 1992, 2010; Sale et al. 2011), there is still little consensus on the mechanisms causing this variability. Coles and Tarr (1990) and Chen et al. (2009) found significantly higher fish abundance in summer than during other seasons within Kuwait Bay. Populations increased in the summer-fall and decreased in late winter-early spring, inversely related with annual temperature cycles. The summer increases in fish numbers occurred in all size classes and were not due to seasonal juvenile recruitment (Coles and Tarr 1990). However, seasonal changes in fish communities have not always been reported. For example, Burt et al. (2009) surveyed fish communities on coral reefs in the UAE seasonally for 1 year and found little change in both species richness and abundance on natural reefs, although dramatic seasonal differences were observed on artificial breakwater habitats (see also Chaps. 8 and 10). Wright (1988) examined monthly trawl surveys of fish communities within both intertidal and subtidal regions within Sulaibikhat Bay, Kuwait. Although the total number of fishes captured in 1986–1987 and 1987–1988 differed by an order of magnitude, seasonal changes in abundance, biomass and diversity in both intertidal and subtidal zones surveyed showed comparable abundance among seasons each year (Wright 1988). Although there is no empirical evidence to suggest the cause of seasonal changes, both Coles and Tarr (1990) and Burt et al. (2009) have argued that seasonal changes in fish communities may be associated with an

increase in off-reef migration in winter. Such migration may be associated with avoidance of greater physical stresses in inshore areas, with high wave action associated with winter shamals substantially affecting shallow reef regions throughout the Gulf (Coles and Tarr 1990). However, the role of mortality with changing seasonal extremes may also play a substantial part. A range of both scientific and anecdotal evidence suggest that seasonal fish kills, associated with warming waters, increasing salinity and increases in the extent of harmful algal blooms, both inside and outside the Gulf during the summer, may be an important factor in reducing Gulf fish populations seasonally (Bauman et al. 2010).

One of the factors which may have a substantial effect on the abundance and diversity of Gulf fish populations is reduced exchange with populations outside the Gulf. For example, in Gulf waters of the UAE, sailfish (*Istiophorus platyperus*) are seasonally resident from October through April (Hoolihan 2003), with confinement of populations year-round within the Gulf (Hoolihan and Luo 2007). Such confinement has been predicted from use of conventional mark-recapture studies that report an absence of any recoveries outside the Gulf, and mitochondrial DNA analysis which indicate phylogeographic isolation of the Gulf population (Hoolihan 2003; Hoolihan et al. 2004). Although the phylogeographic isolation of a highly vagile species is unusual (Hoolihan et al. 2004), such a reduced distribution has also been found in the pelagic narrow-barred Spanish Mackerel (Hoolihan et al. 2006). Mitochondrial DNA analyses of *Scomberomorus commerson* indicate a distinct genetic stock structure for fish inside and outside the Gulf (Hoolihan et al. 2006). Whether less vagile species also show such reduced movement between the Gulf and the wider Indian Ocean is still unknown. The counter-current circulation within the Gulf (Chao et al. 1992) would be expected to facilitate movement of reef fish species pelagic larvae out of the Gulf, especially from populations along the southern Gulf region.

9.4 Coral Reef Communities in a Physically Extreme Environment

There is concern over the integrity of coral reef ecosystems as global climate rapidly changes and the environment may become increasingly marginal in many areas. Marginal reefs are defined as occurring where conditions are close to their environmental thresholds for survival (*sensu* Kleypas et al. 1999), or in areas characterized by ‘sub-optimal’ or extreme fluctuating environmental conditions (Perry and Larcombe 2003). Marginal reef communities predominately occur above 25°N and below 25°S outside the tropical belt or at its edge (i.e., high latitudes, subtropics), with well known examples from South Africa, Japan, Bermuda, Australia, and for

this review, the Gulf. Reef development and coral species diversity within these areas are primarily regulated by low mean annual and seasonally variable temperatures and/or irradiances, and/or low aragonite saturation states (Buddemeier 1997; Kleypas et al. 1999). In the Gulf coral communities exist in harsh conditions with respect to seawater temperatures (<12°C to >36°C) and salinities (>45 ppt) (Kinsman 1964; Coles 1988; Chap. 2). Moreover, the Gulf has significant seasonal insolation fluctuations (Sheppard et al. 2010), and in some areas extreme low tides (Sheppard et al. 1992). Under these challenging conditions, coral communities in the Gulf are limited in their horizontal and vertical growth by reduced reef accretion, restrictions in the depth distribution, and lower species diversity than in the Indian Ocean (Sheppard et al. 1992; Fadlallah et al. 1993). Gulf corals attach and grow directly onto hard substrata or exposed bedrock, thereby restricting the spatial extent of reef development and overall structural complexity (i.e., forming non reef-building communities, *sensu* Riegl 1999). Given that coral communities do occur in extreme marginal environments, it has been suggested that these areas may act as potential refugia in the future as oceans warm and ocean acidification increases (Riegl 2003). Therefore, it is important to understand the dynamics of such communities and their ability to persist and recover in marginal environments. Coral reproduction within the Gulf has received relatively limited attention (but see Fadlallah and Lindo 1988; Harrison 1995; Fadlallah 1996). Reproductive patterns in the Gulf are remarkably similar to other geographical regions. Reproduction of six of the most abundant coral species in the southern Gulf (Table 9.1, Fig. 9.1) was highly seasonal, with peak reproductive activity in April (Fig. 9.1). This is typical for these six species (Baird et al. 2009). Multi-species spawning synchrony was highly probable, in parallel to patterns of spawning synchrony reported globally for these species (Baird et al. 2009). Gametogenic cycles and polyp level fecundities of all six species were similar to conspecifics outside the Gulf, suggesting the six species to be well adapted to extreme environmental conditions in the Gulf (Table 9.1).

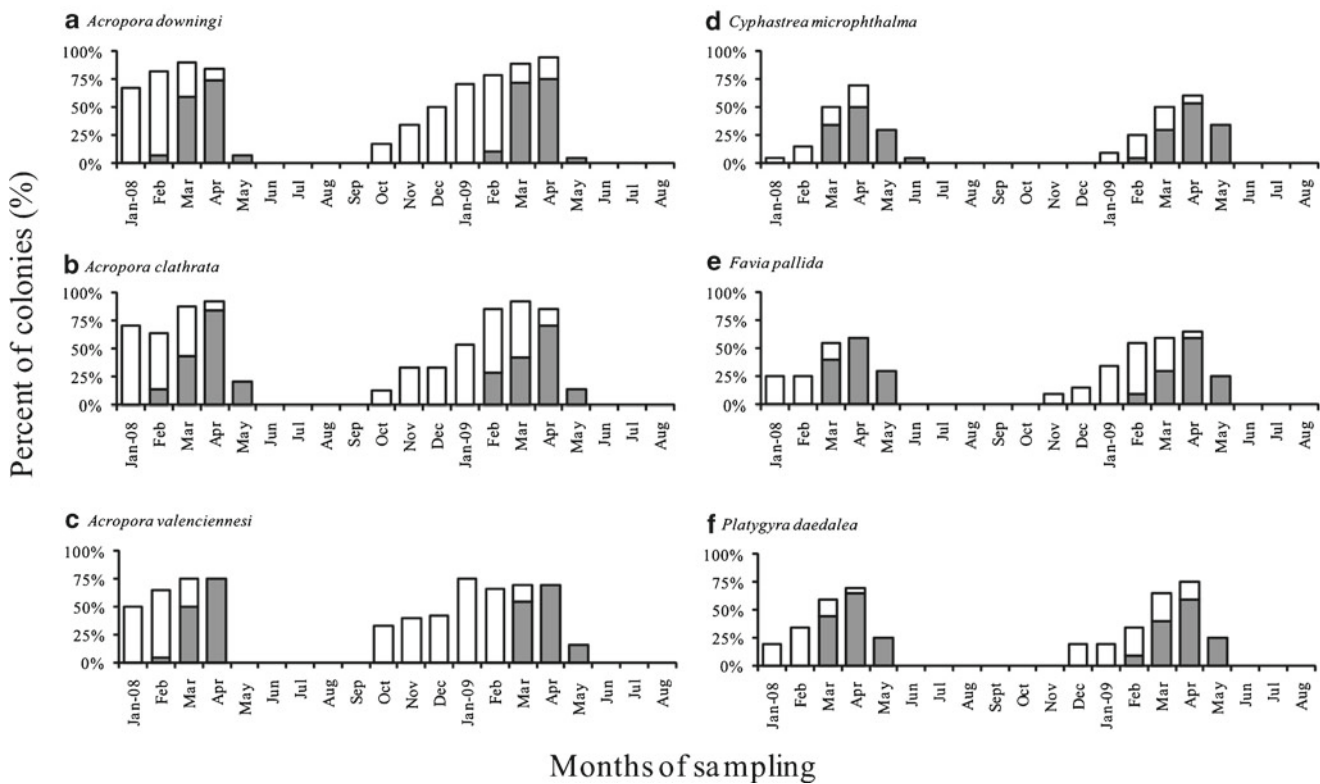
There is increasing evidence suggesting that Gulf reef communities have substantial ability to recover from disturbance events (Riegl 1999; Riegl and Purkis 2009). Following elevated sea surface temperatures in 1996 and 1998, widespread coral mortality occurred in the Gulf, particularly in *Acropora* dominated areas (Riegl 1999). To examine the ability of coral communities to recover from disturbance events, Burt et al. (2008) assessed both the percentage coral cover and species composition of a distinct coral community in Dubai, United Arab Emirates, a decade after the 1996/8 mass bleaching event. Coral communities within this region had undergone extensive loss of *Acropora* species (which had been the dominant habitat forming coral group in this region), associated with elevated sea surface temperatures (Purkis and Riegl 2005;

Table 9.1 Comparisons of mean oocyte size and fecundity (oocytes polyp⁻¹/mesentery⁻¹) at different geographic locations for which data are available for Dubai, UAE. For each species, data are ordered in decreasing mean oocyte size

Species	Location	Oocyte size (mm)	Fecundity	Source
<i>Acropora downingi</i>	UAE	543	14.2 polyp ⁻¹	Bauman et al. (2011)
<i>Cyphastrea microphthalma</i>	Taiwan	310	–	Dai et al. (1992)
	UAE	293	78.1 polyp ⁻¹	Bauman et al. (2011)
	Red Sea	290	105 polyp ⁻¹	Schlesinger et al. (1998)
<i>Platygyra daedalea</i>	Taiwan	415	–	Dai et al. (1992)
	UAE	368	14.2 mesentary ⁻¹	Bauman et al. (2011)
	*Kenya	259	7.9 mesentary ⁻¹	Mangubhai and Harrison (2008)

– No data available

* indicates mean oocyte size and fecundity prior to the major spawning event in Kenya (i.e., bi-annual gametogenic cycles)

**Fig. 9.1** Percent of colonies with mature and immature oocytes in 2008 and 2009 for six coral species. *Shaded percent* of colonies with mature gametes, *white percent* of colonies with immature gametes (Adapted from Bauman et al. (2011) by permission of Springer)

Riegl 2002a, b) but the ability of Gulf reef communities to recover from substantial disturbance is clearly demonstrated (Burt et al. 2008; Purkis and Riegl 2005; Riegl and Purkis 2009). Ten years after mass mortality *Acropora* dominated assemblages were observed in three of the six sites examined and coral cover was double post-bleaching cover (Riegl 2002a). A high prevalence of young *Acropora* colonies was found, indicating that recovery of an *Acropora* dominated community may recur within several years. Although there

has been sustained losses of coral reef communities throughout the Gulf (see reviews in Sheppard et al. 2010; Sale et al. 2011) the ability of Gulf coral communities to rebound following a substantial disturbance event is clearly demonstrated (Riegl 1999, 2002a, b; Purkis and Riegl 2005; Burt et al. 2008; Riegl and Purkis 2009). Further work is needed to understand the mechanisms important in coral reef recovery within the Gulf, although anecdotal evidence (JA Burt and AG Bauman, unpublished data) suggests that potential recovery of reef areas

will be associated with their distance to adjacent reef areas, and the local-scale oceanographic parameters important in the movement of pelagic larvae between suitable settlement sites (GH Cavalcante, unpublished data). Riegl and Purkis (2009) demonstrated in modelling studies the importance of population connectivity.

Changing oceanic climate has already generated novel ecosystems by reshaping and altering many biological communities (Yakob and Mumby 2011). Over the past decade, a range of ecological processes important in structuring coral reef communities have been linked to climate change, including shifts in community structure (species abundances, spatial distribution) and changes in phenology and larval dispersal (Przeslawski et al. 2008). Although shifts in coral community taxonomic structure as a result of climate change have been well documented within the Gulf (Burt et al. 2008; Riegl and Purkis 2009), the size structure of the communities is little understood. Corals size distributions mostly reflect differences among taxa, however within taxa there are also size patterns that are expected to result from growth differences in relation to community structure and different disturbance histories (Meesters et al. 2001). Given the marked coral community shifts in the Gulf as a result of repeated temperature-related mortality events (1996, 1998 and 2002) (Sheppard et al. 1992; George and John 1999; Riegl 1999) we would expect that the size structure of coral populations in the Gulf differ from populations under less extreme environmental conditions. Modelling studies by Riegl and Purkis (2009, chapter 5) indicated size-class shifts towards increasing abundance of small massive corals with increased disturbance-frequency. Bauman et al. (unpublished) found considerable differences in average colony size (i.e., projected surface areas) between four common coral species (*Acropora downingi*, *Favia pallida*, *Porites lobata/lutea* and *Platygyra daedalea*), in the southern Gulf (UAE) and northeastern Gulf (Musandam, Oman). Preliminary analyses indicate that average colony size in all focal species in the north-eastern Gulf was significantly larger. Size-frequency distributions suggest that all four species in the southern Gulf were strongly skewed, with a large number of colonies in the smallest size-classes. In contrast, size frequency distributions for *A. downingi*, *P. daedalea* and *P. lutea/lobata* in the northeastern Gulf had bimodal distributions with peaks in both small and large size-classes of colonies, perhaps reflecting the population-level impact of earlier bleaching events. Mean monthly SSTs calculated to determine the annual range and variability in SST between regions showed an approximately 2°C difference in maximum SSTs during summer months (June–August) despite the two locations being only ~200 km apart (see also Sheppard and Loughland 2002); for more analyses see Chaps. 2 and 5.

9.5 Gulf Reef Fauna Within Extreme Environments: Future Directions for Research

An increasing literature (see also Chap. 7) support the notion that virtually all animal and plant communities are substantially affected by the climatic extremes in the Gulf. Comparison of Gulf communities with those from more benign environments (Gulf of Oman) found reduced levels of diversity and abundance (Feary et al. 2010). Gulf communities are characterized by smaller individuals (Feary et al. 2010; AG Bauman, unpublished data), trophic partitioning of communities with higher abundances of herbivores (Feary et al. 2010) and strong population recovery rates (Burt et al. 2009; Riegl and Purkis 2009). There is little to no difference in coral reproduction and timing to species found outside the Gulf (Bauman, unpublished data) suggesting that species adaptations to the extreme physical environments may be more complex than previously suggested (Sheppard et al. 1992).

Tropical corals and reef fish have optimized molecular and cellular processes to operate in a narrow thermal window to minimize maintenance costs, and are not tolerant of temperatures outside of this range (Portner et al. 2004; Portner and Farrell 2008). Relatively small increases in temperature can result in decreased performance (1–2°C) and death (3°C) of tropical fishes (Munday et al. 2009; Nilsson et al. 2009) and bleaching, inhibition of fecundity, and mortality of corals (Hoegh-Guldberg 1999; Baker et al. 2008), suggesting potentially rapid and profound impacts of climate warming on coral reef fauna. Previous studies of temperature-related changes in aerobic performance in reef fish and the physiological ecology of corals (Hoegh-Guldberg et al. 2007) have focused on fauna from low-latitude reefs with relatively stable temperatures (Fitt et al. 2001; Nilsson and Ostlund-Nilsson 2008; Munday et al. 2009; Nilsson et al. 2009). However, temperature variation increases with latitude, and populations exposed to more variable climatic conditions, such as fish and corals on sub-tropical or high-tropical latitude reefs (such as in the Gulf), may be better able to acclimate and shift their thermal tolerance thresholds (Portner and Knust 2007; Portner and Farrell 2008; Tewksbury et al. 2008; Portner 2010). Fauna in high latitude reefs may therefore be better able to cope with temperature increases projected under climate change, although there is little experimental evidence to accept or negate this hypothesis. Therefore, there is a valuable opportunity for researchers to examine the role of temperature fluctuation in influencing the physiology of Gulf reef communities, and therefore their potential to acclimate to future climate change conditions.

There is still little research examining the importance of gene flow of both coral and reef fish species into and out of

the Gulf. Higher-latitude coral reef populations may support the adaptation of conspecifics on low-latitude reefs via gene flow throughout metapopulations. Both the reef fish and coral communities within the Gulf support species that have dispersive planktonic larvae, that can drift from weeks to several months and thus theoretically travel distances of several to hundreds of kilometers away from the natal reef (Kinlan and Gaines 2003; Kinlan et al. 2005; Shanks et al. 2003). This suggests that there may be flow of Gulf genes, acclimated to extreme physical environments, towards low latitude reefs. Such gene flow may provide genetic variation necessary to allow adaptation of populations in low-latitude tropical areas to increasingly extreme environments. This suggestion is supported by the observation that the strongest impacts to aerobic capacity in thermal experiments with five species of reef fish from the Great Barrier Reef were in *Acanthochromis polyacanthus* (Nilsson et al. 2009), a species that lacks a dispersive larval stage and exhibits strong genetic isolation between populations (Planes et al. 2001), while only slight and non-significant decreases in aerobic capacity were observed in *Dascyllus aruanus* (Nilsson et al. 2009), a species with long dispersal distances relative to other reef fish (Kinlan and Gaines 2003), a wide latitudinal distribution (Froese and Pauly 2010), and relatively homogeneous genetic variation at large spatial scales (Planes et al. 1993). While the acclimation and adaptation of aerobic capacity will not likely apply to species endemic to low-latitude reefs, these observations do provide hope for the resilience of species with wider latitudinal distributions and suggests that the Gulf may represent a source of genetic refuge from the impacts of climate change to connected populations in surrounding regions.

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John A. Burt, Aaron Bartholomew, and David A. Feary

10.1 Introduction

Over 70% of the largest cities on earth are associated with seashores (Duarte et al. 2008), and two thirds of the human population lives within 100 km of a coast (UNEP 2002). The Gulf is no exception, with most major urban centers directly adjacent to coasts, with its people both culturally and economically tied to marine resources. Coastal development has rapidly expanded in the Gulf since the 1950s, leading to an increase in the exploitation of coastal marine resources and the degradation of coastal habitats (Al-Madani et al. 1991; Mohammed and Al-Sadh 1996). Coastal fisheries throughout the Gulf are being increasingly exploited, with demersal reef fisheries stocks declining by over four-fifths in the past three decades (see Chap. 8), while dredging, reclamation, and associated coastal development activities have contributed to the permanent loss or long-term degradation of important intertidal, sea-grass, mangrove, and coral reef habitats throughout the Gulf (Price 1993; Al-Jamali et al. 2005; Khan 2007; Burt et al. 2008, 2009b; Maghsoudlou et al. 2008; Sheppard et al. 2010, chapter 16). It is likely that such impacts will accelerate in the coming decades as population continues to grow and become progressively more urbanized along the Gulf's coastlines (GRWv3 2005).

J.A. Burt (✉)

Division of Science and Mathematics, New York University-Abu Dhabi, P.O. Box 129–188, Abu Dhabi, United Arab Emirates
e-mail: John.Burt@nyu.edu

A. Bartholomew

Department of Biology, Chemistry and Environmental Sciences
American University of Sharjah, P.O. Box 26666, Sharjah,
United Arab Emirates
e-mail: abartholomew@aus.edu

D.A. Feary

School of the Environment, University of Technology,
Sydney, Australia
e-mail: David.Feary@uts.edu.au

Purpose-built artificial reefs are increasingly being promoted as a means to mitigate impacts to coastal resources and habitats in the Gulf (Erfteimeijer et al. 2004). Proponents of artificial reefs in the Gulf suggest that such structures can increase commercial fisheries yield by aggregating target species (Downing et al. 1985; IFRO 2005; Hopkins 2007; Azhdari and Azhdari 2008; EAD 2008), or that artificial reefs can potentially increase demersal reef fisheries yields in areas where reef habitat is limited (Polovina and Sakai 1989; Bohnsack et al. 1997). Indeed, purpose-built artificial reefs to enhance fish catch have been in use for centuries in the Gulf, with these structures (called *shad* in Arabic, pl. *shadood*) being inherited through family lines and their use regulated by the *Senat Al-Bahar* – the ‘code of the sea’ (Al-Oufi et al. 2000; Azhdari 2003; EAD 2008). Unfortunately, such artificial reefs may often attract commercial fish species which are already over-exploited, making them easier to target and further exacerbating stock declines (Grossman et al. 1997).

There is evidence that purpose-built artificial reefs in the Gulf may be effective in attracting commercially valuable species. Within a year of deployment in Kuwait, three 25 m² artificial reefs constructed of tires held over 50 species of fish from 33 families, with sports fish making up 86% of all fish observed and the commercially important grouper *Epinephelus tauvina* and the barracuda *Sphyraena jello* contributing over 50% of the biomass (Downing et al. 1985). These same reefs were also rapidly colonized by epifauna, with serpulid tubeworms, ectoprocts, and oysters dominating the benthos (Downing et al. 1985). Small artificial reefs deployed in the waters of the United Arab Emirates attracted a range of commercially important species, including grouper (Family Serranidae), snapper (Lutjanidae) and sweetlip (Haemulidae) species (Hopkins 2007; Al-Cibahy et al. 2009). Harris and Schroder (2001) described 17 shipwrecks, or groups of wrecks, and 1 artificial reef in the waters of the United Arab Emirates. Of these wrecks, at least eight were purposefully sunk to create

artificial reefs, and at least four of these by local fishermen. Harris and Schroder (2001) report grouper on three wrecks, snapper on seven wrecks, barracuda (Sphyraenidae) on three wrecks, and jacks (Carangidae) on one wreck. The artificial reef Harris and Schroder (2001) describe was situated at 12 m depth, and was constructed of approximately 3,000 hollow concrete foundation blocks. They observed a range of commercially important fishes, including grouper, snapper, barracuda, jacks, and mackerel (Scombridae) on this reef. In addition, a series of artificial reefs deployed in Abu Dhabi, United Arab Emirates attracted six species of commercially important fish *Acanthopagrus bifasciatus* (Sparidae), *Diagramma pictum* (Haemulidae), *Epinephelus coioides* (Serranidae), *Lutjanus fulviflamma* (Lutjanidae), *Lethrinus lentjan* (Lethrinidae) and *Plectorhinchus sordidus* (Haemulidae) after being submerged for approximately 1 year (Al-Cibahy et al. 2009). Hard corals also recruited to these artificial reefs. In addition to fish, artificial reefs in the Gulf have also been deployed to attract commercially important benthic species. Purpose-built artificial reefs in southern Iran have been used to attract lobster (mainly *Panulirus homarus*, *P. versicolor* and *P. polyphagus*) and augment the local fishery, which has declined by over 70% in the past decade (Azhdari and Azhdari 2008).

In addition to their role in fisheries, purpose-built artificial reefs are increasingly being promoted as a means to mitigate anthropogenic impacts to natural reefs. A number of Gulf countries require that financial penalties be paid for negative impacts to coral reefs (Al-Haimi 2007; Richer 2008), and artificial reefs have been proposed as a means to compensate for loss or degradation of natural habitats in Qatar (Abdel-Moati 2006; Al-Haimi 2007; Richer 2008), Bahrain (Barber 2006; Maghsoudlou et al. 2008), Kuwait (Al-Saffar and Al-Tamimi 2006; Maghsoudlou et al. 2008), Iran (Sadatipour et al. 2009), and the United Arab Emirates (EAD 2008).

Despite the suggested benefits of purpose-built artificial reefs in enhancing commercial fisheries production or mitigating impacts to natural reefs in the Gulf, these structures are unlikely to provide significant services due to their small size (Fig. 10.1). Most artificial reefs in the Gulf are on the scale of less than tens of square meters in area, and are generally deployed at a small number of sites (Downing et al. 1985; Hopkins 2007; Al-Cibahy et al. 2009; Sadatipour et al. 2009). Therefore, due to their small size such structures are likely to have relatively small ecological value for enhancement or mitigation (Burt et al. 2009b). Large-scale man-made structures which have not been designed as artificial reefs - such as breakwaters, jetties, oil and gas facilities, and related infrastructure - are likely to serve a far more important role in the ecology of marine systems in the Gulf. Man-made structures now make up more than half of the shoreline in a number of coastal cities in the region (Price 1993; Burt et al. 2009a, b). Although not designed as artificial



Fig. 10.1 Purpose-built artificial reefs, such as these in Al-Yasat, western Abu Dhabi, are unlikely to provide substantial ecological benefits given their limited size versus natural reefs and larger man-made structures such as breakwaters (Image: J. Burt)

reefs, such structures provide a substantial amount of complex hard-bottom habitat upon which marine communities develop in the Gulf (John and George 1998, 1999; Stachowitsch et al. 2002; Burt et al. 2009b). Mature artificial reefs in the Gulf usually contain extensive coral communities that provide food, settlement habitat, and shelter for a variety of reef organisms (John and George 1998; Burt et al. 2009a, b), and increase their aesthetic appeal and recreational value.

Gulf coastal development has accelerated at an unprecedented rate in the past decade (Khan 2007). Large-scale coastal real-estate developments in the Gulf include ‘Pearl City’ in Kuwait, the ‘Durrat Al Bahrain’, ‘Amwaj’, and ‘Dyar Al Muharraq’ developments in Bahrain, ‘The Pearl’ in Qatar, ‘Al Khaleej’ in Half Moon Bay, Saudi Arabia, and ‘The World’ and ‘Palm Island’ developments in Dubai, UAE (Fig. 10.2). There has also been rapid development of infrastructure for ports, oil, gas, and other industrial facilities (Khan 2007), with coastal nuclear power infrastructure to follow in the coming decade (Brumfiel 2008). Although such developments have led to the loss or degradation of coral reef habitats in some areas in the Gulf (Price 1993; Khan 2007; Burt et al. 2008, 2009b; Maghsoudlou et al. 2008; Sheppard et al. 2010), there is increasing recognition that such developments, when properly designed, monitored, and managed, may have the capacity to mitigate at least some of their impacts and provide important, new, hard-bottom habitat.

Research over the past decade in the Gulf and elsewhere has only just begun to shed light on the importance of man-made coastal ecosystems. Oil and gas-related infrastructure in the Gulf can provide important large-scale fish habitat as well as hard substrates for corals and other benthos to settle upon (Al Hassan 1994; Stachowitsch et al. 2002). Because the submerged legs of oil rigs are heavily covered with benthic invertebrates used as food by fish, these structures may form important trophic resources for a variety

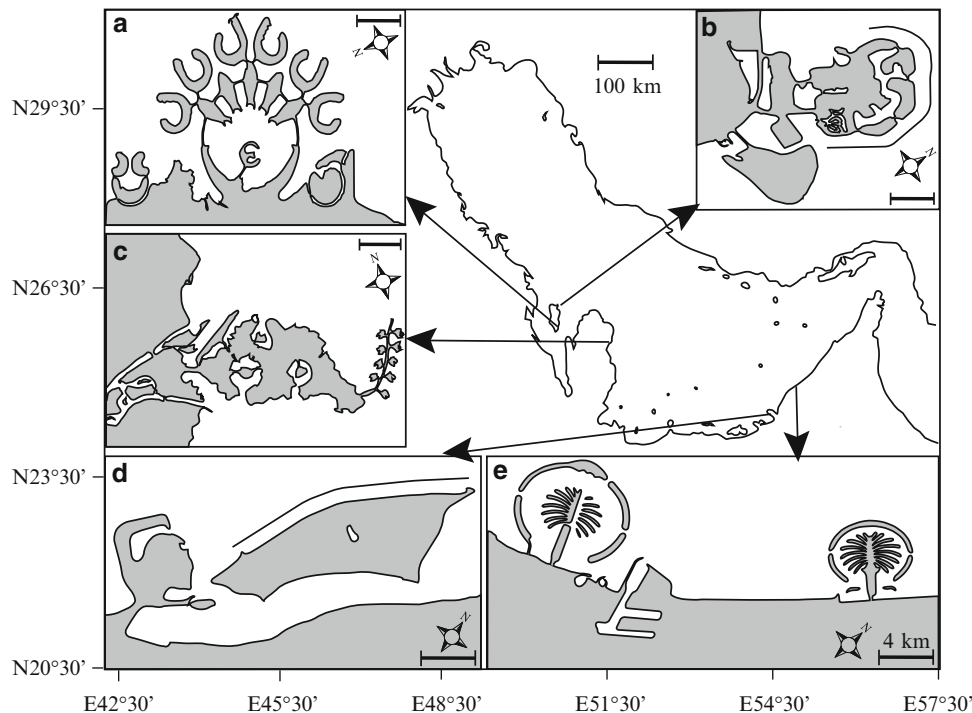


Fig. 10.2 Map illustrating the location of several of the large-scale man-made coastal developments in the Gulf; all were constructed within the past decade, and others are in construction or planning phases. (a) Durrat Al

Bahrain, (b) Amwaj Bahrain, (c) Pearl Qatar, (d) Marina (left) and Lulu (right) islands, Abu Dhabi, UAE, and (e) Palm Jebel Ali (left) and Palm Jumeirah (right), Dubai, UAE. Scale bar=1 km unless otherwise indicated

fishes and support relatively abundant communities while also promoting high growth rates for resident fish (Johnson et al. 1994). Upon decommissioning, obsolete oil and gas platforms can be converted into long-lasting, large-scale artificial reefs in programs commonly known as ‘rigs to reefs’ (Kasprzak 1998); such structures can support abundant and diverse communities of coral, other benthic invertebrates and fish, including commercially valuable species (Shinn and Wicklund 1989; Bull and Kendall 1994; Page et al. 1999; Stachowitsch et al. 2002). Given that there are estimated to be over 2,000 well-head platforms and thousands of kilometers of sub-sea pipeline in the Gulf (Stachowitsch et al. 2002), such structures are likely to play an ecologically important role in the marine ecology of the Gulf. Man-made coastal defense structures such as breakwaters, sea-walls, jetties, and groynes are also likely to play an important role in the Gulf marine systems due to their large size, complexity, and ubiquity along much of the Gulf’s coastline. Coastal defense structures often develop communities of fish, corals, and other fauna with densities that are comparable to, or greater than, that of nearby natural reefs (Lincoln-Smith et al. 1994; Stephens et al. 1994; Pondella et al. 2002; Moschella et al. 2005; Wen et al. 2007; Burt et al. 2009b; Viyakarn et al. 2009; Sheppard et al. 2010). These structures may also serve as important habitats for juvenile settlement and perhaps larval production of both fish and benthic invertebrates

(Pondella et al. 2002; Stephens and Pondella 2002; Guidetti 2004; Bulleri 2005b). The development of communities associated with coastal defense structures may also have some economic benefits, supporting both recreational diving companies and commercial fisheries (Stephens et al. 1994; Burt et al. 2009b).

Despite their potential importance, there is only limited understanding of the patterns and processes governing community development on artificial structures, particularly in the Gulf. Man-made structures can be constructed in ways that enhance the development of coral and fish communities, but such ecological aspects are generally not considered in their design (Burt et al. 2009a; Burt 2010a). Communities on artificial structures can differ substantially from those on natural reefs, both in terms of structure (i.e. diversity and abundance) and function (i.e. reproduction, competition, etc.) (Bulleri 2005a, b; Moschella et al. 2005; Clynick et al. 2008; Burt et al. 2009a, b). An understanding of the factors affecting when and how communities develop on artificial structures in the Gulf, and the similarities/dissimilarities between such structures and natural reefs is not well understood, but is essential if we are to guide the construction and management of these unique and important coastal ecosystems (Burt et al. 2009a, b; Sheppard et al. 2010).

This chapter concentrates on benthic and fish communities associated with breakwaters in Dubai, United Arab

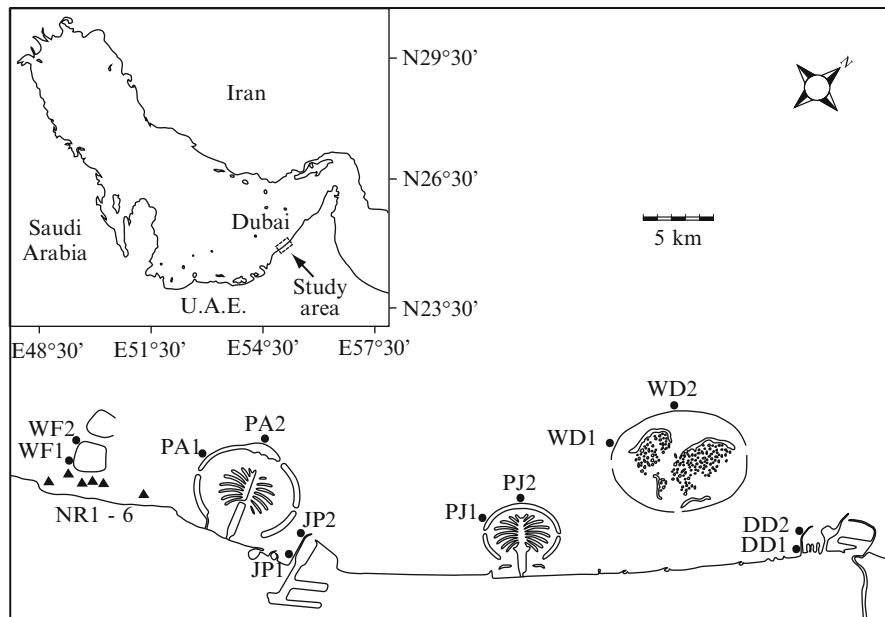


Fig. 10.3 Location of breakwater (●) and natural reef (▲) sampling sites described in the various studies herein. Site names and age (at the time of study): *NR* natural reefs, *WF* Dubai Waterfront (1.5 years old),

PA Palm Jebel Ali (3.5 years), *JP* Jebel Ali port (31 years), *PJ* Palm Jumeirah (5.5 years), *WD* The World (1 year), *DD* Dubai dry docks (25 years) (From Fig. 1 in Burt et al. (2011))

Emirates, a city that has undergone substantial coastal development over the past decade. The construction of large-scale breakwaters in this area may be particularly important as natural reefs in Dubai are limited in area, existing only in a series of discontinuous patch reefs isolated to a 10 km near-shore band in western Dubai, with the remaining coastal area dominated by mobile sands and silt unsuitable for most hard-bottom organisms (Riegl 1999; Burt et al. 2008). Design aspects of breakwater construction (materials used, wave exposure) were examined to determine their influence on associated coral and/or fish communities. Coastal developments that are properly designed may better promote the development of high biomass and/or diversity communities associated with them, which may better support commercial fisheries and recreational diving in the region. We compared biotic communities on breakwaters of different ages with those of nearby natural reefs to determine if and when these communities on man-made structures resembled communities on natural reefs. Such comparisons between breakwaters and natural reefs are necessary if we are to assess the value of coastal defense structures for habitat loss mitigation, and to understand their ecological role in structuring the marine ecosystem. By exploring the patterns of breakwater community development and the processes shaping these communities, we may gain a more complete understanding of the ecological role of these large-scale artificial reefs in the Gulf, and whether there are ways to improve the design of these now near-ubiquitous structures.

10.2 Dubai: A Case Study in the Ecology of Urban Reefs

10.2.1 Study Area and Methods

From 2006 to 2009 a series of studies were conducted on breakwaters and natural coral reef habitats in Dubai, United Arab Emirates (Fig. 10.3) for the purpose of understanding the ecology of these large-scale man-made structures. Major coastal development in Dubai first began in the late 1970s with the construction of the Jebel Ali Port, followed by the Dubai dry docks a few years later, with further minor modification over the next two decades with the construction of small fishing ports (Burt et al. 2009a, b). Large-scale development of off-shore islands began in 2002 with the construction of the Palm Jumeirah, followed by the construction of the Palm Jebel Ali, The World, and the Dubai Waterfront islands, all of which are at various stages of construction at the time of writing (Fig. 10.3). These islands were mainly constructed from sediments dredged from borrow areas approximately 25 km off-shore of the Dubai coastline, and each is protected by a large rocky breakwater running along its outer perimeter. Breakwaters were constructed from 4 to 6 ton quarried rock placed in waters of approximately 6–12 m depth, except for the Jebel Ali Port which was constructed from 4 ton concrete tetra-foil jacks. The major breakwaters of interest as well as the natural reefs are labeled in Fig. 10.3, which will be referred to when discussing the sampling of specific locations in the following sections.

Coral reefs in Dubai are restricted to areas of emergent limestone cap-rock occurring in 1,500–2,500 m² patches approximately 1 km off-shore along the western 10 km of Dubai in the Jebel Ali area (Fig. 10.3), with the sea-bottom to the east of Palm Jebel Ali mainly composed of mobile sands and silts unsuitable for corals (Riegl 1999; Burt et al. 2008). Corals in Dubai generally have limited framework development and are best classified as ‘coral carpets’ rather than true reefs (Riegl 1999). These discontinuous coral patches generally have low relief and are surrounded by mobile sands and silts, which can become suspended during storms. Occasional overtopping by sands during storms represents one of the major stressors to corals on these reefs (Riegl 1999). Over the course of these studies, six natural coral patches were sampled in Jebel Ali. From 2006 to 2009, sampling of breakwater and natural reef sites included censuses of fish, corals, and/or other invertebrates. Composition of coral and other invertebrate communities was sampled using high-resolution photographs of the benthic community. Six replicate 30 m line transects were photographed at 3 m intervals using a digital camera mounted on a PVC quadrat frame enclosing a 0.25 m² area, for a total of 66 photo-quadrats per site. Sampling was standardized at approximately 5–6 m depth at each site. Digital photographs were then analyzed using 50 random point intercepts with CPCE image analysis software, version 3.5 (Kohler and Gill 2006). Fish were sampled at 3 month intervals to allow examination of seasonal changes in abundance. At each site fish abundance was visually estimated from eight replicate 1 m wide by 30 m long belt transects, with all fish within 1.5 m above the bottom included.

10.2.2 The Effect of Breakwater Material on Coral Recruitment and Early Benthic Communities

Breakwaters in Dubai, as in other regions worldwide, are made from a variety of materials including various types of quarried stone and concrete. Breakwaters are colonized by major habitat-forming sessile fauna (e.g. corals, sponges, oysters, etc.), and some materials will be more suitable than others for encouraging the growth of different fauna (Fig. 10.4). Unfortunately, the effect of substrate material on the resulting sessile benthic community remains relatively understudied (Baine 2001). Many organisms are selective of the geochemical signatures of substrates they will settle on (Anderson 1996; Maldonado and Uriz 1998; Qian 1999), and differences in the material preference of benthic larvae could result in the development of divergent communities if different substrate materials are used to construct separate breakwaters. Given that coral and other sessile fauna can provide food, shelter, and settlement habitat for a variety of reef-associated organisms, including fish (Elliott et al. 1995;

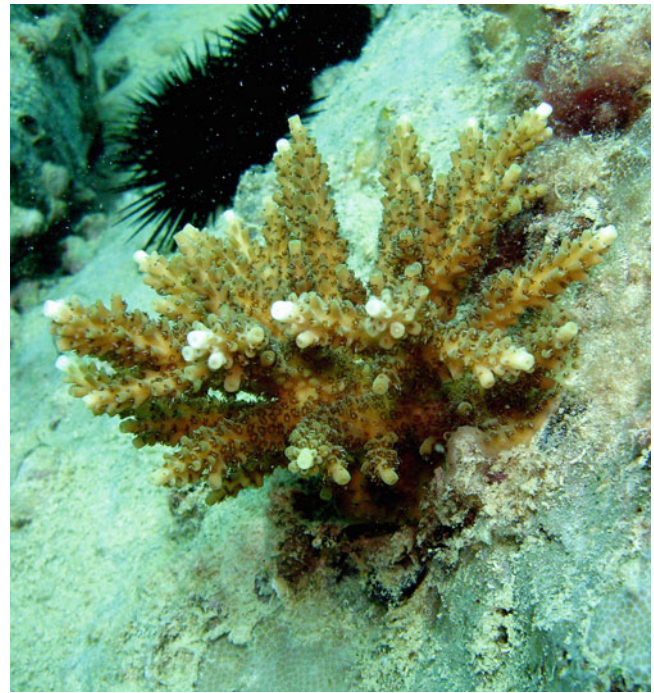


Fig. 10.4 Breakwaters and other coastal defense structures in the Gulf are rapidly colonized by coral juveniles, such as this *Acropora* spp., and differences in the types of materials used in construction can affect recruitment patterns (Image: K. Wilson, EMEG)

Qian 1999; Crossman et al. 2001; Hartney and Grorud 2002; Nishizaki and Ackerman 2004), construction material may have an impact on the reef communities that develop on these structures, and therefore have management implications.

Burt et al. (2009a) examined the influence of materials commonly used in the construction of breakwaters on early coral recruitment, as well as on wider benthic community development, by comparing communities that developed on four materials: concrete, gabbro, granite, and sandstone. Standardized blocks of each material were machine-cut to a tile size of 100×100×15 mm using a diamond-tipped rock saw. Twenty-five tiles of each material were bolted 2 cm above the benthos using an underwater drill at four sites, including two breakwaters (Dubai dry docks, Jebel Ali port) and two natural reef sites (NR1, NR6) (Fig. 10.3). Tiles were deployed in April 2007 and collected 1 year later. The abundance of coral juveniles settling on each tile was tabulated, and image analysis was also used to examine the benthic communities on the different types of tiles, and in the different locations (see above).

Coral recruitment was extremely low at three of the four sites (with less than 0.3 juveniles per 100 cm² tile, on average, at the two natural reef sites and the Jebel Ali port site). This was likely due to thermal stress during a period of elevated water temperatures and associated coral bleaching in Jebel Ali during the study. As a result of the low recruit densities and associated high variability, there were no consistent

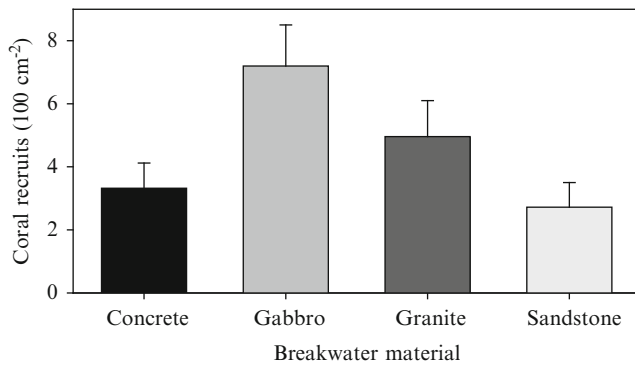


Fig. 10.5 Juvenile coral abundance on tiles made of different breakwater materials at the Dubai dry dock breakwater (Adapted from Fig. 2 in Burt et al. (2009a))

differences in coral recruitment among materials at these three sites. However, there were substantial differences in coral recruitment at the Dubai dry docks (Fig. 10.5), an area unaffected by bleaching, where corals recruited at 4.9 recruits per tile on average. Gabbro had the highest densities of coral juveniles compared with all other materials, and had significantly higher densities than both concrete and sandstone (Fig. 10.5; Burt et al. 2009a). Different breakwater material had no effect on wider benthic community development, with among-site differences more important in driving community differences than materials (Burt et al. 2009a).

The results of this study are important for improving our understanding the role of recruitment in structuring communities the Gulf. First, this work demonstrates the importance of stochastic processes in structuring benthic marine communities, including those associated with man-made structures. In this study, large differences in coral recruit abundance occurred at sites only tens of kilometers apart, likely due to differences in planktonic larval supply and/or differences in juvenile mortality associated with a warm-water event in Jebel Ali. This emphasizes the importance of factoring such natural processes into plans for ecological engineering. Secondly, the results of this study indicate that in areas where coral recruitment is high, substrate material may have a substantial effect on successful coral settlement on man-made structures. Currently, the majority of sea-walls, jetties, and breakwaters around the world are made from concrete, granite, and sandstone (Baine 2001; Bulleri 2005a; Moschella et al. 2005; Creed and DePaula 2007). Gabbro is very widespread both globally and around the Gulf (Sen 2001), yet it has been rarely used in man-made coastal protection. These results indicate that, where possible, gabbro should be used preferentially over both concrete and sandstone in order to enhance coral community development. Finally, the results indicate that different materials do not have a substantial effect on the wider benthic community development, despite having an effect on coral recruitment. Benthic communities

are likely to develop similarly during their first year, regardless of the materials used.

10.2.3 The Influence of Breakwater Wave Exposure on Benthic and Fish Communities

In addition to substrate material, one of the most fundamental aspects of breakwater design that may influence community development is exposure to wave action. Differing levels of wave exposure can substantially influence the composition and abundance of benthic communities on breakwaters and related structures in temperate environments (Southward and Orton 1954; Moschella et al. 2005), and has been associated with differences in fish and coral community structure on tropical coral reefs (Clark 1997; Riegl and Piller 1997; Reinicke et al. 2003; Steiner 2003; DeMartini et al. 2009). However, the influence of wave exposure on the development of coral and fish communities on breakwaters in tropical or sub-tropical areas such as the Gulf is poorly understood (Fig. 10.6).

Wave exposure can have direct or indirect effects on community development. It is known that on natural coral reefs, the physical action of waves can affect coral and associated fish communities through differences in the supply of larval recruits, trophic resources, or through differences in the physical effects of wave energy on faunal composition (Riegl and Velimirov 1994; Fulton and Bellwood 2004; Fulton et al. 2005; Floeter et al. 2007; Golbuu et al. 2007; DeMartini et al. 2009). However, differences in wave exposure can also drive differences in communities indirectly by affecting sedimentation rates. Sedimentation rates, in turn, can affect the growth and survival of corals, as well as other habitat-forming fauna important for fish (Hodgson 1990; Birrell et al. 2005; Crabbe and Smith 2005; Depczynski and Bellwood 2005; Santin and Willis 2007). No previous studies have examined the influence of wave exposure on breakwater community development in tropical or sub-tropical areas. Understanding the role of wave exposure in structuring coral and fish communities may improve our ability to effectively design breakwaters to enhance these communities.

Influence of wave exposure on coral community development in Dubai was examined by sampling communities on two exposed windward sites (PJ2, PJ4) and two sheltered leeward sites (PJ1, PJ5) on the 5.5 year old Palm Jumeirah breakwater, and compared these to a natural reef (NR6) (Fig. 10.3) over 1 year from July 2007 to July 2008. In addition, fish communities were surveyed and compared among these sites, with sampling conducted over 2 years from August 2007 to May 2009.

The results of benthic surveys showed that coral communities on wave-exposed windward breakwaters were more

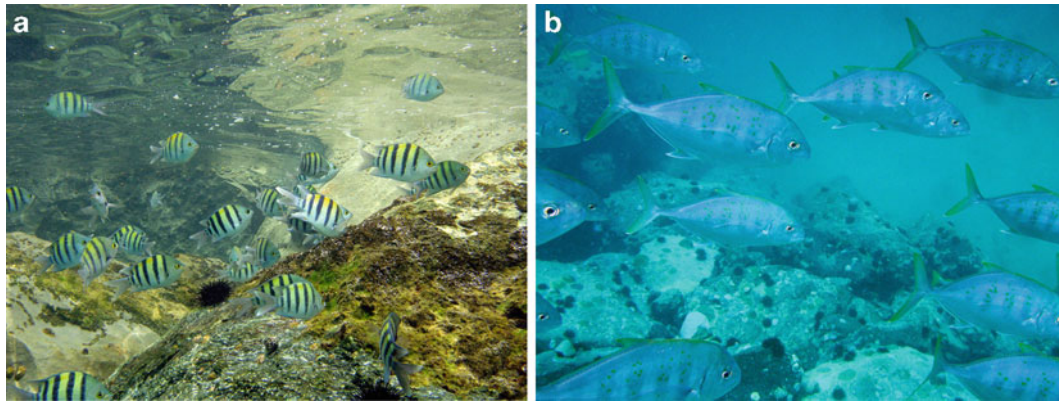


Fig. 10.6 Man-made structures such as breakwaters represent an important habitat for a diverse assemblage of fish in the Gulf, including the (a) ubiquitous Indo-Pacific sergeant, *Abudefduf vaigiensis*, and (b) the commercially important blue trevally, *Carangoides ferdau* (Images: K. Wilson, EMEG)

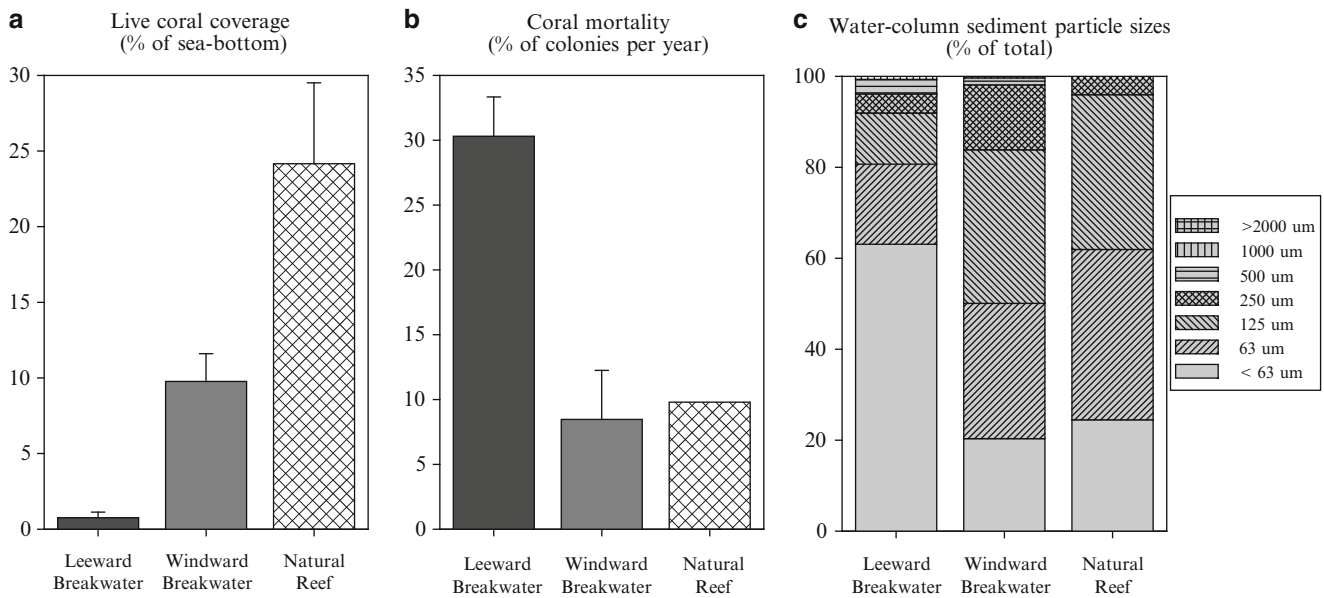
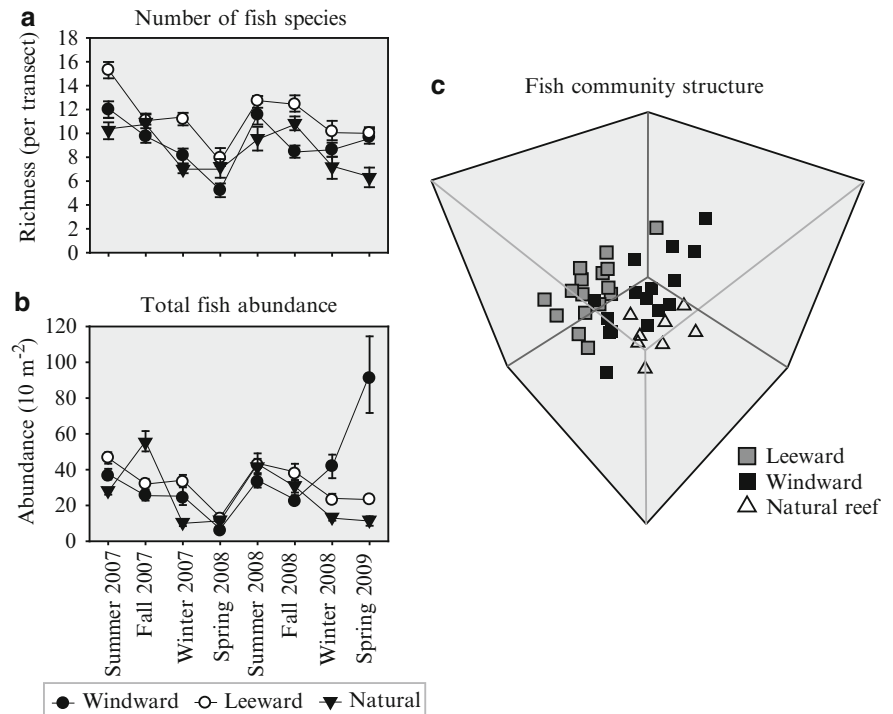


Fig. 10.7 Differences in (a) the amount of live coral, (b) the mortality rates of coral colonies, and (c) depositional sediment grain-size between leeward and windward breakwaters, with a comparison to a natural reef. Data shown from October 2008 only; Seasonal data over 1 year can be found in Burt et al. (2010)

similar to natural reefs than those on protected leeward breakwaters. At the conclusion of the study, wave-exposed windward breakwaters contained nearly five times more coral cover than leeward breakwaters (Fig. 10.7a). Both windward and leeward breakwaters contained less coral cover than the natural reef, which is not surprising given the relatively young age of the breakwater (5.5 years). An analysis of juvenile coral recruitment and growth rates over the course of the study in both breakwater and natural reef habitats indicated that these did not differ with breakwater wave exposure, or between breakwaters and natural reefs. However, there was substantially higher coral mortality on the sheltered leeward breakwa-

ters compared with both the windward breakwater and the natural reef (Fig. 10.7b), with coral mortality resulting in the loss of nearly a third of all coral colonies on the leeward sites during the study period. The high mortality was associated with relatively high deposition of fine sediments (<63 mm grain size) on leeward breakwaters (Fig. 10.7c). These results suggest that coral community structure on breakwaters can differ substantially with wave exposure, with higher deposition of fine sediment increasing coral mortality in leeward-facing breakwater structures where water movement is limited. Fish communities associated with Palm Jumeirah breakwaters were also affected by differences in wave exposure.

Fig. 10.8 The influence of wave exposure on fish associated with the windward and leeward breakwaters on the 5.5 year old Palm Jumeirah with a comparison to a natural reef in terms of (a) number of fish species (30 m⁻² transect), (b) total abundance of fish (10 m⁻²), and (c) overall community structure in NMS ordination (Adapted from Burt (2010a))



Species richness on leeward breakwaters was consistently slightly higher than that of windward breakwaters and the natural reef over the 2 years of study (Fig. 10.8a), whereas windward breakwaters and natural reefs had similar species richness. These data also show a strong seasonal component to changes in community structure, with fish species richness and diversity increasing during the warmer summer and fall seasons and declining in the cooler winter and spring, likely as a result of migration on and off the breakwaters, consistent with earlier studies in the Gulf (Fig. 10.8a, b; Coles and Tarr 1990; Burt et al. 2009b). Fish abundance varied considerably among seasons on each reef type, and there were no consistent differences in abundance between windward and leeward breakwaters, or natural reefs (Fig. 10.8b). However, multivariate analyses of the fish communities indicated strong differences in overall assemblage composition between reef types. Figure 10.8c is an ordination scatterplot produced from non-metric multidimensional scaling (NMS) showing that fish communities on leeward breakwaters differed substantially from those on natural reefs. There was some overlap of windward breakwater communities with both natural reefs and leeward breakwaters over the 2 year study. Further analyses with Analysis of Similarity (SIMPER, Clarke and Warwick 2001) indicated that the strongest differences in communities were between leeward breakwaters and natural reefs ($R=0.71$), and that leeward and windward breakwater communities differed moderately ($R=0.41$). There were similar communities on windward breakwaters and natural reefs, which differed only weakly ($R=0.33$).

SIMPER analyses indicated that windward breakwaters were characterized by having higher abundance of *Lutjanus ehrenbergii* than the other reef types. Leeward breakwaters contained more *Cheilodipterus novemstriatus* than other reef types, and more *Amblygobius albimaculatus* than windward breakwaters. Natural reefs were characterized by having higher abundance of *Lutjanus fulviflamma* than other reef types, and more *Parupeneus margaritatus* than windward breakwaters. Overall, these results indicate that while wave exposure may have a limited effect on overall fish abundance and species richness, exposure does affect the types of fish species that live in each habitat.

The fish community divergence with wave exposure may be the result of differences in physical wave action, or due to differences in the sessile benthic organisms between the areas, which fish use as food and/or habitat. The leeward portion of the Palm Jumeirah breakwater has a significant wave height that is half of that of the exposed windward section (Smit et al. 2005). It is possible that fish community differentiation resulted from the different areas supporting species with different swimming abilities (Fulton and Bellwood 2004; Fulton et al. 2005). However, it is more likely that the observed differences in fish communities resulted indirectly from differences in the benthic organisms present in the different habitats. The leeward breakwaters on the Palm Jumeirah are dominated by oysters and turf algae, while the windward breakwaters are dominated by corals and bare pavement. These different benthic habitats provide distinct food sources and microhabitat for fish fauna, and

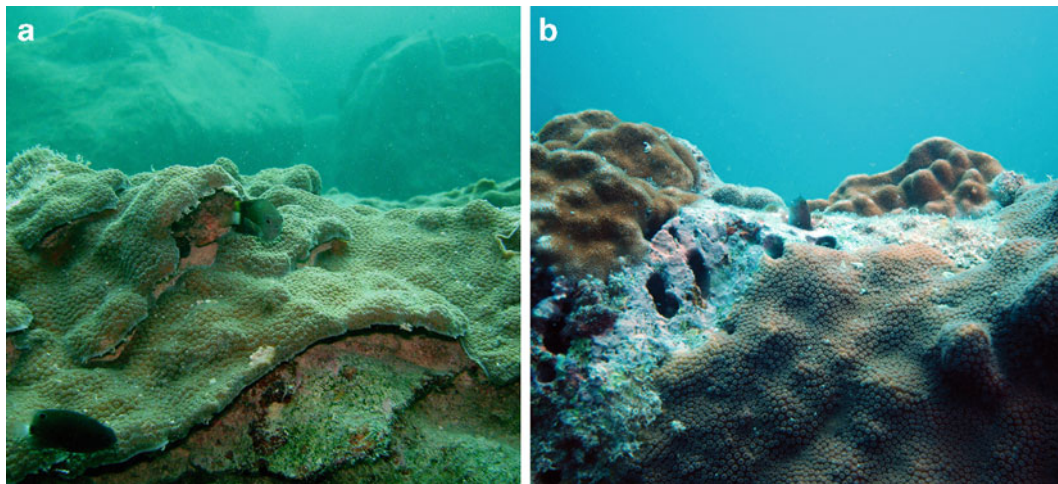


Fig. 10.9 Benthos such as corals growing on breakwaters in the Gulf provide important biogenic habitat for a variety of reef fauna including (a) the slender damsel, *Pomacentrus leptus*, (centre), the

pale-tail damsel, *Pomacentrus trichourus*, (left), as well as the (b) Gulf blenny, *Ecsenius pulcher* (Images: K. Wilson, EMEG, and J. Burt)

such differences have been found to structure fish communities on natural reefs (Fig. 10.9; Crossman et al. 2001; Depczynski and Bellwood 2005; Nanami et al. 2005; Floeter et al. 2007; Santin and Willis 2007). It is possible that similar processes are operating on these breakwaters, driving differences in community structure between exposed and protected breakwaters as well as natural reefs.

Overall, these results suggest that differences in environmental conditions related to wave exposure can have a pronounced effect on coral and fish communities in the Gulf. Differences in wave exposure can affect the type of sediments that are deposited on the breakwater surface, resulting in distinct benthic communities in exposed versus sheltered areas. In conjunction with physical differences, these benthic community differences probably affect the types of fish communities that occur.

10.2.4 Breakwater Age and the Development of Benthic Communities

Benthic communities associated with breakwaters often contain species of importance to marine management for their nuisance or aesthetic value (Airoldi et al. 2005) and they provide food, settlement habitat and shelter for numerous reef associated fauna, including those targeted by commercial fisheries (Elliott et al. 1995; Qian 1999; Hartney and Grorud 2002; Nishizaki and Ackerman 2004). However, the few existing studies have typically focused only on the very early stages of colonization (Osman and Whitlatch 2004; Bulleri 2005a, b) or on established communities (Moschella et al. 2005), including those examining breakwaters in the Gulf (Burt et al. 2009a, b). There is limited knowledge of how

breakwater benthic communities develop over time, and if and when they become similar to those on natural reefs as they mature (Bacchiocchi and Airoldi 2003; Airoldi et al. 2005). This is particularly true in tropical areas like the Gulf, where slow-growing corals may come to dominate benthic communities (Fig. 10.10). To gain an understanding of the patterns of community development in the Gulf, the benthic communities associated with breakwaters ranging from 1 to 31 years of age were examined by Burt et al. (2011). Sampling included virtually all major breakwaters in Dubai (see Fig. 10.3), including those associated with The World (1 year old at the time of study), the Dubai Waterfront (1.5 years), the Palm Jebel Ali (3.5 years), the Palm Jumeirah (5.5 years), the Dubai dry dock (25 years), and the Jebel Ali port (31 years). The different ages of these structures provided an opportunity to infer temporal patterns of community development on Dubai breakwaters. In addition, these breakwater communities were compared to those on natural reefs (NR1 – 6, Fig. 10.3) to determine if and when breakwater communities were comparable to those in natural habitats.

Benthic communities associated with breakwaters differed with age, and became more similar to those on natural reefs as the breakwater communities matured (Fig. 10.11). Benthic communities on the youngest breakwaters (~1.5 years) were dominated by algal turf, which declined in percent coverage with increasing breakwater age. The oldest 25 and 31 year old breakwaters had similar percent coverage of algal turf as natural reefs. Oysters were more common on the 3.5 and 5.5 year old breakwaters, and also declined in coverage on the mature (>25 years) breakwaters to levels comparable to natural reefs. The most striking change in abundance was the increase in coral cover on breakwaters of successive age, such that the 25 and 31 year old breakwaters

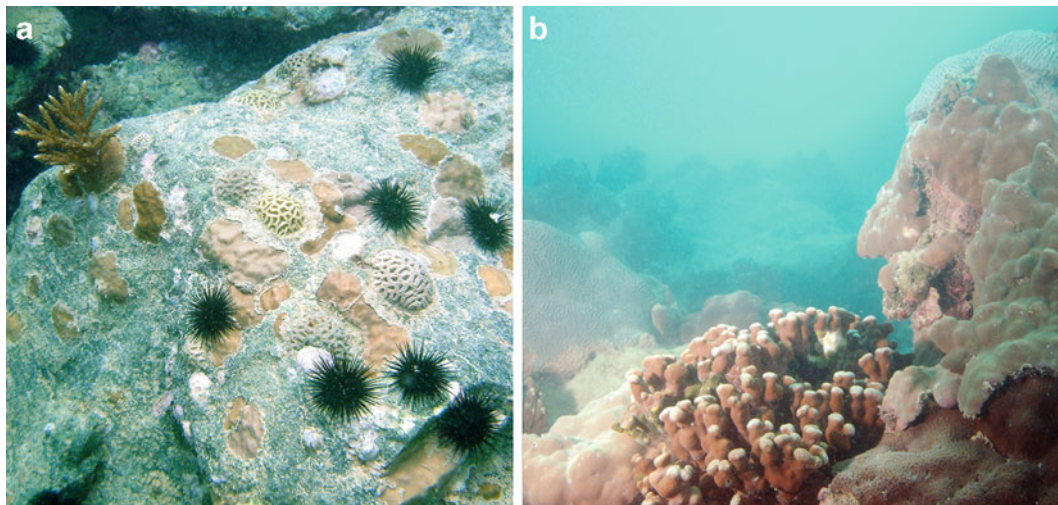


Fig. 10.10 Corals often colonize breakwaters in the Gulf within a year of construction. (a) A diverse assemblage has recruited to the Palm Jebel Ali 5 years after construction, and (b) coral communities

on the 25 year old Dubai dry dock breakwater have developed dense and complex three-dimensional structure (Images: K. Wilson, EMEG, and J. Burt)

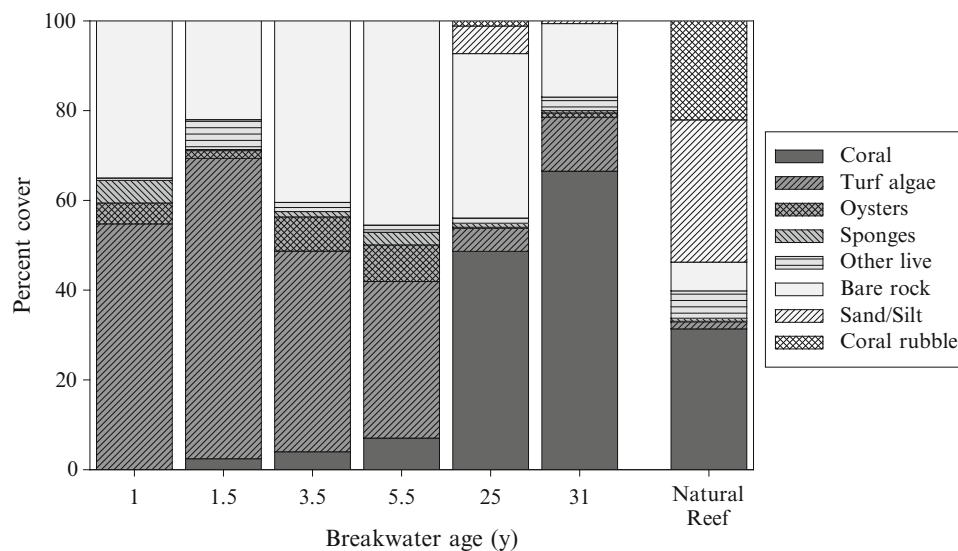


Fig. 10.11 A comparison of the relative abundance of all living and non-living community members on breakwaters of differing age and natural reefs. Breakwater names associated with these ages are listed in Fig. 3 (Adapted from Fig. 3 in Burt et al. (2011))

contained significantly more coral than was observed on natural reefs in Dubai.

Multivariate analyses of community structure indicated that there were significant changes in benthic assemblages between breakwaters of each successive age, with the exception of 3.5 and 5.5 year old breakwaters. In general, as breakwater age increased, communities became more similar to those on natural reefs. However, even the oldest 31 year old breakwater had a community that differed from those in the natural habitat. These findings are similar to observations made in temperate climates, where communities

on coastal defense structures generally differ from those on natural rocky reefs (Connell and Glasby 1999; Glasby 1999; Glasby and Connell 2001; Knott et al. 2004), with differences between natural and artificial reefs likely driven by a combination of variation in substratum material, microhabitat, and environmental conditions between habitats (Burt et al. 2009a, b). Such community differences may be important for increasing regional biodiversity. Breakwaters in the Gulf have been shown to contain fauna not observed on natural reefs (Burt et al. 2009b), indicating that coastal developments may enhance regional species richness as

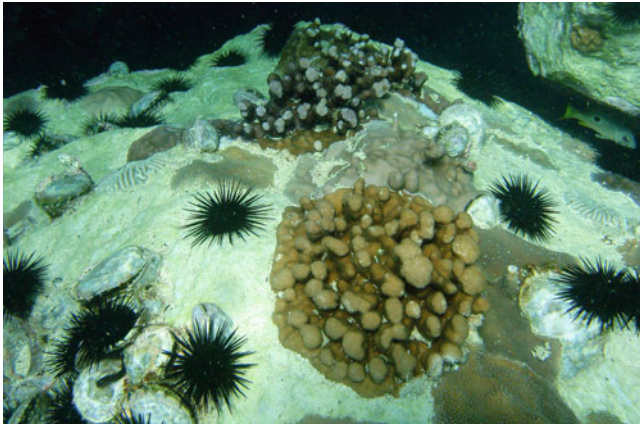


Fig. 10.12 Breakwaters with developing coral communities, such as this assemblage at Palm Jebel Ali, can be thought of as large-scale artificial reefs. However, such communities are not surrogates for those on natural reefs (Image: K. Wilson, EMEG)

long as they do not degrade natural reefs during their construction. This echoes findings in Kuwait, where lagoonal coastal developments contained benthic diversity far in excess of that prior to construction (Jones et al. 2007). In addition, because different breakwater communities are often at different stages of successional development due to differences in the timing of construction, age-related differences in communities may also enhance diversity in the area. Overall, these results suggest that the development of communities on breakwaters over time, and their differences from natural reefs, can have substantial implications for both marine ecology and management.

10.2.5 Can Breakwaters Replace Natural Reefs?

Breakwaters can be engineered in ways that enhance the development of reef-like communities through selection of appropriate materials and by modifying the profile to increase exposure to wave action. Also, benthic communities associated with these structures tend to converge towards those on natural reefs with increasing age. As such, it may be suggested that, with significant limitations, breakwaters can act as replacements for natural reefs that have been degraded during coastal development by acting as large-scale artificial reefs that provide substantial amount of hard-bottom habitat to Gulf coastlines (Fig. 10.12). Studies in other regions indicate that breakwaters often contain similar or higher abundance and/or diversity of fish, corals, and other fauna compared with nearby natural reef habitats (Bohnsack et al. 1994; Lincoln-Smith et al. 1994; Stephens et al. 1994; Pondella et al. 2002; Wen et al. 2007; Viyakarn et al. 2009), indicating the potential importance of these man-made habitats in mitigating impacts to natural habitats. However, the majority of studies comparing breakwater communities with

those of natural reefs were performed in temperate regions, and none had been performed in the Gulf. To examine whether breakwaters could act as surrogates for natural reefs in Dubai, Burt et al. (2009b) compared the coral and the fish communities associated with two mature breakwaters (>25 years old, Dubai dry dock and Jebel Ali port) with those of six natural reef sites (NR1-6); (See Fig. 10.3).

Older breakwaters in Dubai were shown to contain higher percent cover of corals than natural reefs in the area (Fig. 10.13a), indicating the importance of these structures in providing rocky hard-bottom habitat for coral growth. The higher coral cover on breakwaters likely resulted from the difference in environmental conditions between the two habitats, since breakwaters are elevated above the mobile sands, while corals on the relatively low lying natural reefs are exposed to frequent smothering by wave-driven sands (Riegl 1999). This smothering likely results in reduced growth rates and/or survivorship compared with those on breakwaters (Burt et al. 2009b). These results have substantial implications for the total amount of coral in Dubai in the coming decades. Over 65 km of rocky breakwaters have been constructed in Dubai in the past decade, providing >500 km² of sub-tidal artificial reef habitat for colonization by coral larvae in an area typically dominated by unsuitable sand habitat. Although most of these breakwaters currently have low coral cover due to their young age (Fig. 10.11 for examples) or because they are sheltered from wave action (Fig. 10.7), these results indicate that these structures are likely to become substantial coral reef habitat within the next 20 years. Conservatively assuming an average overall coral cover of 20% on breakwaters, by 2030 Dubai will contain an additional 100 km² of coral in excess of the approximately 10 km² of natural framework-building coral habitat in the area in the mid-1990s (Riegl 2002). However, these encouraging observations must be tempered with the observation that coastal development in Dubai (Burt et al. 2008, 2009b; Burt 2010b), and elsewhere in the Gulf (Price 1993; Khan 2007; Maghsoudlou et al. 2008; Sheppard et al. 2010), often results in the loss or long-term degradation of natural reef habitats, thus negating much of the potential benefits that breakwaters may provide. In addition, Burt et al. (2009b) demonstrated that breakwater coral communities were distinct from those on natural reefs. Breakwater coral assemblages were lower in diversity, having an average of a fifth fewer species compared with natural reef sites (Fig. 10.13b) and significantly lower Shannon-Wiener diversity (Burt et al. 2009b). In all, just three coral species made up over three-quarters of all coral coverage on breakwaters, while there was a more even distribution of coral cover among species on the natural reefs (Burt et al. 2009b). Further, multivariate analyses indicated that there was little similarity in coral community structure between breakwaters and natural reef habitats (Fig. 10.13c). On breakwaters, communities were characterized by higher

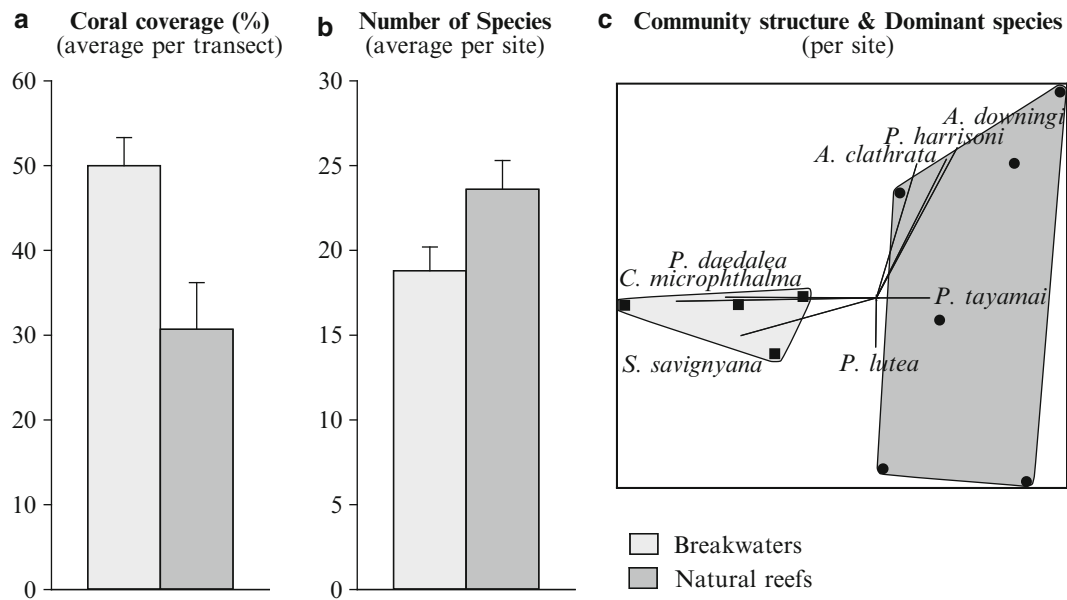


Fig. 10.13 Comparison of (a) coral abundance, (b) species richness, and (c) overall community structure between mature (>25 years old) breakwaters and natural reefs. Note: points in scatter-plot represent

overall coral community at one site; Overlain joint plots indicate the strength and direction of species driving these differences (Adapted from Table 1 and Fig. 2 in Burt et al. (2009b))

abundance of *Platygyra daedalea*, *Cyphastrea microphthalmalma*, and *Siderastrea savignyana*, while *Acropora downingi*, *A. clathrata* and *Porites harrisoni* were more common on natural reefs (Fig. 10.13c; Burt et al. 2009b). Overall, these results indicate that while mature breakwaters may develop extensive and dense coral assemblages compared with natural reefs, their diversity is low and their community structure is distinct from natural reefs.

Fish communities associated with mature breakwaters also differed from those on natural reefs. Burt et al. (2009b) showed higher seasonal variability in fish abundance and species richness on breakwaters compared with natural reefs (Fig. 10.14a, b), with peaks in both abundance and richness occurring in the warmer summer and fall seasons on breakwaters. In summer, fish abundance on breakwaters was three times that of natural reefs, and species richness significantly higher (Fig. 10.14a, b; Burt et al. 2009b). These seasonal changes were likely due to the migration of adult fish onto the breakwaters during the warmer periods, perhaps as a result of increased feeding resources (Burt et al. 2009b). Although the seasonally high densities of fish associated with breakwaters indicates that they are an important habitat, the dramatic seasonal changes in abundance suggest that communities associated with these structures may function differently than those on natural reefs. Differences in fish assemblages between breakwaters and natural habitats are also evident in multivariate fish community structures (Fig. 10.14c). While there was some overlap in community structure between habitats, mainly due to convergence in the winter/spring (Burt et al. 2009b), ordination indicated

substantial differences between breakwater and natural reef communities overall (Fig. 10.14c) and the habitats differed significantly (Burt et al. 2009b).

Overall, these results indicate that older breakwaters support substantial reef communities, with higher coral cover and summer fish abundance than natural reefs in Dubai (Fig. 10.15). By providing substantial hard-bottom habitat upon which communities develop, breakwaters in the Gulf have the potential to increase the total coral cover and fish production in the region. Further research in this area is warranted, particularly given the projected increase in coastal urban development in the Gulf (GRWv3 2005). However, the results of this research also highlight the importance of natural reefs. Breakwaters are not replacements for natural coral reefs, as each contains distinct coral and fish communities. Thus, the goal of coastal developers and marine management in the Gulf should be to construct man-made coastal structures in as ecologically a sensitive a way as possible, while aiming to design breakwaters in ways that enhance their similarities to natural reefs.

10.3 Conclusions

In recent years there has been a growing global awareness that man-made coastal developments represent important marine ecosystems that can be designed in ways that enhance species or communities of interest (Airoldi et al. 2005; Martin et al. 2005; Moschella et al. 2005; Bulleri and Chapman 2009). In the Gulf, the rapid development of

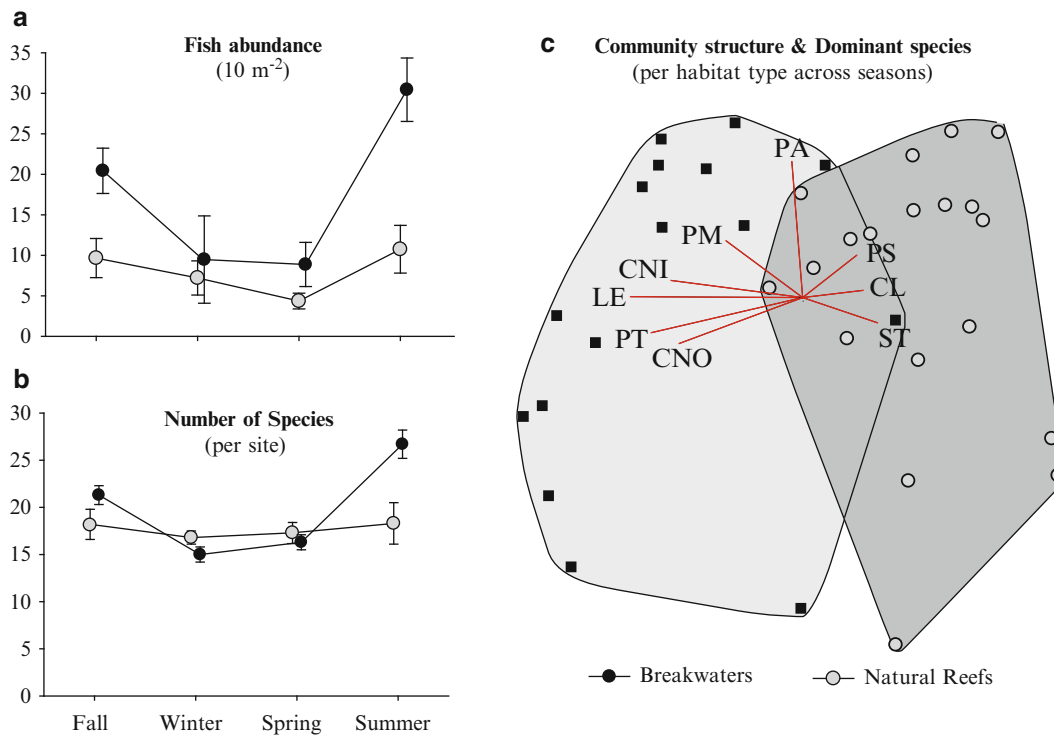


Fig. 10.14 Comparison of fish abundance, species richness, and community structure between mature (>25 years old) breakwaters and natural reefs from fall 2006 to summer 2007. Note: points in scatter-plot represent overall fish community at one site during one season; Overlain joint plots indicate the strength and direction of species driving these differences. Fish species driving differences

include *PM Pomacanthus maculosus*, *CNI Chaetodon nigropunctatus*, *LE Lutjanus ehrenbergii*, *PT Pomacentrus trichourus*, *CNO Cheilodipterus novemstriatus*, while natural reefs were dominated by *ST Scolopsis taeniatus*, *CL Cryptocentrus lutheri*, *PS Plectorhynchus sordidus* (Adapted from Figs. 3, 4 and 7 in Burt et al. (2009b))

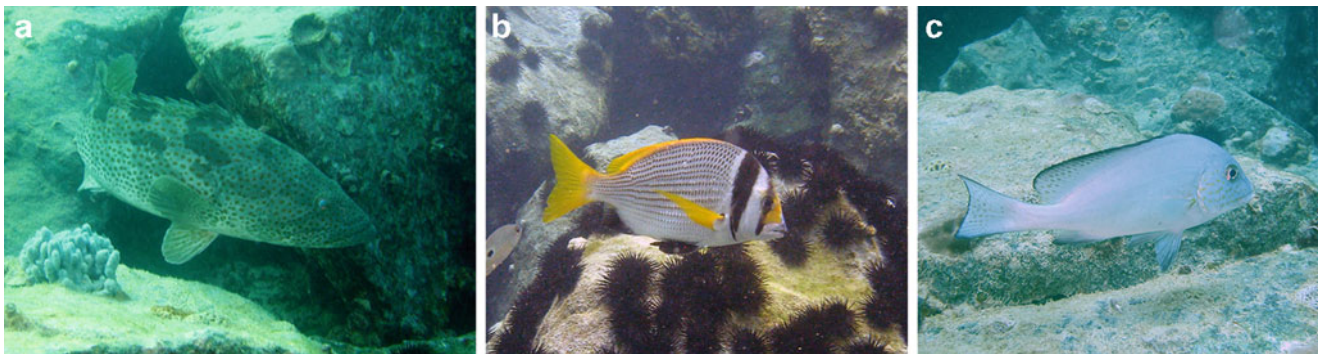


Fig. 10.15 Abundance of commercially important fish species such as (a) the orange-spotted grouper or 'hammour' in Arabic, *Epinephelus coioides*, (b) the twobar seabream, *Acanthopagrus bifasciatus*, and (c) the painted sweetlip, *Diagramma pictum*, change seasonally on break-

waters, increasing in abundance during the warmer summer and fall seasons as fish migrate onto breakwaters from surrounding habitats (Images: K. Wilson, EMEG)

coastal real-estate projects in the past decade has focused public and scientific attention on environmental impacts in Gulf waters (Khan 2007; Maghsoudlou et al. 2008; Sheppard et al. 2010), resulting in increasing interest in improving their ecological design. Multidisciplinary teams of scientists have been working with property developers in several Gulf

countries in the past several years to monitor and enhance the design of coastal developments (Al-Jamali et al. 2005; Jones et al. 2007; Sheppard et al. 2010; Sale et al. 2010). However, our scientific understanding of the ecological patterns and processes structuring communities in and around these developments remains in its infancy, and the use of data-based

science to drive marine management is sorely lacking (Sale et al. 2010). Further research on the ecological implications of coastal developments and its integration into decision-making is warranted.

The results of this chapter indicate that hard-bottom breakwater habitats represent an important and unique ecosystem in the Gulf. These structures occupy far more area than purpose-built artificial reefs, provide substantial amounts of complex three-dimensional habitat, are ubiquitous throughout the Gulf, and are likely to become increasingly common as coastal urban areas expand in the coming decades. Results here show that breakwaters are rapidly colonized and develop abundant and diverse communities that continue to change over periods in excess of 30 years. While these breakwater assemblages become more similar to natural reefs over time, they do remain distinct from them. This suggests that we should proceed with coastal development with extreme caution, developing man-made habitats only in areas where impacts to natural reefs and other diverse ecosystems like seagrass beds and mangroves are likely to be minimal.

While this chapter has outlined what is currently known about the ecology of breakwater habitats in the Gulf, there is much that is yet to be learned. The development of coastlines must go hand in hand with robust, multi-disciplinary monitoring programs if we hope to better understand and manage the ecological implications of coastal development in the Gulf.

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Bernhard M. Riegl, Francesca Benzoni,
Kaveh Samimi-Namin, and Charles Sheppard

11.1 Introduction

The harsh climate of the Gulf puts severe constraints on coral survival and, therewith, on biodiversity by restricting the number of coral species that can survive in these conditions. Despite this and despite being at the western high-latitude edge of Indo-Pacific reef coral distribution, the Gulf's coral fauna is surprisingly rich. Within the region, the richest Gulf coral fauna has been recorded from Saudi Arabia, around the islands of Jana and Karan (50 species, Basson et al. 1977). Fadlallah et al. (1993) subsequently recorded 23 and 19 species in specific sample sites on these two islands and suggested that species richness may actually be lower than suggested by Basson et al. (1977). This is also supported by data in Vogt (1996). The UAE presently has the second-richest documented coral fauna, with 34 scleractinian species (Riegl 1999). More comprehensive studies in other areas and the region would likely reveal a quite homogeneous fauna with a gentle diversity gradient across the Gulf proper. The

Iranian coral fauna is only sketchily known but likely rich. Due to counter clock wise pattern of the water circulation in the Gulf, the northern part and the Iranian coastline has better environmental conditions (lower temperature, lower salinity, better aragonite saturation, greater depth, see Chap. 2). This results in increasing species richness towards the Straits of Hormuz. In general, coral diversity decreases from east to west and from north to south. This has been seen in octocorals (Samimi-Namin and van Ofwegen 2009) and the same trend exists for hard corals (Samimi-Namin, unpublished data). It is still unclear where the main species boundaries are located and therefore further studies are necessary to fully reveal coral diversity in the Gulf.

Species richness in the Gulf is subject to temporal fluctuations caused by mass mortality events that affect preferentially certain species (Shinn 1976; George and John 1999; Riegl 1999; Chaps. 2 and 5). A study in Jebel Ali, Dubai, showed six species of *Acropora* having at least temporarily disappeared from the region's live fauna after the sea-surface temperature anomaly of 1996 but they later recruited into the area again (Riegl 1999). Subsequently, most of the area's fauna was lost to coastal reclamation. It is likely that the rampant alteration of coastal and shallow marine habitats will lead to further, potentially irreversible losses in coral diversity (Sheppard et al. 2010; Chap. 16).

Overall, much confusion exists with regards to the precise number of species occurring in the Gulf (Table 11.1). There is reason to believe that a detailed taxonomic reanalysis would reduce the number of reliably recorded species within the inner Gulf to around 40. The recent discovery of *Psammocora albopicta* (Benzoni 2006) also demonstrates the unsatisfactory status of our taxonomic understanding of Gulf corals. A markedly richer fauna exists in the Straits of Hormuz and apparently even on some of the Iranian islands within the Gulf proper. Depending on whether one counts islands like Hormuz and Larak as situated within the Gulf or not, the species richness of the fauna changes quite dramatically (see Table 11.1). In this chapter, we concentrate on the species widely distributed inside the Gulf proper.

B.M. Riegl (✉)
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA
e-mail: rieglb@nova.edu

F. Benzoni
University of Milano-Bicocca, Piazza della Scienza,
I-20126 Milano, Italy

Institut de Recherche pour le Développement (IRD),
101 Promenade Roger Laroque, BP A5, 98848 Noumea Cedex,
New Caledonia, France
e-mail: francesca.benzoni@unimib.it

K. Samimi-Namin
Netherlands Centre for Biodiversity Naturalis, 2300 RA Leiden,
The Netherlands
e-mail: Kaveh_s_n@yahoo.com

C. Sheppard
University of Warwick, Coventry, CV4 7AL, UK
e-mail: charles.sheppard@warwick.ac.uk

Table 11.1 List of hermatypic coral species names mentioned as occurring in the Gulf.

Species	Record in	Remarks
<i>Acropora clathrata</i> (Brook 1891)	1,2,3,4,5,6,7,9	According to Wallace (1999) this species does not occur in Gulf According to Veron (2000), records are partly <i>Acropora downingi</i> , but also <i>A. clathrata</i> . We provide evidence in the following that it does indeed occur
<i>Acropora pharaonis</i> (Edwards and Haime 1860)	1,5,6,8	
<i>Acropora horrida</i> (Dana 1846)	1,4,5,6	
<i>Acropora valenciennesi</i> (Edwards and Haime 1860)	1,5,6,8	
<i>Acropora arabensis</i> (Hodgson and Carpenter 1995)	2,3,4,5,6,8,9	
<i>Acropora florida</i> (Dana 1846)	5	
<i>Acropora valida</i> (Dana 1846)	3,5,6	
<i>Acropora nasuta</i> (Dana 1846)	6,8	
<i>Acropora tenuis</i> (Dana 1846)	5,6	Status doubtful, no records after 1996
<i>Acropora downingi</i> Wallace 1999	6,8,9	
<i>Acropora divaricata</i> (Dana 1846)	8	
<i>Acropora muricata</i> (Linnaeus 1758)	8	
<i>Montipora verrucosa</i> (Lamarck 1816)	6	
<i>Montipora venosa</i> (Ehrenberg 1834)	6	Record probably from Arabian Sea
<i>Montipora mollis</i> Bernard 1897	6	
<i>Montipora efflorescens</i> Bernard 1897	6	
<i>Montipora tuberculosa</i> (Lamarck 1816)	6	Record probably from Arabian Sea
<i>Montipora monasteriata</i> (Forskål 1775)	6	Record probably from Arabian Sea
<i>Montipora foliosa</i> (Pallas 1766)	6	Record probably from Arabian Sea
<i>Montipora stellata</i> Bernard 1897	6	Record probably from Arabian Sea
<i>Montipora aequituberculata</i> Bernard 1897	2,6,9	
<i>Montipora circumvallata</i> (Scheer and Pillai 1983)	1	
<i>Montipora informis</i>	9	
<i>Montipora spongiosa</i>	9	
<i>Astreopora expansa</i> Brueggemann 1877	6	Record probably from Arabian Sea
<i>Astreopora myriophthalma</i> (Lamarck 1816)	6	
<i>Stylocoeniella guentheri</i> Basset-Smith 1890	6	Record probably from Arabian Sea
<i>Madracis kirbyi</i> Veron and Pichon 1976	6,7,9	
<i>Pocillopora damicornis</i> (Linnaeus 1758)	1,2,6,9	
<i>Pocillopora verrucosa</i> (Ellis and Solander 1786)	2,6	
<i>Seriatopora caliendrum</i> Ehrenberg 1834	6	Record probably from Arabian Sea
<i>Stylophora pistillata</i> (Esper 1797)	1,2,3,4,5,6,9	
<i>Euphyllia glabrescens</i> (Chamisso and Eysenhardt 1821)	6	Record probably from Arabian Sea
<i>Physogyra lichtensteini</i> (Edwards and Haime 1851)	6	Record probably from Arabian Sea
<i>Galaxea fascicularis</i> (Linnaeus 1767)	6	
<i>Pseudosiderastrea tayamai</i> Yabe and Sugiyama 1935	1,5,6	This species likely does not occur in the Gulf (Benzoni, see below)
<i>Anomastrea irregularis</i> Marenzeller 1901	1,2,6,7,9	
<i>Siderastrea savignyana</i> Edwards and Haime 1850	1,2,3,5,6,7,9	
<i>Psammocora contigua</i> (Esper 1795)	1,2,3,4,5,6,7	
<i>Psammocora haimeana</i> Edwards and Haime 1851	1,6	
<i>Psammocora superficialis</i> Gardiner 1898	6,7	A recently described new species
<i>Psammocora stellata</i>	9	
<i>Psammocora albopicta</i> Benzoni 2006	9	
<i>Coscinaraea monile</i> (Forskål 1775)	1,2,5,6,7,9	
<i>Coscinaraea columna</i> (Dana 1846)	6,7	
<i>Pavona cactus</i> (Forskål 1775)	1,2,6	
<i>Pavona frondifera</i> (Lamarck 1816)	6	Record probably from Arabian Sea
<i>Pavona varians</i> (Verrill 1864)	1,2,6	
<i>Pavona explanulata</i> (Lamarck 1816)	1,2,6,7	

(continued)

Table 11.1 (continued)

Species	Record in	Remarks
<i>Pavona diffluens</i> (Lamarck 1816)	1,6	
<i>Pavona venosa</i> (Ehrenberg 1834)	6	Record probably from Arabian Sea
<i>Pavona decussata</i> (Dana 1846)	6,7,9	Record probably from Arabian Sea
<i>Pavona duerdeni</i> Vaughan 1907	6	
<i>Leptoseris solida</i> (Quelch 1886)	6	Record probably from Arabian Sea
<i>Leptoseris mycetoseroides</i> Wells 1954	6	Record probably from Arabian Sea
<i>Leptoseris foliosa</i> Dinesen 1980	6	Record probably from Arabian Sea
<i>Gardineroseris planulata</i> Dana 1846	6	Record probably from Arabian Sea
<i>Cycloseris curvata</i> (Hoeksema 1989)	6,9	Hoeksema 1989 designated <i>Cycloseris cyclolites</i> , previously recorded by Burchard, to this species
<i>Echinophyllia aspera</i> (Ellis and Solander 1788)	1,6,9	
<i>Oxypora lacera</i> (Verrill 1864)	6	Record probably from Arabian Sea
<i>Hydnophora exesa</i> (Pallas 1766)	1,6,7	
<i>Hydnophora pilosa</i>	9	
<i>Hydnophora microconos</i> (Lamarck 1816)	6	Record probably from Arabian Sea
<i>Turbinaria peltata</i> (Esper 1794)	1,2,3,4,5,6,7,9	
<i>Turbinaria reniformis</i> (Bernard 1896)	1,2,5,6,7,9	
<i>Turbinaria mesenterina</i> (Lamarck 1816)	1,6	
<i>Tubastrea aurea</i> (Quoy and Gaimard 1833)	1	
<i>Blastomussa merleti</i> (Wells 1961)	1,6	
<i>Acanthastrea echinata</i> (Dana 1846)	1,3,5,6,7,9	
<i>Acanthastrea hillae</i> Wells 1955	1,6	
<i>Acanthastrea maxima</i> Sheppard and Salm 1988	6,9	
<i>Symphyllia radians</i> Edwards and Haime 1849	6,9	Iran only
<i>Symphyllia agaricia</i> Edwards and Haime 1849	6	Record probably from Arabian Sea
<i>Favia pallida</i> (Dana 1846)	1,2,3,5,6,7,9	
<i>Favia speciosa</i> (Dana 1846)	6,7,9,10	
<i>Favia fava</i> (Forskål 1775)	1,2,4,5,6,9	
<i>Favia rotumana</i> (Gardiner 1898)	1,5,6	
<i>Barabattoia amicum</i> (Edwards and Haime 1850)	5	Status doubtful
<i>Favites pentagona</i> (Esper 1794)	1,2,3,4,5,6,7,9	
<i>Favites spinosa</i> Dana 1846	6	
<i>Favites chinensis</i> (Verrill 1866)	1,6	
<i>Favites abdita</i> (Ellis and Solander 1786)	6	
<i>Favites acuticollis</i>	9	
<i>Favites complanata</i> (Ehrenberg 1834)	1,6	
<i>Platygyra daedalea</i> (Ellis and Solander 1786)	1,2,3,4,5,6,7,9	
<i>Platygyra lamellina</i> (Ehrenberg 1834)	5,6	
<i>Platygyra sinensis</i> (Edwards and Haime 1849)	1,6	
<i>Platygyra cf. crosslandi</i> (Matthai 1928)	5	
<i>Leptoria phrygia</i> (Ellis and Solander 1786)	6	Record probably from Arabian Sea
<i>Plesiastrea versipora</i> (Lamarck 1816)	1,2,3,5,6,7,9	
<i>Cyphastrea microphthalma</i> (Lamarck 1816)	1,2,3,4,5,6,7,9	
<i>Cyphastrea serailia</i> (Forskål 1775)	1,2,3,5,6,7,9	
<i>Leptastrea purpurea</i> (Dana 1846)	1,6,9	
<i>Leptastrea transversa</i> Klunzinger 1879	1,2,3,5,6,7,9	
<i>Leptastrea inaequalis</i> Klunzinger 1879	6	Record probably from Arabian Sea
<i>Parasimplastrea sheppardi</i> Veron 2000	6	Record probably from Arabian Sea
<i>Echinopora gemmacea</i> Lamarck 1816	6	Record probably from Arabian Sea
<i>Echinopora lamellosa</i> (Esper 1795)	6	Record probably from Arabian Sea
<i>Porites lutea</i> Edwards and Haime 1851	1,2,3,4,5,6,7,9	
<i>Porites solida</i> (Forskål 1775)	5,6	
<i>Porites lobata</i> (Dana 1846)	5,6,9	

(continued)

Table 11.1 (continued)

Species	Record in	Remarks
<i>Porites compressa</i> Dana 1846	1,2,3,4,5,6,7,9	<i>Porites harrisoni</i> Veron 2000
<i>Porites nodifera</i> Klunzinger 1879	1,2,5,6	
<i>Porites cf. mayeri</i> Vaughan 1918	5,6	Status doubtful (Veron 2000)
<i>Porites lichen</i> Dana 1846	6,9	
<i>Goniopora lobata</i> Edwards and Haime 1860	2,6,7,9	
<i>Goniopora djiboutensis</i> Vaughan 1907	1,6	From the Straits of Hormuz
<i>Goniopora columna</i> Dana 1846	6,9	Iran only
<i>Goniopora somaliensis</i> Vaughan 1907	6	
<i>Goniopora tenuidens</i> (Quelch 1886)	6	Record probably from Arabian Sea
<i>Alveopora tizardi</i> Basset-Smith 1890	6	
Species encountered only on Iranian islands in the Straits of Hormuz		
<i>Goniastrea retiformis</i> (Lamarck 1816)	9	
<i>Goniopora planulata</i> (Ehrenberg 1834)	9	
<i>Echinopora irregularis</i> Veron, Turak and DeVantier 2000	9	
<i>Cyphastrea chalcidicum</i> (Forskål 1775)	9	
<i>Favia matthai</i> Vaughan 1918	6,9	
<i>Hydnophora pilosa</i> Veron 1985	6,9	
<i>Stylophora danae</i> Edwards and Haime 1850	6,9	
<i>Montipora informis</i> Bernard 1857	9	
<i>Montipora spongiosa</i> Ehrenberg 1834	9	

Published records: 1 = Sheppard and Sheppard (1991), 2 = Fadlallah et al. (1993), 3 = Hodgson and Carpenter (1995), 4 = Vogt (1996), 5 = Riegl (1999), 6 = Veron (2000), 7 = Carpenter et al. (1997), 8 = Wallace (1999), 9 = this compilation. Species listed prior to Sheppard and Sheppard (1991) are ignored in favor of their re-evaluation by these authors. Annotations regarding species distribution in (6) are courtesy of Veron (personal communication)

The taxonomic composition of Gulf corals is typically Indo-Pacific, with most species occurring in a wide geographic area. Two regionally-endemic (Gulf, Arabian Sea, parts of Red Sea) *Acropora* species are known (*Acropora arabensis*, Hodgson and Carpenter 1995, *Acropora downingi* Wallace 1999) and one regionally-endemic *Porites* (*P. harrisoni* Veron 2000). The closest faunistic proximity to other reefs of the Indo-Pacific is to the Red Sea (Sheppard and Sheppard 1991; Wallace 1999; Veron 2000) and Gulf of Aden (Pichon et al. 2010) due to a shared paleoceanographic history of restriction during the last sea-level low stand and simultaneous flooding during the Holocene transgression (Sheppard and Sheppard 1991; Uchupi et al. 1996). While the Red Sea has marked endemism (18 species), this is not the case in the Gulf (Sheppard and Sheppard 1991; Wallace 1999; Veron 2000).

In the following we give a taxonomic account of our interpretation of the names commonly used for the species occurring in the Gulf.

11.1.1 Note on the Ongoing Changes in Scleractinia Taxonomy

Molecular phylogenies of the Scleractinia and reconstruction of phylogenetic relationships between hard coral taxa have shown that traditional taxonomy and systematics based on skeleton morphology are, to a large extent, incompatible and

most of the currently recognised families and genera are polyphyletic (Fukami et al. 2008; Huang et al. 2011). Reconciling the results of molecular phylogenies with traditional taxonomy is an ongoing process, and the most promising tool to reach this objective seems to be a multidisciplinary approach including molecular, macrostructural, microstructural, reproductive and ecological data (Budd et al. 2010). This being said, in most cases the revisions will take years to be formalised.

In the context of this treatment of the hermatypic scleractinian coral fauna of the Gulf, the traditional morphology-based taxonomy is followed. Nevertheless, when molecularly driven taxonomic changes are impending this is noted in the genus description.

11.2 Taxonomic Account

Family Acroporidae Verrill 1902

Genus *Acropora* Oken 1815

Generic synonymy

Acropora Oken, 1815

Madrepora Ellis and Solander 1786

Heteropora Ehrenberg 1834

Acropora is the largest extant coral genus that is, or at least used to be until very recently, also ecologically dominant throughout the world's reef belts (but it has been removed

from many reefs by disease outbreaks and bleaching over the last few decades). These corals are easily identifiable in the field by their branching or tabular growth form, determined by the differentiation of corallites into an axial corallite, that determines a branch's growth direction, and radial corallites, sprouted off the axials, that determine a branch's thickness and overall appearance. In the Gulf, *Acropora* were among the dominant corals in the "better" environments, i.e. the upwind fringes of islands and exposed coastlines. Since 1996, however, many such environments have suffered severe dieback of their *Acropora* populations (Sheppard et al. 2010), so that *Acropora* has virtually disappeared as an ecologically important species from most of Bahrain, Qatar and western Abu Dhabi, but large stands remained in Kuwait (Benzoni et al. 2006) until 2010 and Iran and they are regenerating in some areas of Abu Dhabi. They have been almost entirely removed from Dubai and Sharjah due to coastal reclamation. Interpretations of *Acropora* taxonomy differ with regards to the most common species (*A. downingi* and *A. clathrata*), most importantly between Wallace (1999), followed partly by Claereboudt (2006), and Veron (2000). We follow Veron (2000) in keeping *A. downingi* and *A. clathrata* separate, which we justify by the consistency of different branching pattern throughout the Gulf (see account below). Our interpretation of *Acropora* taxonomy differs somewhat from that of Claereboudt (2006) in his study of Oman corals. Our interpretation of *A. downingi* and *A. clathrata* is based primarily on the clear presence of (sub)vertical branchlets in *A. downingi* (Wallace 1999) and their absence in *A. clathrata*, following Wallace (1999). The situation of Claereboudt's *A. khayranensis* (Claereboudt 2006) is unclear, since it shows affinities to both species. Moreover, since the holotype registration number is not provided and therefore there is no type designation for the species in its original description (Claereboudt 2006), this remains, from a taxonomic standpoint, a *nomen nudum* (literally "naked name") and, as such, not formally valid. No easy solution is available on morphological grounds only, and final clarification of the taxonomic status of Arabian *Acropora* will have to await molecular analysis.

***Acropora downingi* (Wallace 1999)**

Corallum: usually large tabular with a flat top, diameter up to 2 m and more. Branches mostly horizontal, from which many branchlets (length up to 50 mm) are given off in a sub-vertical, rarely vertical direction. Degree of development of sub-vertical branches can vary greatly, but spacing of branchlets is usually regular. Horizontal branches can at times fuse to form a plate. From this plate, branchlets protrude at between 60° and 90° angle.

Corallites: Clearly developed, exsert axials with outer diameter 1.5–2.5 mm, inner diameter up to 1 mm. Primary septa well developed (up to 2/3R), secondary septa not always

developed, but when present up to 1/4R. Radials have a variety of shapes and sizes and are mostly tubular, often appressed (but not always), and can vary widely from dimidiate to oblique openings. Primary septa always present, secondary septa vary from completely absent to complete to 1/4R.

Columella: not developed.

Coenosteum: On radials costate or rows of laterally compressed spines. Between radials reticulate or spinulose.

Color: reddish brown

Distribution: Common throughout the entire Gulf. Co-occurs with all other *Acropora* species. Can be told from *A. clathrata* by the often profuse development of vertical branchlets. Both vertical and horizontal branches (branchlets) tend to be thinner in diameter than neighboring *A. clathrata*, giving them a more fragile appearance (Fig. 11.1).

***Acropora clathrata* (Brook 1891)**

Corallum: very similar to *Acropora downingi*. Usually large tabular with a flat top, diameter up to 2 m and more. Branches mostly horizontal, from which few branchlets (length up to 50 mm) are given off, never clearly sub-vertical or vertical, but usually markedly prostrate and at a small angle to the main branch. Sometimes almost no branchlets are produced, on other colonies many. Horizontal branches can at times fuse to form a plate. From this plate few branchlets barely protrude. Sometimes branchlets reduced to only an axial with a rosette of attendant radials.

Corallites: Clearly developed, axials moderately to usually markedly exsert, conical and tapering from the base (outer diameter 2.5–3 mm, at base, 1.9–2.1 mm at top), inner diameter up to 1 mm. Primary septa well developed (up to 2/3R) and dentate, secondary septa not always developed, but when present up to 1/4R. Radials have a variety of shapes and sizes and are mostly tubular, often appressed (but not always), and can vary widely from dimidiate to oblique openings. Usually more widely spaced than in *A. downingi*. On horizontal branches, often no exsert radials at all are formed and most or all are immersed. Primary septa always present, secondary septa vary from completely absent to complete to 1/4R.

Columella: not developed.

Coenosteum: On radials rows of laterally flattened spines. Between radials reticulate or spinulose.

Color: reddish brown

Distribution: Common throughout the entire Gulf. Co-occurs with all other *Acropora* species (Fig. 11.2).

***Acropora pharaonis* (Milne Edwards and Haime 1860)**

Corallum: arborescent to tabular; in the Gulf, mostly tabular, forming more open, and more fragile tables than *A. downingi* and *A. clathrata*. Tables can reach large size, but are usually up to 1 m diameter. Branches mostly sub-horizontal, forming vase-shaped coralla with deeper centres than the other two tabular species. Branches usually show less fusion than in the other tabular species. Towards the

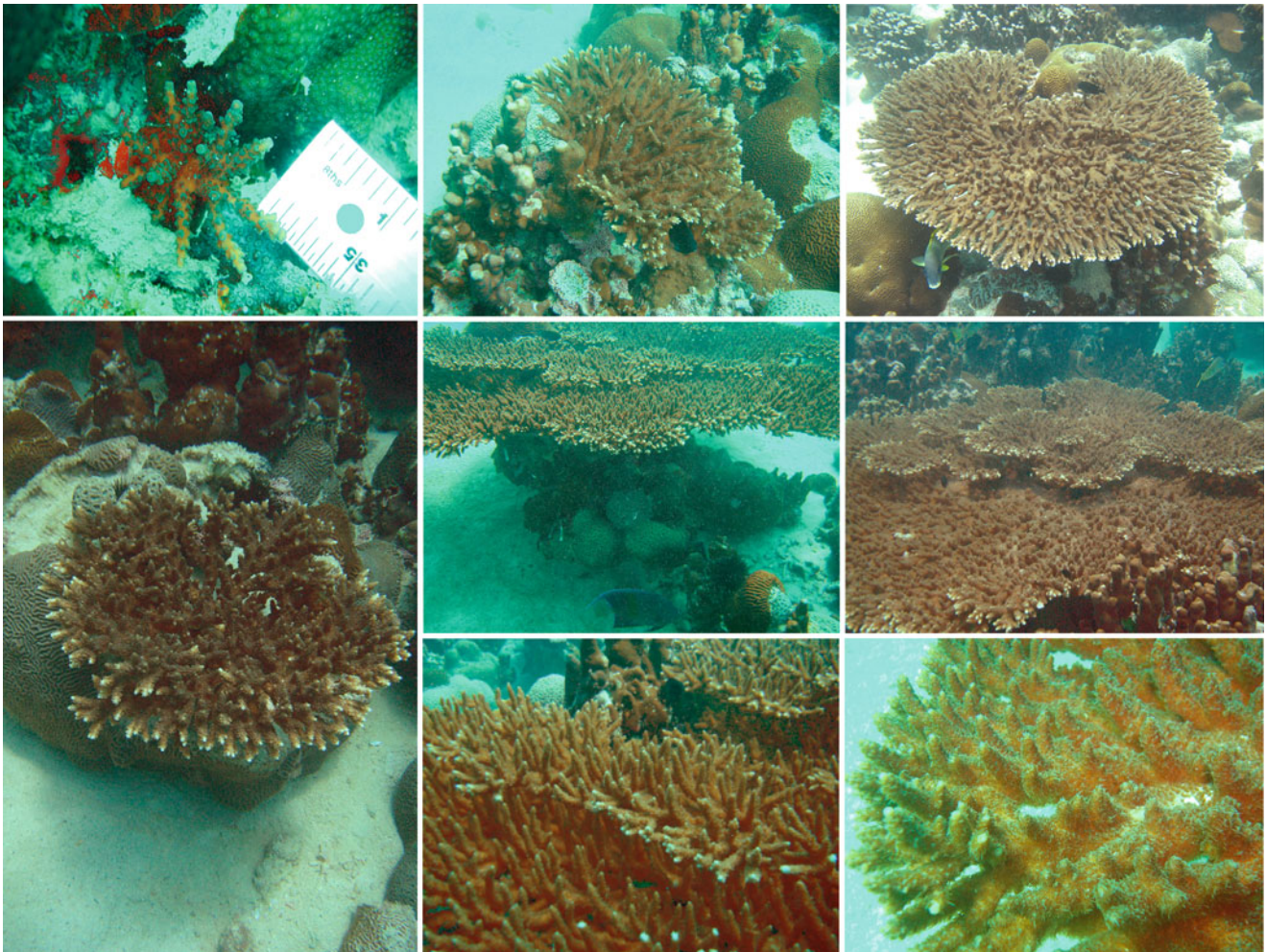


Fig. 11.1 *Acropora downingi* from Abu Dhabi (All photos from the region between Saadiyat and Ras Ghantoot)

apices of main branches often a profusion of secondary branchlets. From main branches numerous branchlets of various size arise, often only incipient axials with a rosette of attendant radials. This gives the branch a bottlebrush appearance, which is never observed in the other tabular species. Fusion of horizontal branches to plate never observed.

Corallites: Clearly developed, axials usually markedly exsert, tubular to conical and tapering from the base (outer diameter 1.5–2.5 mm, at base, 1.9–2.1 mm at top), inner diameter ~1 mm. Primary septa developed (up to 1/4R) and dentate, secondary septa usually absent. Radials have a variety of shapes and sizes that depends on the development of the branch(let); mostly tubular, often appressed (but not always), and can vary widely from dimidiate to oblique or rounded openings. Sometimes arranged in spirals. On horizontal branches, many incipient axials and short branchlets are formed, sometimes even on the undersides. Primary septa usually poorly developed, secondary septa usually absent.

Columella: not developed.

Coenosteum: On radials often clearly costate. Between radials reticulate or spinulose.

Color: reddish brown

Distribution: Uncommon throughout the entire Gulf. Co-occurs with all other *Acropora* species, but is less frequent (Figs. 11.3 and 11.4).

Acropora arabensis Hodgson and Carpenter 1995

Corallum: digitate to caespitose, in some colonies even low arborescent. Branches long and markedly terete. Orientation of branches is often fairly irregular, which can give the colonies a somewhat untidy appearance. Branches have only few divisions into sub-branches and rarely form several branchlets. Branch diameter 10–15 mm, length up to 250 mm. The growth form makes confusion with the previous three species unlikely.

Corallites: Axials usually markedly exsert, conical, outer diameter 2–2.7 mm, inner diameter ~1 mm. Primary septa developed (up to 1/4R), secondary septa usually present and up to 1/3 R. Radials appressed tubular, with oblique or rounded openings near branch tips, nariform to dimidiate at branch bases. Primary septa up to ¼ R, secondary septa usually absent.

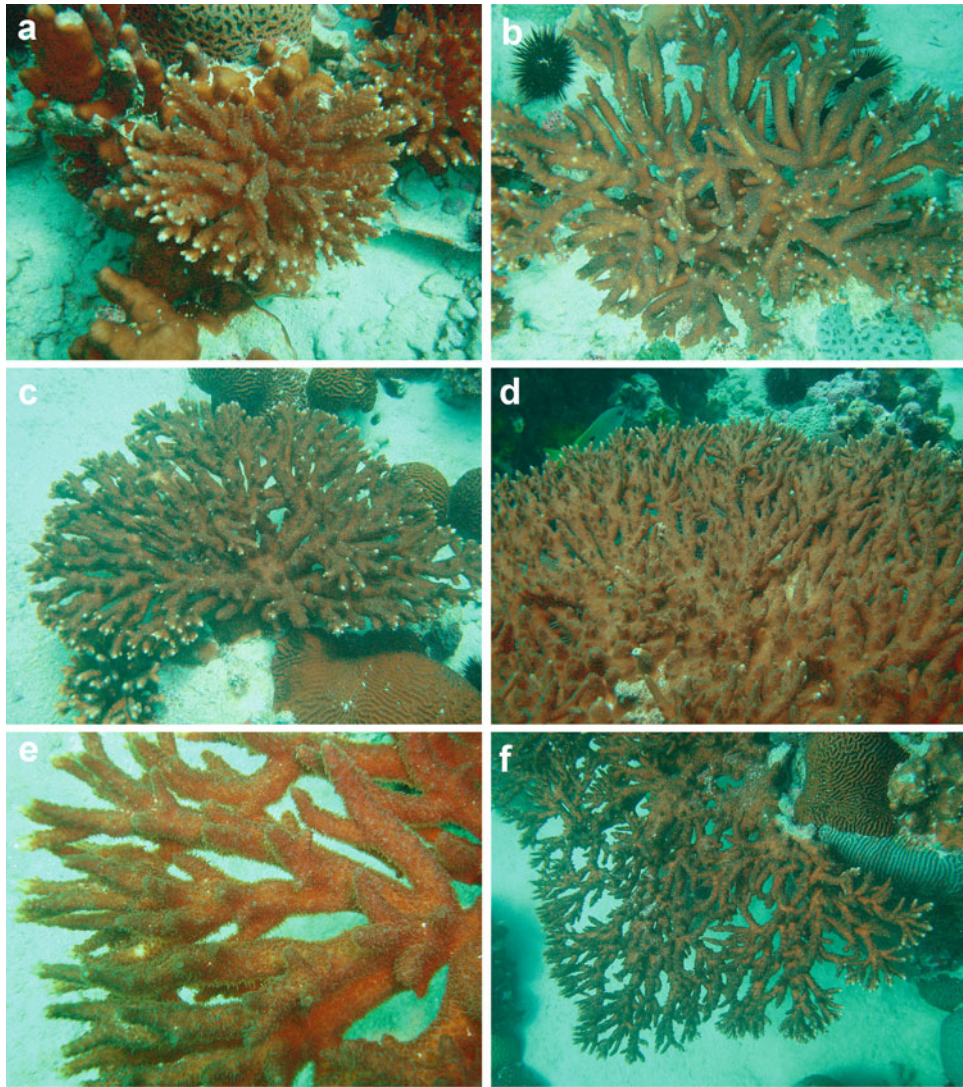


Fig. 11.2 *Acropora clathrata* from Abu Dhabi (a-f). All specimens photographed in the region between Saadiyat and Ras Ghanada

Columella: not developed.

Coenosteum: On radials reticulate with simple spines, sometimes arranged in lines. Between radials reticulate or spinulose.

Color: reddish brown

Distribution: Uncommon to moderately common throughout the entire Gulf from Kuwait to UAE, and Iran. Co-occurs with all other *Acropora* species (Fig. 11.5).

It is likely that more species of *Acropora* than treated above actually occur in the Gulf. Several potentially new records require collection and formal identification. It is possible that prior to the 1996/1998 coral mass mortality event (Chap. 5), *A. valida* and maybe even *A. nasuta* occurred in the SE Gulf, since Riegl (1999 and personal communication, specimens housed in the Department of Earth Sciences, Karl-Franzens University Graz, Austria) collected material that shows characters of these two species. However, the material is from a limited geographic

range (Jebel Ali, Dubai, UAE) and from only a single specimen each. It is possible, even likely, that these fell actually within the natural variability of *A. arabensis*. However, it is no longer possible to verify this, since almost all *Acropora* died in the study region, the Jebel Ali reefs were all but destroyed by the Palm Island developments, and no similar specimens were ever found in nearby Abu Dhabi. Recent material photographed at Abu Musa falls within the variability of *A. valida* and potentially *A. gemmifera* (Fig. 11.6). *A. horrida* is close to *A. pharaonis* and has been reported from several regions, but could not be verified for this study. The reports of *A. valenciennesi* could have been aberrant *A. downingi*, or the species has disappeared since. The name is, however, used by Bauman et al. (2011) and by the same authors in Chap. 9, but the accuracy is unclear. The same goes for reports of *A. tenuis*. Neither could be confirmed for the present study. Also

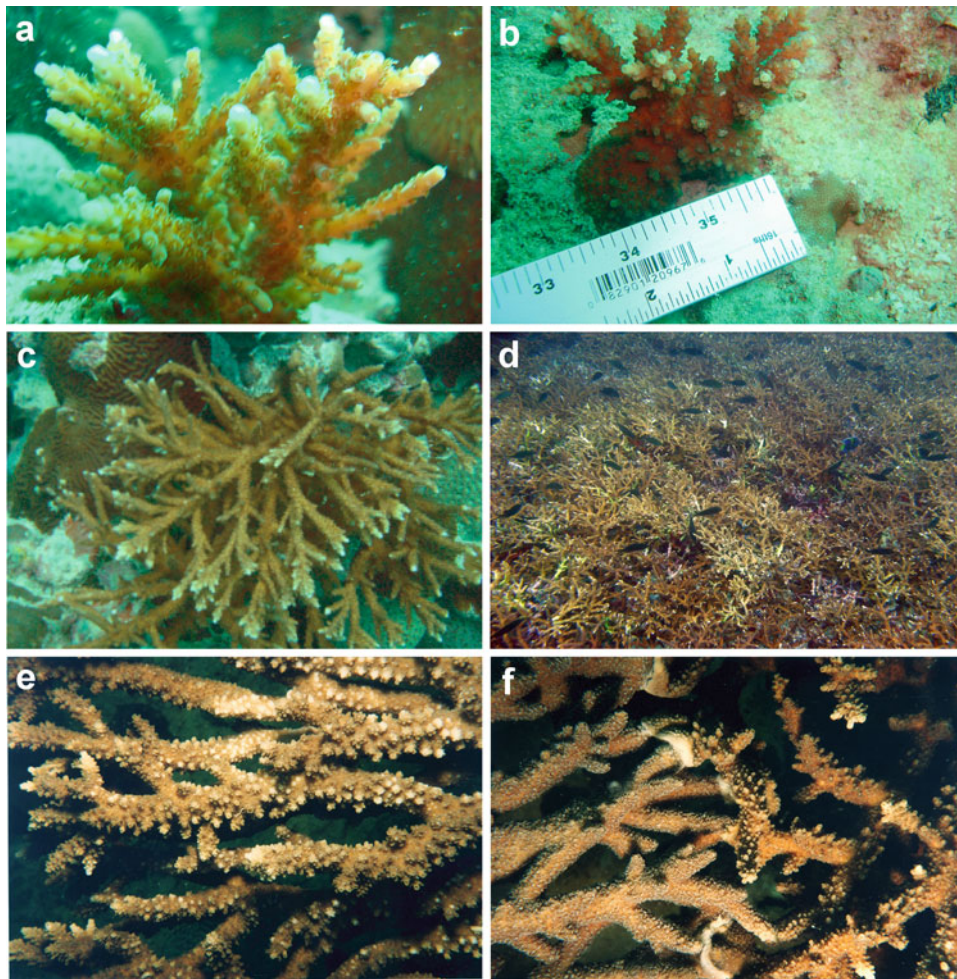


Fig. 11.3 *Acropora pharaonis* in the UAE. (a, b, c) From Abu Dhabi, between Saadiyat and Ras Ghanada. (d) dense thickets of open arborescent growth form at Abu Musa, Iran. No specimens are in hand, thus

identification is uncertain. (e) An extreme, almost *A. florida*-like morph from Jebel Ali (Dubai). (f) *A. downingi* to the left, *A. pharaonis* to the right. Jebel Ali, Dubai

reports for *A. muricata* and *A. divaricata* require verifications.

Genus *Montipora* de Blainville 1830

Generic synonymy

Montipora de Blainville 1830

Manopora Dana, 1846

The Indo-Pacific genus *Montipora* is characterised by a wide array of corallum morphologies from thinly encrusting to knobby, submassive, foliose and branching, at times with different growth forms occurring in the same colony. Unlike in the closely related *Acropora* in this genus there is no distinction between axial and radial corallites. Polyps in *Montipora* are very small, 1 mm in diameter, and although they are mostly expanded during the day, they are hardly visible in the field. The coenosteum is typically reticular and covered in spinules that can form tubercles or verrucae.

Corallites are small, and first order septa are reduced to spines projecting horizontally in the calice. The small corallite and coenosteum features, the high morphologic variability of the corallum, and the large number of described species have contributed to a complex genus taxonomy which has not been revised since Bernard (1897). In the Gulf, records of *Montipora* seem to have decreased in the last two decades. The genus, once abundant around Qatar (Emara et al. 1985), is no longer found there (SCENR 2007; Sheppard et al. 2010). It has not been reported from the UAE. The species presented was recorded in Kuwait in 2004 where two colonies were observed. It appears to be rare otherwise. Material collected was examined and the corallite and coenosteum ornamentation morphology matched with that of the holotype of *Montipora aequituberculata* (NHM 1892.12.1.19) deposited at the NHM. In Iran, *Montipora* can be found around the islands closer to the Straits of Hormuz, where they can form monospecific stands. The eastern side

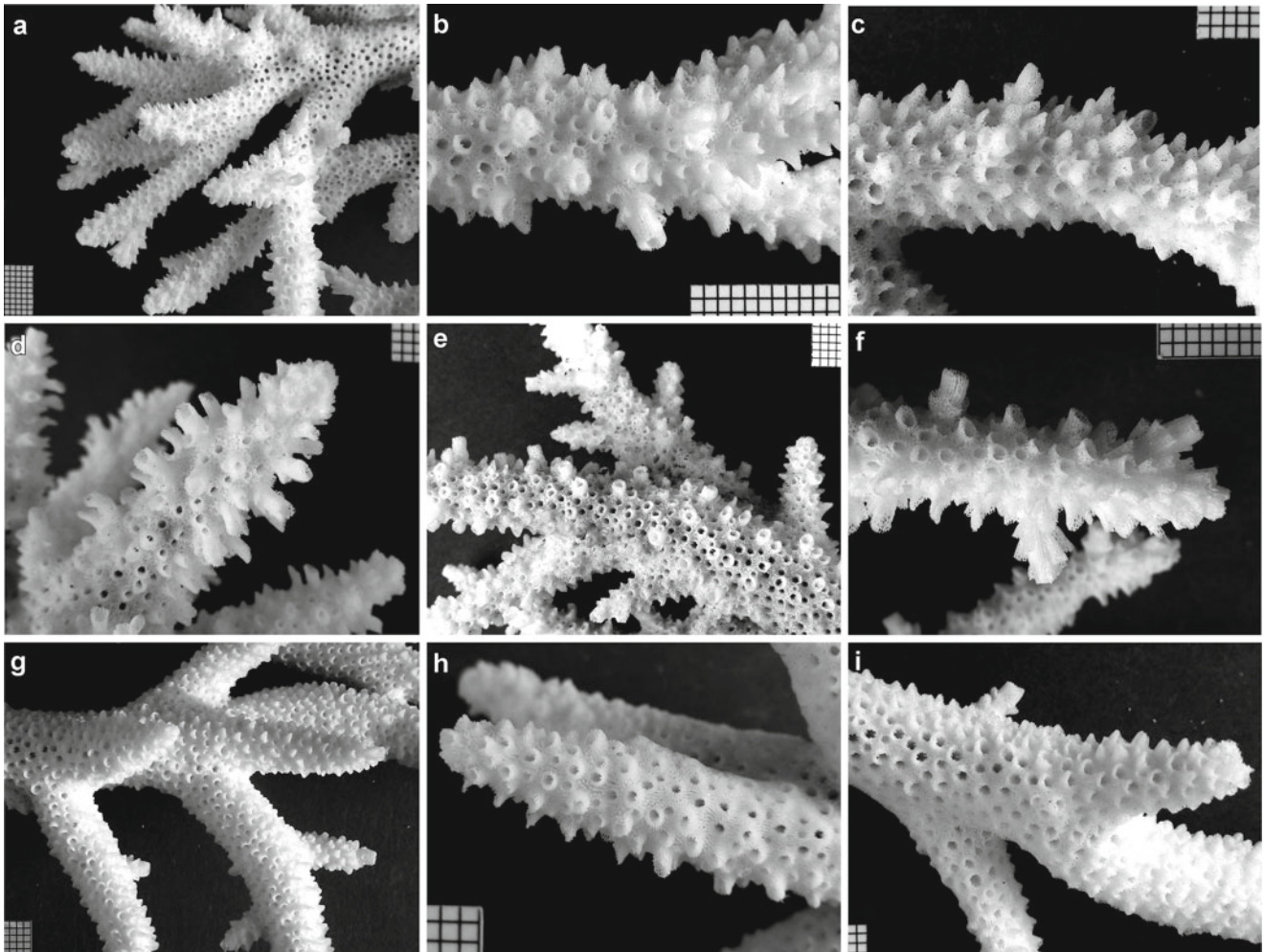


Fig. 11.4 Close-ups of Gulf *Acropora*: (a, b, c) *A. downingi*, (d, e, f) *A. pharaonis*, (g, h, i) *A. clathrata*. Scale bar in mm

of Hengam Island is dominated by at least three species of *Montipora*, close to the shoreline (2–3 m depth) and subaerially exposed during low tides.

***Montipora aequituberculata* Bernard 1897**

Corallum: encrusting to foliose, in larger colonies tiers of whorls can form (Fig. 11.5a). Colony size up to 1 m in diameter.

Corallites: small, 0.6 mm diameter and separated by reticulate coenosteum covered in elongated thecal papillae. Septa reduced to spines, the six primary more developed than the secondary. Directive septa are visible in most corallites.

Columella: absent.

Coenosteum: well developed and covered in elongate reticulum papillae giving corallum surface a hirsute appearance.

Color: reddish brown to dark pink, corallum margins are often paler or whitish

Distribution: rare. This appears to be the first circumstantial record for Kuwait as the species was not listed with the other

reef corals of the area (Carpenter et al. 1997). Also occurs in Iran (Fig. 11.7).

***Montipora informis* Bernard 1897**

Corallum: encrusting or foliose to massive, often overgrowing other organisms.

Corallites: small, 0.4–0.6 mm diameter and uniformly distributed. Well-developed septal spines in two cycles, the smaller cycle usually incomplete or can be completely absent. Directive septa sometimes distinguishable.

Columella: absent.

Coenosteum: well developed and covered in papillae of uniform size giving corallum surface a smoother appearance than in other species. No thecal papillae.

Color: reddish brown, polyps whitish.

Distribution: So far only recorded from Iran.

***Montipora spongiosa* (Ehrenberg 1834)**

Corallum: clumps of short branches.

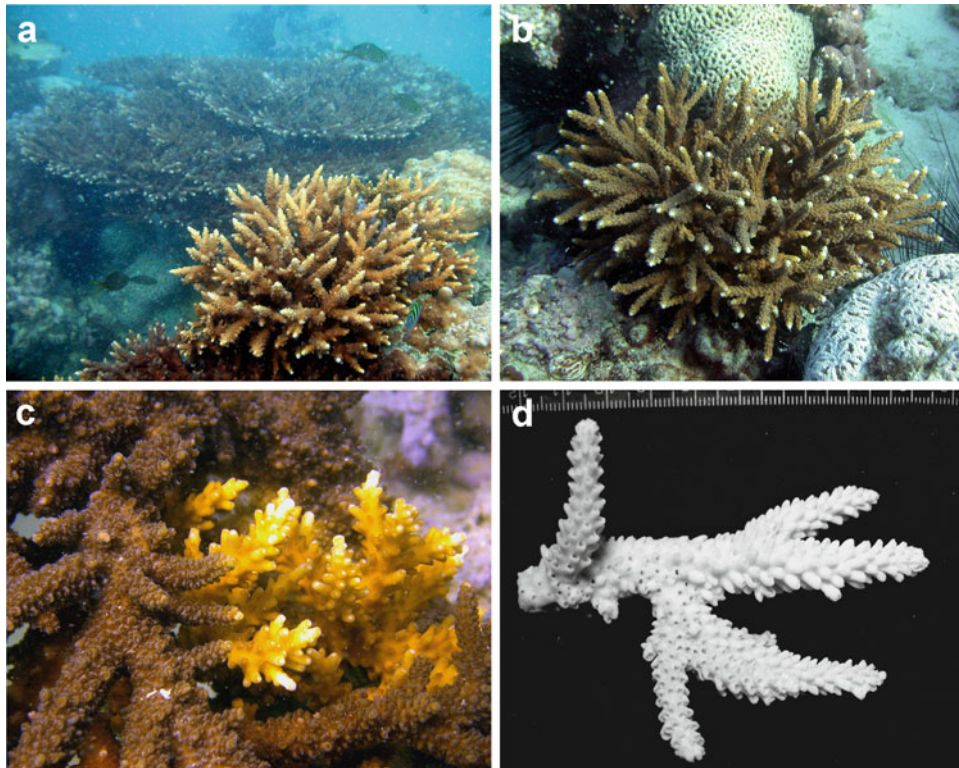


Fig. 11.5 *Acropora arabensis* from Kuwait. (a, b) Note the bushy (typically corymbose) growth form in contrast to the tabular growth form of the other species, (c) colony with Arabian yellow band disease, (d) skeleton (M. Pichon coll.)

Corallites: small, 0.4–0.6 mm diameter. Deep, with well-developed lower lip.

Columella: absent.

Coenosteum: well developed and covered in strongly ornamented papillae.

Color: reddish brown, polyps whitish.

Distribution: So far only recorded from Iran.

Family Pocilloporidae Gray 1842

Genus *Stylophora* Schweigger 1819

Generic synonymy

Madrepora (pars) Pallas (1766)

Porites (pars) Lamarck (1816)

Stylophora Schweigger 1819

Sideropora de Blainville (1830)

Anthropora Gray (1835)

Enallastrea d'Orbigny (1849)

Phyllopora Tenison-Woods (1879)

This is one of the most common coral genera in the Indian Ocean, however, in most Gulf localities, *Stylophora* are among the rarer corals. The center of diversity seems to be the Red Sea/western Indian Ocean region, where important local endemism is recorded (Sheppard and Sheppard 1991; Veron 2000). In gross morphology, Gulf *Stylophora* deviate

markedly from their Indian Ocean conspecifics, however, the calicular characteristics are insufficiently distinct to warrant an easy separation into a species of its own. Clearly, molecular analysis is needed. The columella is clearly visible as a styliform boss in the center of the calyx and septa are usually visible at least as rudiments attached to the walls. This differentiates *Stylophora* from *Pocillopora*, which has a much wider columella nor equally well-developed septa. There is much variability in *Stylophora* in Iran and further collections are likely to reveal the presence of more than one species.

Stylophora pistillata (Esper 1794)

Corallum: digitate to caespitose, colonies are relatively small (mostly <20 cm) and bushy. Branches are mostly sub-vertical, mostly slender, taper markedly, and are adorned with irregular side-branches that gives them a “knobbly” appearance. Branches are 10–15 mm in diameter and much thicker at the bases than the tips. When branchlets are formed, the main branches often markedly reduced in diameter. In many basal areas of the branches, branchlets are only sparsely developed. Gulf specimens have a different appearance from Indian-Ocean specimens.

Corallites: Characteristically hooded, which refers to the upper section of the wall developed more strongly than the

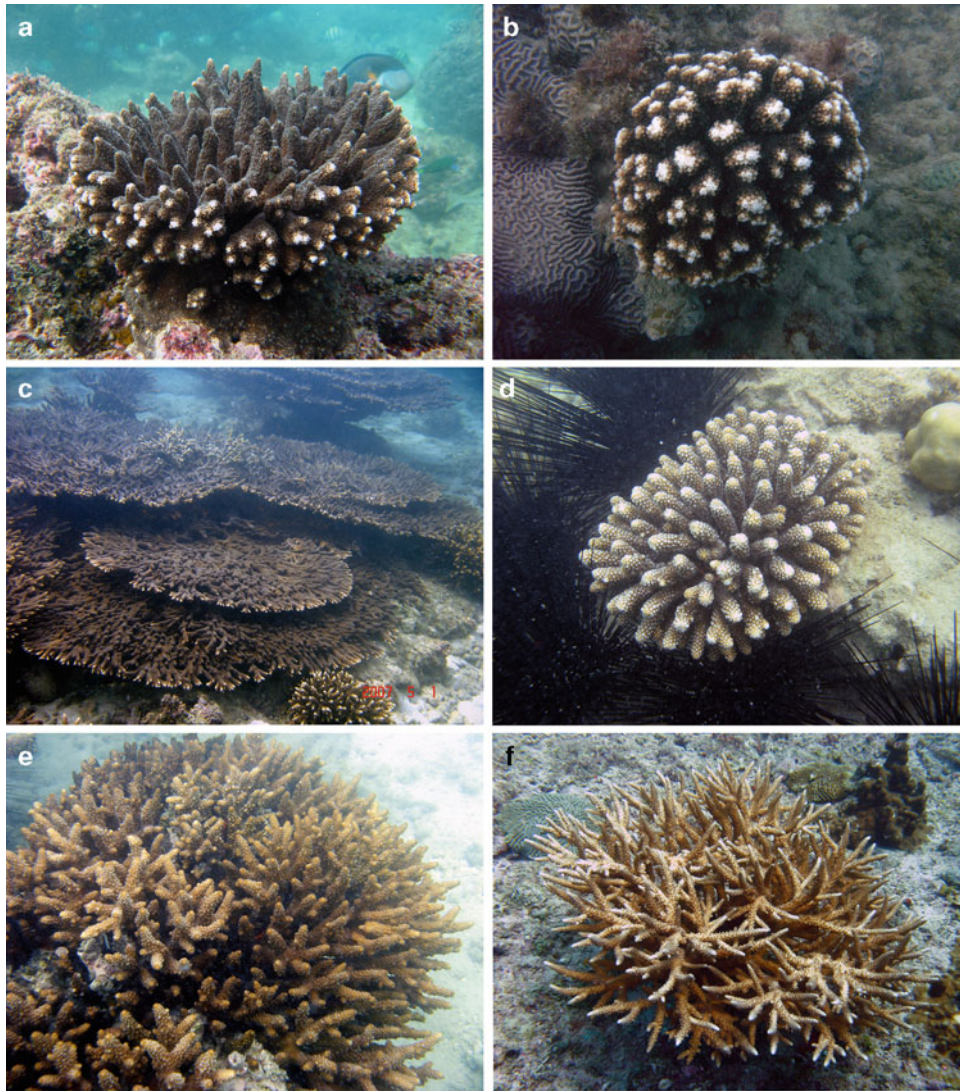


Fig. 11.6 (a) *Acropora downingi* from Larak Island, Iran; (b) *Acropora* species from Hengam Island; (c) *Acropora clathrata* from Kish Island, Iran; (d) *Acropora cf. gemmifera* from Hengam Island, Iran; (e)

Acropora cf. valida from Abu Musa Island; (f) *Acropora cf. pharaonis* from Abu Musa Island, Iran

lower section, thus giving a “visor-like” appearance. In most Gulf specimens, however, this is not very obvious, rather the entire corallite wall is raised. Corallites are plocoid, not crowded, and up to 1 mm. A single cycle of six smooth septa is very clearly developed

Columella: a solid, very visible rod in the corallite’s center. This “stylus” gives the genus its name.

Coenosteum: Smooth with a dense arrangement of spines.

Color: reddish brown

Distribution: Uncommon throughout the entire Gulf.

Stylophora danae Edwards and Haime 1850 is reported from Iranian islands in the Straits of Hormuz but no collected material was available for review (Figs. 11.8 and 11.9).

Genus *Pocillopora* Lamarck 1816

Generic synonymy

Pocillopora Lamarck, 1816.

This is a common coral genus in the Arabian Sea and on Iranian islands in the Straits of Hormuz, but it is rare inside the Gulf. Sheppard and Sheppard (1991) report it from the Saudi offshore islands. No voucher specimens exist, therefore some doubt to its presence remains. *Pocillopora* are among the most wide-spread corals on earth, occurring throughout the entire Indo-Pacific. The corallites characteristically lack clearly-developed septa and the columella is very wide, occupying most of the corallite, thecae and coenosteum are usually solid and have small, regular spines.

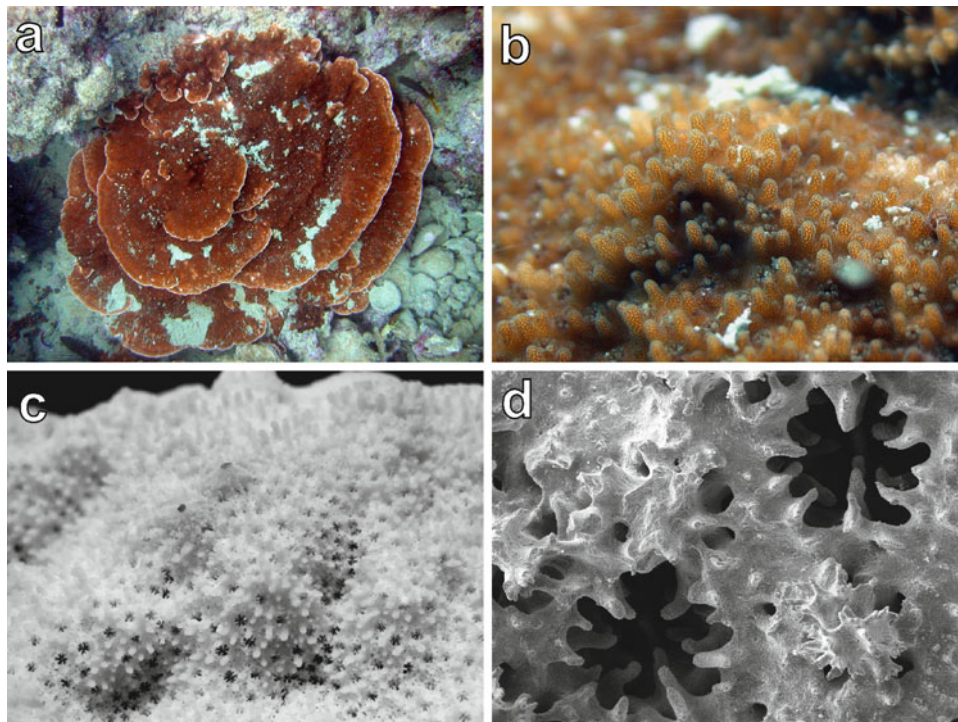


Fig. 11.7 (a) *Montipora aequituberculata* at Mudayra reef Kuwait, (b) a close up of a colony on Qaro reef Kuwait, (c) a close up of a specimen of the same colony showing the typical verrucae, and (d) SEM image of the corallites and coenosteum ornamentation

Pocillopora damicornis (Linnaeus 1758)

Corallum: Untidy clumps with spiky appearance due to numerous small branches formed by enlarged verrucae. Branches arise from an encrusting to submassive base.

Branches: Branchlets clearly originate from enlarged verrucae and can subdivide repeatedly. However, in Gulf specimens, they are thicker than in specimens from the Arabian Sea. No long, thin verrucae exist on Gulf specimens. Rounded in their basal parts, they become irregular in shape due to the sprouting of branchlets.

Verrucae: Typically the longest and most “independent” of all *Pocillopora* species, but this is not well developed in Gulf specimens. Towards the bases of the branches verrucae tend to be attendant to the main branches, but sprout into branchlets once main branches have flared enough to offer space. Branchlets form throughout the upper portions of the branches.

Calices: Diameter up to 1 mm, towards the branch tips sometimes larger, up to 1.5 mm. Irregularly arranged over colony. Inter-calice distance usually <1 calice diameter. Towards the tips of the branches more crowded, leading to the development of polygonal calices. Calices occur all around, and directly on branch and branchlet tips.

Septa: Poorly developed or absent in most corallites. Sometimes rudiments of up to two cycles of 1/10 calice radius.

Columella: present, mostly very developed and occupying most of the fossa.

Distribution: not recorded from Kuwait, Bahrain and western Iran. In Saudi Arabia only recorded on offshore islands (Sheppard and Sheppard 1991). Possibly restricted to eastern Gulf and the islands (Fig. 11.10).

Genus *Madracis* Milne Edwards and Haime 1849

Generic synonymy

Madracis Milne Edwards and Haime, 1849.

Axhelia Milne Edwards and Haime, 1849

Axohelia Milne Edwards and Haime, 1857

Reussia Michelotti, 1860

Pentalophora Saville-Kent, 1871

***Madracis kirbyi* Veron and Pichon 1976**

Corallum: encrusting, sometimes nodular to sub-ramose.

Corallites: Cerioid, angular, ~1.5–2 mm diameter, walls thick and well-defined with a single row of flattened spines along the crest

Septa: usually ten septa in well-developed first cycle, fused to the solid, rod-like columella, one well-defined septal tooth from which the septum descends steeply towards the centre. No other dentations. Sometimes a second cycle is developed.

Columella: clearly defined, a vertical rod.

Distribution: This species is recorded by Carpenter et al. (1997) from Kuwait and is rare elsewhere. It has not been reliably recorded from the SE and N Gulf (Fig. 11.11).

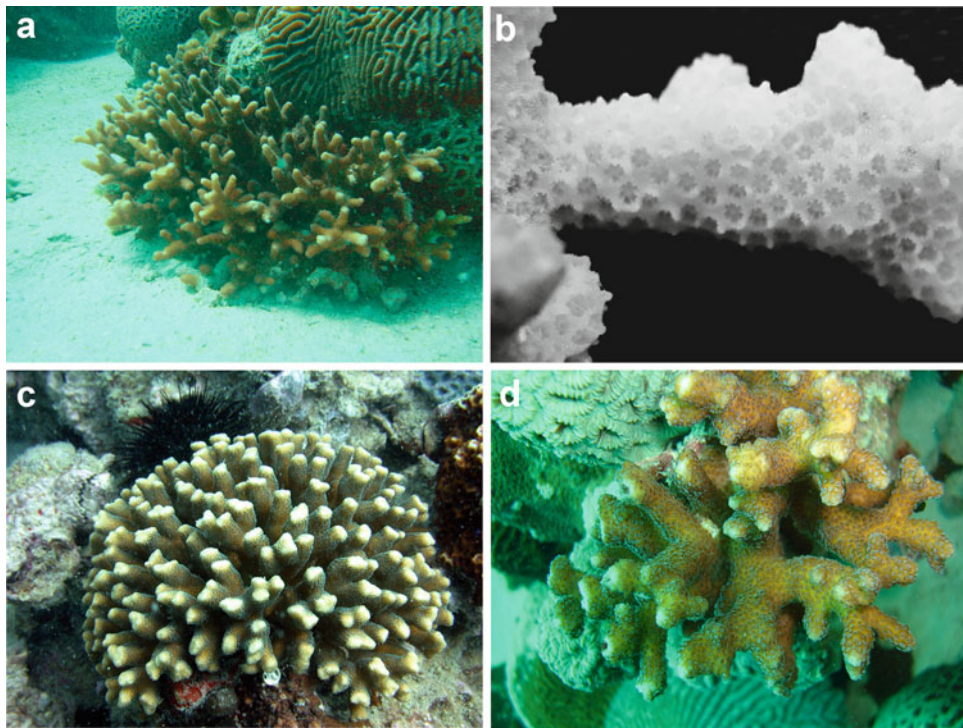


Fig. 11.8 (a, b, d) *Stylophora pistillata* from Ras Ghanada, Abu Dhabi; (c) From Umm al Maradem, Kuwait (M. Pichon coll.)

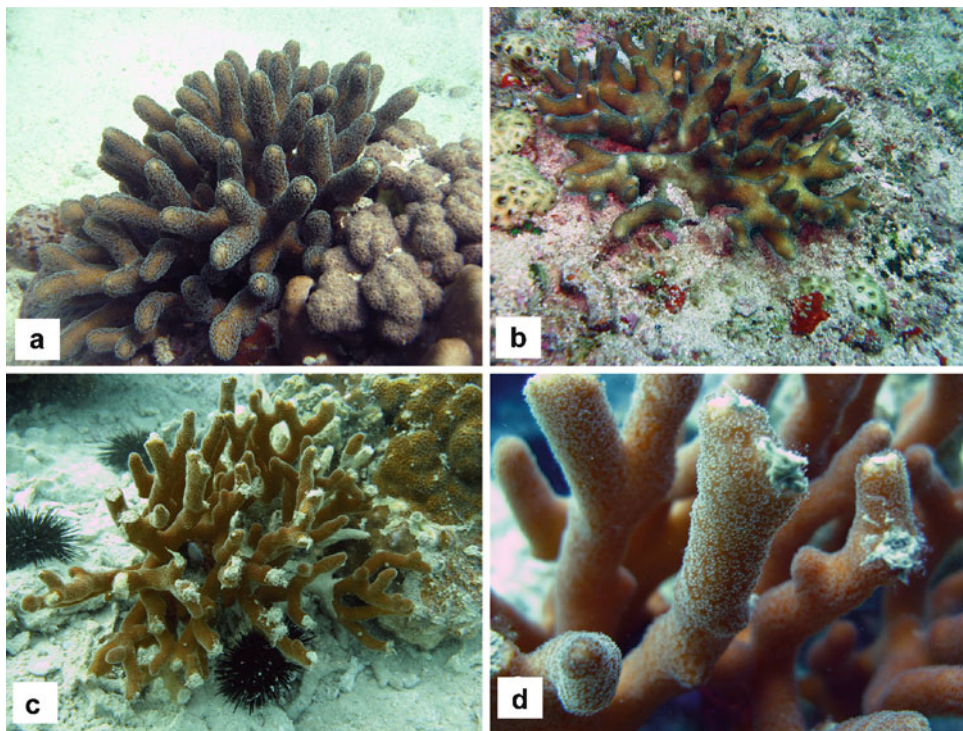


Fig. 11.9 (a) *Stylophora pistillata* from Iran; (a, c, d) Kharku Island; (b) Abu Musa Island, from 15 m depth

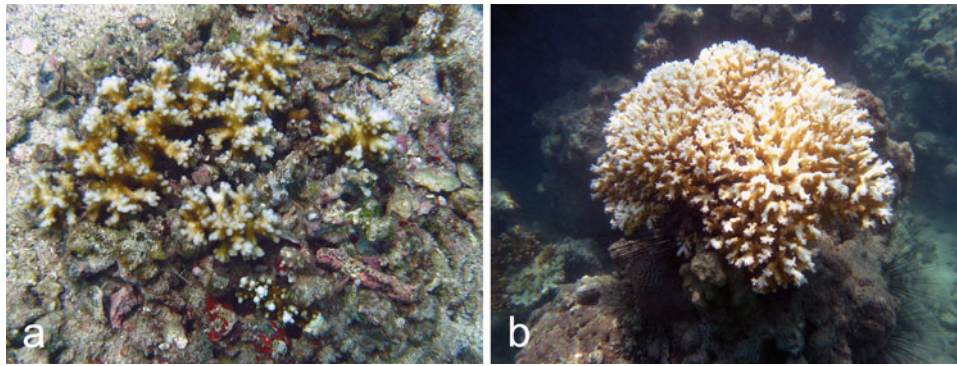


Fig. 11.10 (a) *Pocillopora damicornis* from Abu Musa Island; (b) a bleached colony from Hengam Island

Family Faviidae Gregory 1900

One of the most challenging tasks in the taxonomy of the shallow water zooxanthellate corals is represented by the family Faviidae which is in need of formal revision. This group of corals has been recently shown to be closely related, on molecular basis, to the Mussidae Ortmann 1890 and Pectiniidae Vaughan and Wells 1943, and, like these, highly polyphyletic (Fukami et al. 2004, 2008) to the point that they have been defined altogether the “Bigmessidae” (Huang et al. 2011). Among the genera found in the Gulf, *Favia* (type genus of the family), *Favites*, *Cyphastrea* and *Platygyra* are actually closely related. However, *Leptastrea* and *Plesiastrea* are not (see after). Finally, the traditional separation of the genera *Favia* and *Favites* based on the fusion of the corallite wall, seems to be artificial on the basis of both the high intercolonial variability of this character, and of the latest molecular phylogenies (Huang et al. 2011).

Genus *Favia* Oken 1815

Generic synonymy

Favia Oken 1815

Favia is a common genus with a world-wide distribution. The most common growth-form is massive and colonies can reach large sizes. Chevalier (1971) considers the following traits characteristic:

- corallites generally well separated, but they sometimes show a tendency to fuse (this is also observed in the closely-related genus *Favites*)
- budding is mainly intra-tentacular, mono- to tri-stomodeal. Only in a few species (e.g. *Favia laxa*) are both forms of budding observed.
- Paliform lobes are commonly formed by one simple or compound trabecula. But also true, multitrabecular pali can be formed that are made up from one uniform fan system.

This is probably the most common coral genus in the Gulf, maybe even the Indian Ocean. Where corals can occur

in the Gulf, there usually are some *Favia*, which can be found even in the most marginal habitats.

Favia fava (Forskål 1775)

Corallum: usually massive hemispherical but sometimes flat, very obviously plocoid.

Corallites: plocoid and large (>12 mm diameter), conical, often crowded and polygonal but crowding less obvious than in *F. pallida*. Calices unequal, spacing usually ~2.5–3.5 mm; in general, calices are more (about twice as much) spaced than in *F. pallida*; calices deep (up to 9 mm), average diameter ~8 mm.

Septa: not clearly arranged in orders but 2–3 size classes can often be found that do not necessarily represent cycles (in cycles, septa would alternate regularly in size, this is not the case), larger septa usually reach the columella, Septa descend steeply into the calyx immediately from the periphery towards the center. Some septa with distinct paliform lobes and well-developed dentations of uniform size. All septa evenly exsert and hardly thickened over the theca. Septocostae are also well developed and extend a short distance onto the coenosteum. Same dentations as the septa.

Columella: present but less developed than in other *Favia*. Trabecular, spongy, often incorporating twisted septal teeth.

Theca: thick. Coenosteum blistered.

Color: highly variable, from yellow to reddish, to mottled grey and red. Often with lighter oral field.

Distribution: very common and regular throughout the entire Gulf in all habitats.

Favia pallida (Dana 1846)

Corallum: usually massive hemispherical but sometimes flat, very obviously plocoid.

Corallites: plocoid and smaller than in *F. fava* (8–12 mm), less conical and more tubular than in *F. fava*, often crowded and polygonal. Calices unequal, spacing usually ~2.5–3.5 mm; in general, calices are less spaced than in *F. fava*; calices deep (up to 9 mm), average diameter ~8 mm.

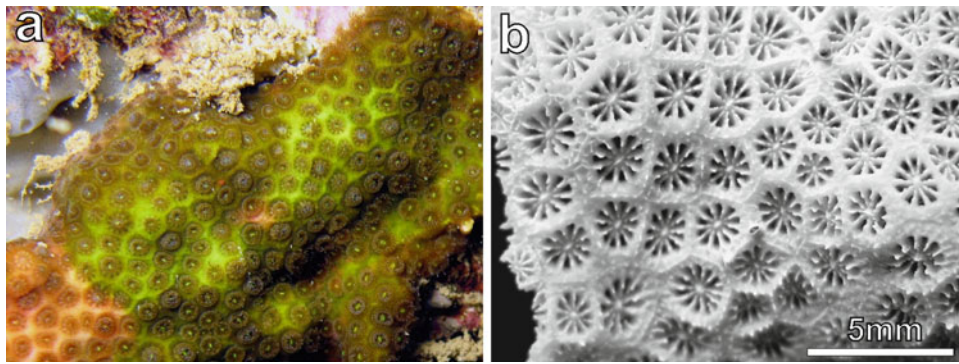


Fig. 11.11 *Madracis kirbyi*, material from Mayotte Island (a, b)

Septa: irregular, mostly in 2–3 orders, first order always reaches the columella, second order sometimes reach or some individual septa markedly shorter. As in *F. favus*, septa descend steeply into the calyx immediately from the periphery towards the center. Distinct paliform lobes frequently developed on most first-order, but not all higher-order septa. exsert and thickened over the theca. Small, regular dentations, well-developed paliform crown, else dentate septal sides with fine granulations. Costae are also well developed and differentiated into a first and a second order which can differ in size, or not. Dentate.

Columella: always present, usually dense, spongy, consisting of twisted and fused trabeculae, but development can vary.

Theca: thick

Color: highly variable, from yellow to reddish, to mottled grey and red. Often with lighter oral field.

Distribution: very common and regular throughout the entire Gulf in all habitats.

Favia speciosa (Dana 1846)

Corallum: massive hemispherical, very obviously plocoid.

Corallites: plocoid, round to polygonal where crowded, diameter ~6–10 mm, mostly around 7 mm, clearly exsert.

Septa: in 2–3 orders, first order always reaches the columella, second order sometimes reaches columella, third order reduced to abortive. Very similar to *F. pallida*. Septa are thin and regularly exsert. Fragile dentations on peripheral parts of septa, irregular dentations on their inner part; paliform lobes or spines not always present and generally less conspicuous than in *F. pallida*.

Columella: spongy, consisting of twisted and fused trabeculae, often also incorporating septal dentations; in some corolla, the columella is not well developed.

Theca: thick

Color: reddish, to orange. Often with lighter oral field.

Distribution: uncommon, but likely throughout the entire Gulf in all habitats.

Differences Between *Favia pallida* and *F. speciosa*

The differences between these species are rather ill-defined and a reliable differentiation of the species in the field is difficult since the tissues hide many important characters. Distinguishing characters given by Veron (1986, 2000) are the size of the corallites and the shape (conical or not). Sheppard and Sheppard (1991) and Carpenter et al. (1997) use the spacing of septa (more widely spaced in *F. pallida*), but this can vary with corallite crowding and environmental condition (Wijsman-Best 1974), the degree to which the corallites are exsert (9–13 mm in *F. pallida*; 12–14 mm in *F. speciosa*; Carpenter et al. 1997), but the ranges overlap, and the reported smaller size of calices in *F. speciosa* can also vary with environmental variation. Chevalier (1971) and Veron et al. (1977) distinguished the two species by their septal dentations and granulations (longer and rougher dentations, more obvious paliform lobes in *F. speciosa*) and this works in other Indian Ocean localities as well (Riegl 1996).

According to Sheppard and Sheppard (1991), the Gulf species are *F. pallida* and *F. favus*, which are also the two species listed by Claereboudt (2006) as occurring in Oman, while Carpenter et al. (1997) list *F. pallida* and *F. speciosa*. We believe that our specimens support the presence of all three species. Some specimens from Dubai show very well-exsert corallites, which has led Riegl (1999) to assign them tentatively to *Barabattoia*. However, they are more likely extreme *Favia favus* (Sheppard and Sheppard 1991) and/or *F. speciosa*. As is the case with dubious *Acropora*, it is also difficult to obtain new specimens, since the areas where these corals occurred and were sampled have been since lost to dredging and filling (Figs. 11.12 and 11.13).

Genus *Favites* Link 1807

Generic synonymy

Favites Link, 1807.

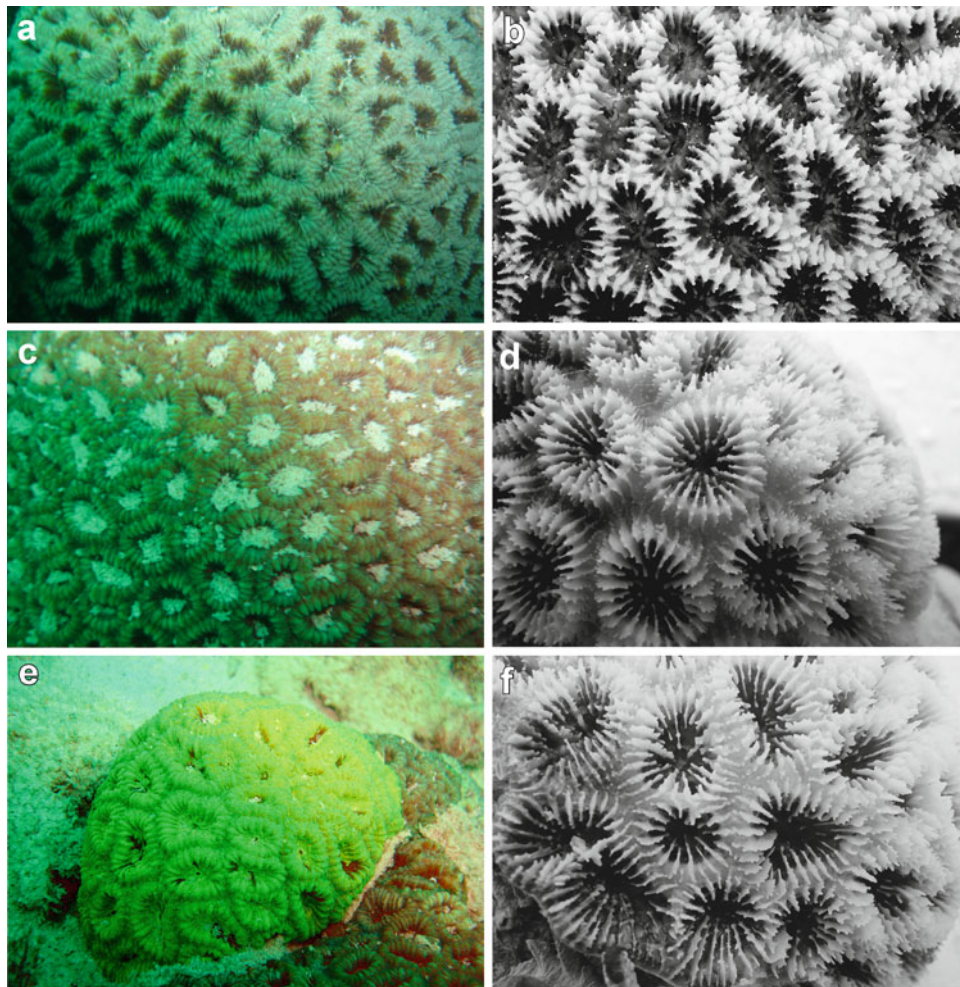


Fig. 11.12 (a, b) *Favites pallida*, (c, d) *Favites favus*, (e, f) *Favites speciosa* (All from Ras Ghanada, Abu Dhabi)

The primary difference between *Favites* and *Favites* is the absence of distinct spacing between the calices. Thus, *Favites* are always typically cerioid, while *Favites* are always typically plocoid. In some species that do not occur in the Gulf (*F. flexuosa*, *F. complanata*, *F. halicora*) there can be a progression towards a sub-cerioid condition. The single species in the Gulf is always cerioid. *Favites* is also close to *Goniastrea* due to the presence of true pali in *F. pentagona*. Since *Goniastrea* is absent in the Gulf, no opportunity for confusion exists.

***Favites pentagona* (Esper 1794)**

Corallum: flat encrusting, may be hillocky to sometimes submassive.

Corallites: cerioid, not crowded, round to polygonal, diameter ~6–10 mm, mostly around 7 mm

Septa: in 2–3 orders, first order always reaches the columella, second order sometimes reaches columella, third order reduced to abortive. Small, regular dentations, well-developed

paliform crown, septal sides granulated, often a trabecular linkage between paliform lobe and septum

Columella: spongy, consisting of twisted and fused trabeculae

Theca: thick

Color: reddish, to orange. Often with lighter oral field.

Distribution: uncommon but regular throughout the entire Gulf. Easily identified (Fig. 11.14).

***Favites acuticollis* (Ortmann 1889)**

This species is likely to have been previously recorded in the Gulf as *Favites abdita* or as *F. chinensis* with which it was put in synonymy by Veron et al. (1977) until Veron (2000) restored it. Comparison of the species holotype depicted in Veron et al. (1977, Fig. 83) with the examined material from the Gulf suggests this taxon has been overlooked in the Indian Ocean, and its distribution may be actually wider than that indicated in Veron's (2000) distribution map.

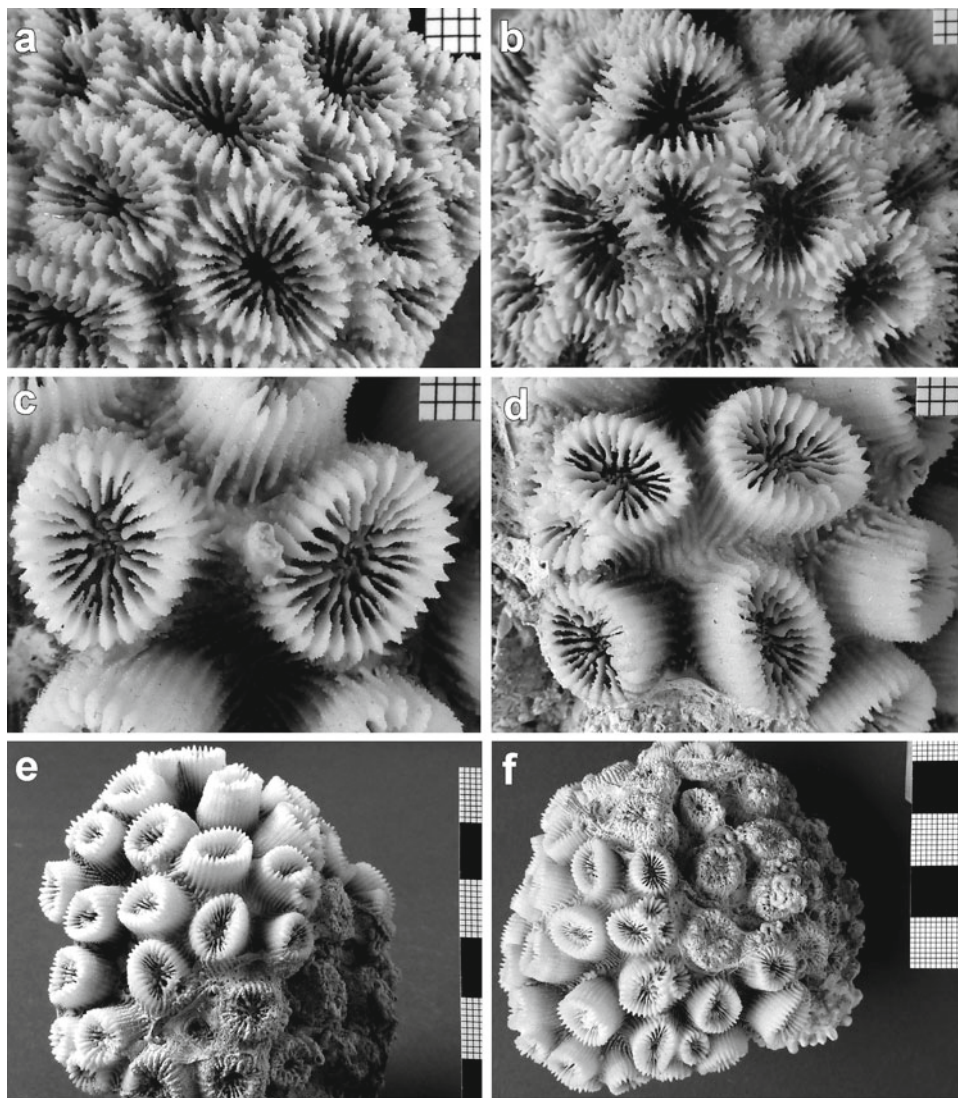


Fig. 11.13 Variability in Gulf *Favia*: (a) *Favia favus*, (b) *Favia palida*, both species showing intratentacular budding. (c, d, e, f) The specimen assigned to *Barabattoia amicornum* by Riegl (1999). It is characterized by mainly extratentacular budding, has clearly more exserted calices than any other Gulf *Favia*, equal costae and moderately to

poorly developed paliform lobes. With that it falls within *Barabattoia* as defined by Veron (2000). The species has only been recorded from this single specimen. The sampling site does not exist anymore, therefore the presence of this species in the Gulf cannot be confirmed

Corallum: encrusting to massive.

Corallites: cerioid, may become crowded in parts of the colony, round to oval, largest diameter 10–12 mm.

Septa: in 3 orders, first and second order reaches the columella, third reduced, never reaches the columella and can be incomplete in irregular corallites. Small, regular dentations, paliform crown present, septal sides granulated, septal margin dentate

Columella: spongy, consisting of twisted trabeculae

Theca: thick

Color: green with brown oral discs.

Distribution: locally common but not regular throughout the entire Gulf. *In situ* it can look superficially similar to smooth

colonies of *Favites pentagona*, which has smaller corallites (Fig. 11.15).

Genus *Cyphastrea* Milne Edwards and Haime 1848

Generic synonymy

Cyphastrea Milne Edwards & Haime 1848

Solenastreaa (pars) Milne Edwards & Haime 1848

The genus is quite easily identified by the small size of the corallites (usually ~3 mm) that are mostly round, not crowded, and the two very distinct size-classes of septa. Corallites are plocoid and, in many species, well-spaced. The coenosteum is blistered and/or covered with spinules.

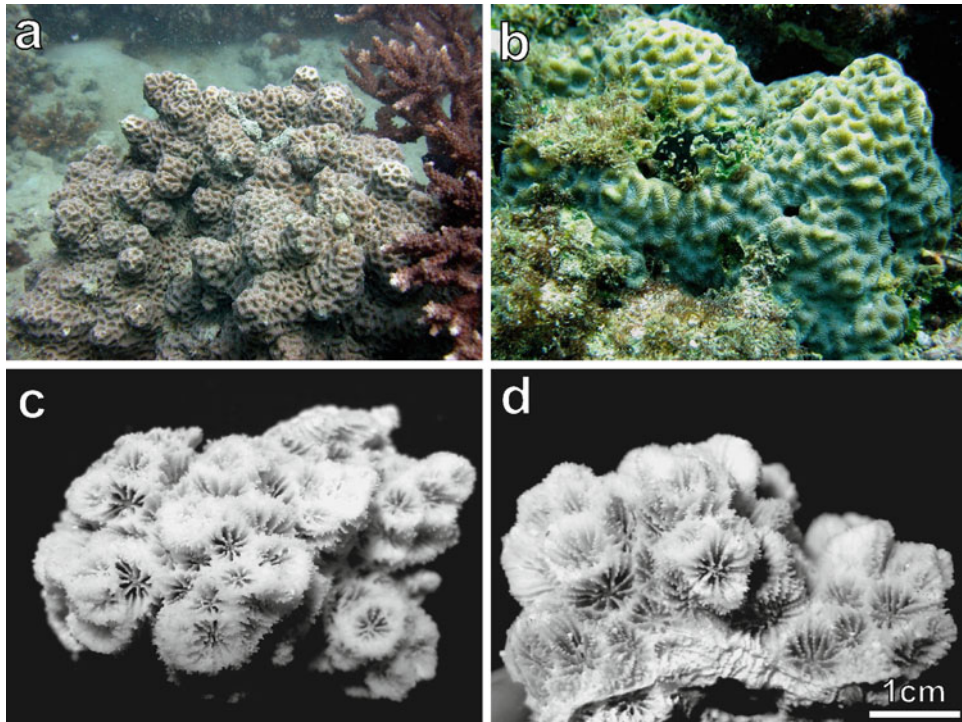


Fig. 11.14 *Favites pentagona*: (a) from Kubbar Kuwait showing a hillocky growth form; (b) from Halul Qatar, *top* (c) and *side* (d) view of a specimen from Kuwait (M. Pichon coll.)

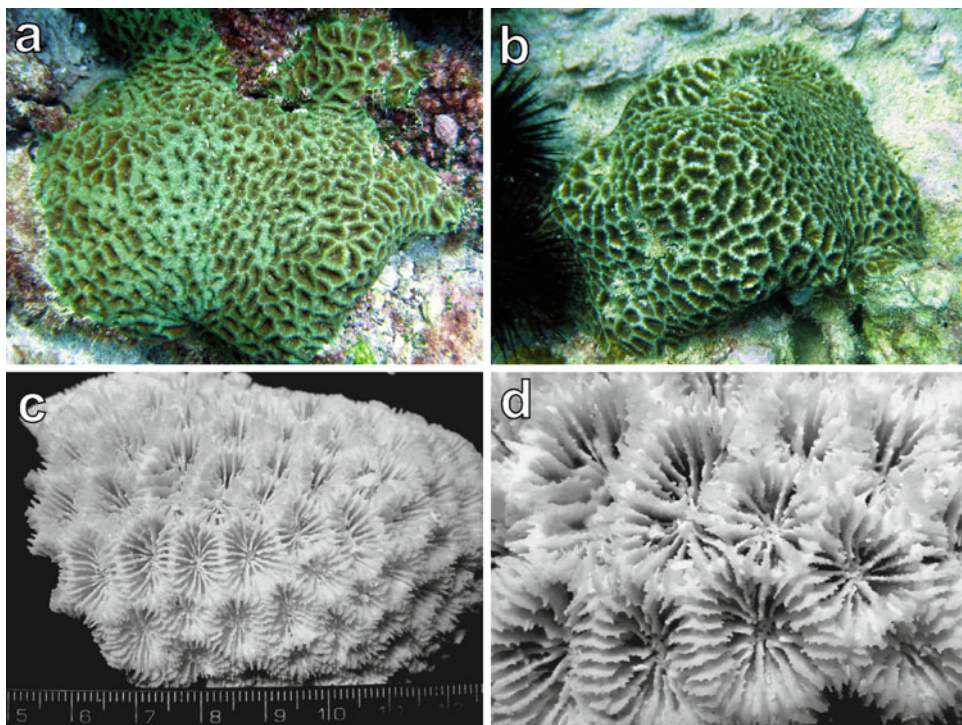


Fig. 11.15 *Favites acuticollis*: (a, b) from Halul Qatar (F. Benzoni coll.); and (c, d) a specimen from Kuwait (M. Pichon coll.)

Septal arrangement is distinct: there is a circle of 12 large septa alternating with 12 smaller septa that are 1/3–1/2 the size of corallite radius and do not reach the columella. The larger septa are often thickened over the theca, thus giving a somewhat wedge-shaped appearance.

***Cyphastraea microphthalma* (Lamarck 1816)**

Corallum: massive, hemispherical to columnar.

Corallites: plocoid, round, diameter up to ~3.5 mm, generally well-spaced. Thecae can be variable and either be thick and well-exsert or confluent with coenosteum. Extratentacular budding.

Septa: in most specimens 10 first order septa, the number is unusual for the hexacorallia, but is easily verified since this is the best diagnostic character in the field. First order is markedly bigger and thicker and is a single well-defined cycle. Paliform lobes are present on septa of this cycle and can take the form of one or two twisted dentations. The 10 septa of first big cycle reach the columella; septa of the second order are reduced to thin lamellae along the wall. Septal sides of all orders are strongly granulated.

Columella: well developed, trabecular.

Costae: exsert, first order larger than second order.

Coenosteum: covered with ornamented spines.

Color: whitish coenosarc, sometimes a darker oral field.

Distribution: common and regular throughout the Gulf. One of the most distinctive and abundant corals in all habitats.

***Cyphastraea serailia* (Forskål 1775)**

Corallum: massive, hemispherical.

Corallites: plocoid, round, diameter up to ~3.5 mm, generally well-spaced. Thecae can be variable and either be thick and well-exsert or confluent with coenosteum. Extratentacular budding.

Septa: 24 in 2 orders, the first order is markedly bigger and thicker and is differentiated into two cycles of different size. Paliform lobes are present on septa of this cycle as are big dentations. Septa of first big cycle reach the columella; septa of the second order are reduced, do not have paliform lobes and do not reach the columella. Septal sides of all orders are strongly granulated.

Columella: well developed, trabecular.

Costae: first and second order of equal size.

Coenosteum: covered with ornamented spines.

Color: whitish coenosarc, sometimes a darker oral field.

Distribution: common and regular throughout the Gulf in all habitats (Fig. 11.16).

Genus *Leptastrea* Edwards and Haime 1848

Generic synonymy

Leptastrea Edwards and Haime 1848; *Baryastrea* Edwards and Haime 1848.

Leptastrea has small, basically rounded to polygonal corallites that are, however, usually distorted due to crowding. This is regularly the case in the only Gulf species. Corallites

less exsert than in *Cyphastraea*. Septa are in two or more size-classes. Columella is well-developed and consists of rod-like trabeculae. Paliform lobes not always developed, certainly not in the Gulf species.

The genus *Leptastrea* is more closely related to the Fungiidae and Psammocoridae than to the rest of the Faviidae (Fukami et al. 2008) and its current status within the family Faviidae is likely to be revised soon.

***Leptastrea purpurea* (Dana 1846)**

Corallum: small colonies encrusting to submassive, often irregular colony outline. Large colonies can be almost massive

Calices: plocoid (sub-ceroid, *sensu* Veron et al. 1977), mostly polygonal, a clear groove separates the calices, diameters 1–4 mm.

Septa: around 30, in up to three size classes, small septa sometimes fuse to bigger septa, thus only the bigger septa-class (usually the biggest cycles) reach the center of the calice, where they fuse to the columella. The size difference between the septal cycles is less pronounced than in *L. transversa*. Septa descend gently into calice, are finely serrated on their upper edges and granulated on their sides. Septa weakly exsert. No clear paliform lobes (or teeth) were observed in our specimens.

Columella: well developed and conspicuous, consisting of fused vertical rods with free tips.

Color: green, light blue to brown.

Distribution: Generally rare, but occurring throughout the Gulf.

***Leptastrea transversa* Klunzinger, 1879**

Corallum: small colonies encrusting to submassive

Calices: plocoid to sub-ceroid, polygonal, and highly variable in size from 2 to 7 mm, the groove separating the calices narrower and less visible than in *L. purpurea*, but present.

Septa: first and second cycles of septa almost equally developed with tendency to fuse, third cycle reduced

Columella: well developed, consists of a few trabeculae that are often fused.

Color: green, light blue to brown.

Distribution: Generally rare (Fig. 11.17)

Genus *Echinophyllia* Klunzinger, 1879

Generic synonymy

Echinophyllia Klunzinger, 1879; Vaughan and Wells 1943

Oxyphyllia Yabe and Eguchi 1935

Previously ascribed to the Family Pectiniidae, this genus is actually closely related to genera traditionally ascribed to the Faviidae (Fukami et al. 2008).

***Echinophyllia aspera* (Ellis and Solander, 1786)**

Corallum: encrusting to partially foliose, the central part can be knobby, with protruding corallites. Colonies can reach up to 50 cm in diameter.

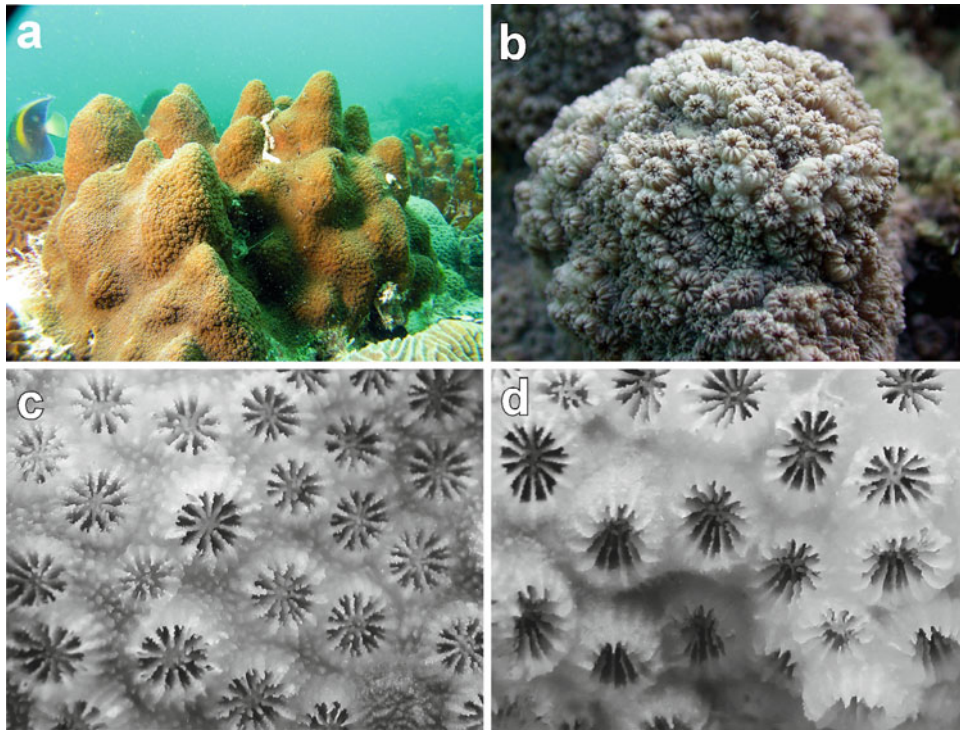


Fig. 11.16 (a, c) *Cyphastrea microphthalma*, Abu Dhabi; (b, d) *Cyphastrea serailia*; (b) from Qaro, Kuwait (M. Pichon coll.); (d) from Saadiyat, Abu Dhabi

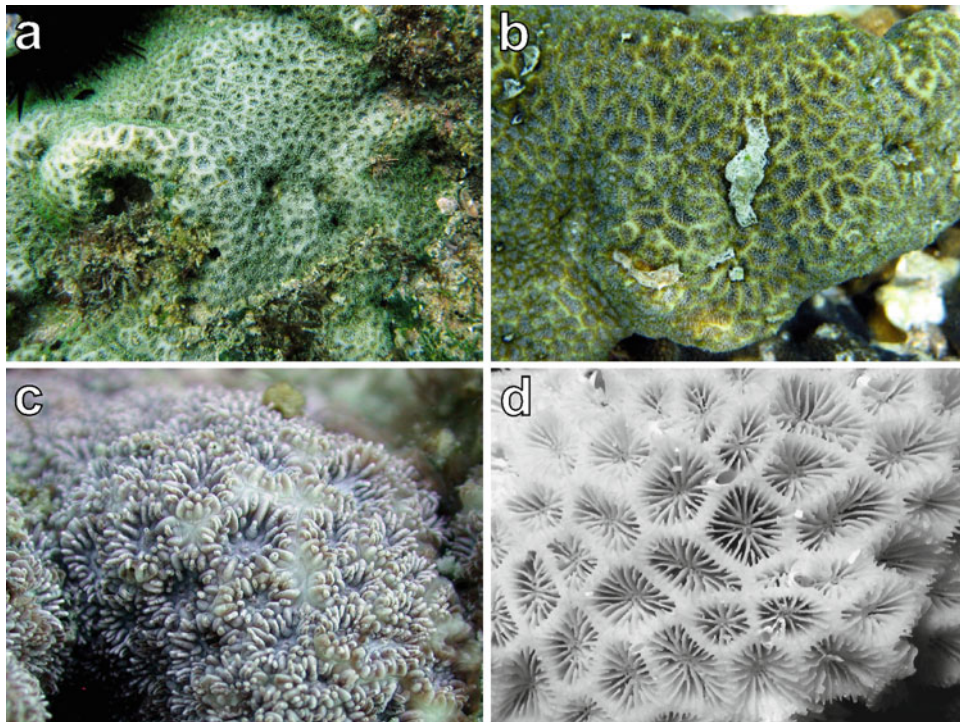


Fig. 11.17 (a, b) *Leptastrea transversa* on Halul Island Qatar. A close up of polyps (c) and corallites (d) from Kubbar Kuwait (M. Pichon coll.)

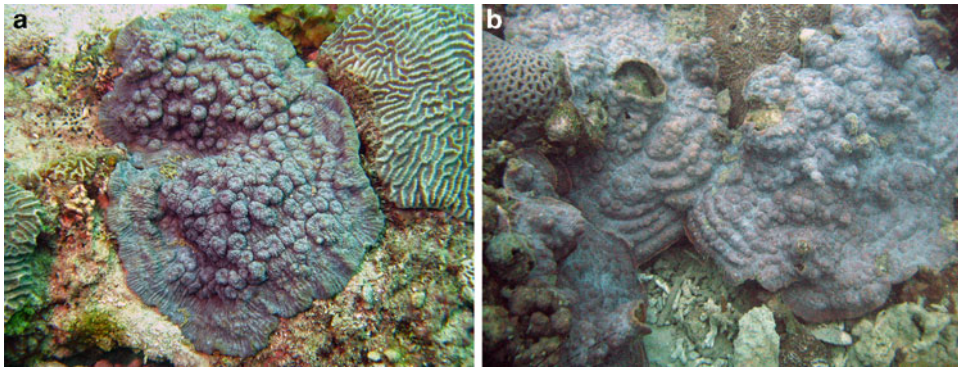


Fig. 11.18 (a) *Echinophyllia aspera* from Abu Musa Island, Iran; (b) from Kharku Island, Iran

Calices: mostly plocoid, exert and up to 1 cm in diameter, they can be inclined towards the margins of the corallum

Septa: first order always complete, second order complete or partially incomplete, sub-equal or equal. Septa continue after the wall and become costae covering the coenosteum. Septa and costae strongly dentate.

Columella: well developed and conspicuous, consisting of twisted trabeculae.

Color: brown to green

Distribution: This genus has not been observed in the southern part of the Gulf, however, it can be found in the northern part from the Strait of Hormuz to Khark and Kharku island (Fig. 11.18).

Genus *Plesiastrea* Edwards and Haime 1848

Generic synonymy

Astraea (pars) Lamarck 1816.

Plesiastrea Edwards and Haime 1848; *Orbicella* (pars) Vaughan, 1907; Yabe, Sugiyama and Eguchi (1936).

Favia (pars) Matthai 1914

This common genus is morphologically close to *Montastraea* (Veron et al. 1977). However, from the evolutionary standpoint it is closer to *Trochocyathus efaatensis* Cairns, 1999 (traditionally in the Caryophylliidae Dana 1846) and *Cyathelia axillaris* (Ellis and Solander, 1786) (currently in the Oculinidae Gray, 1847) than to any other taxon in the Faviidae (Kitahara et al. 2010). *Plesiastrea* is distinguished by the regular presence of true pali, rather than paliform lobes. A detailed account of its micromorphological features (Benzoni et al. 2012) supports the strong differences with the rest of the taxa traditionally ascribed in the same family. It occurs in most habitats in the Gulf and is one of the more common species.

***Plesiastrea versipora* (Lamarck 1816)**

Corallum: massive, hemispherical, sometimes with laminar edges

Corallites: plocoid, diameter ~2–3 mm, crowded, round to slightly polygonal where crowded.

Septa: in 3 orders, the first two may be of the same size with the third then much smaller; true pali on the first and second order, forming two pali crowns around the columella; first and second order septa project horizontally into the calyx for about 2/3 of calyx radius, then descend abruptly; septa moderately exert and thickened over the septa, pali also thickened.

Columella: weakly developed, consists of only a few rodlike trabeculae.

Costae: equal to subequal, continue onto the coenosteum.

Coenosteum: smooth, blistered.

Color: whitish to greenish coenosarc, sometimes a darker oral field.

Distribution: common and regular throughout the Gulf (Fig. 11.19)

Genus *Platygyra* Ehrenberg 1834

Generic synonymy

Platygyra Ehrenberg 1834

Astoria Edwards and Haime 1848

Coeloria Edwards and Haime 1848; Matthai (1928); Crossland (1952); Alloiteau (1957).

Meandroid. Colony formation by linear intramural, polystomodeal budding. Thecae are narrow and those of adjacent valleys are fused. The genus is unmistakable and one of the most common in any environment in the Gulf. Several species are described. Recent genetic and morphometric analyses (Miller 1992; Miller and Babcock 1997; Miller and Benzie 1997) suggests that maybe only one valid species, namely *P. daedalea*, exists. Sheppard and Sheppard (1991), Riegl (1999) and Veron (2000) also list *P. crosslandi* and *P. sinensis* as occurring in the Gulf, but insufficient justification exists to verify the records. The locations where Riegl's specimens were collected (Jebel Ali, Dubai) are now lost due to land reclamation. There exists enough morphological variability to allow adhering to a separation of *P. daedalea* and *P. lamellina*, as maintained by Veron (2000). In the field, when

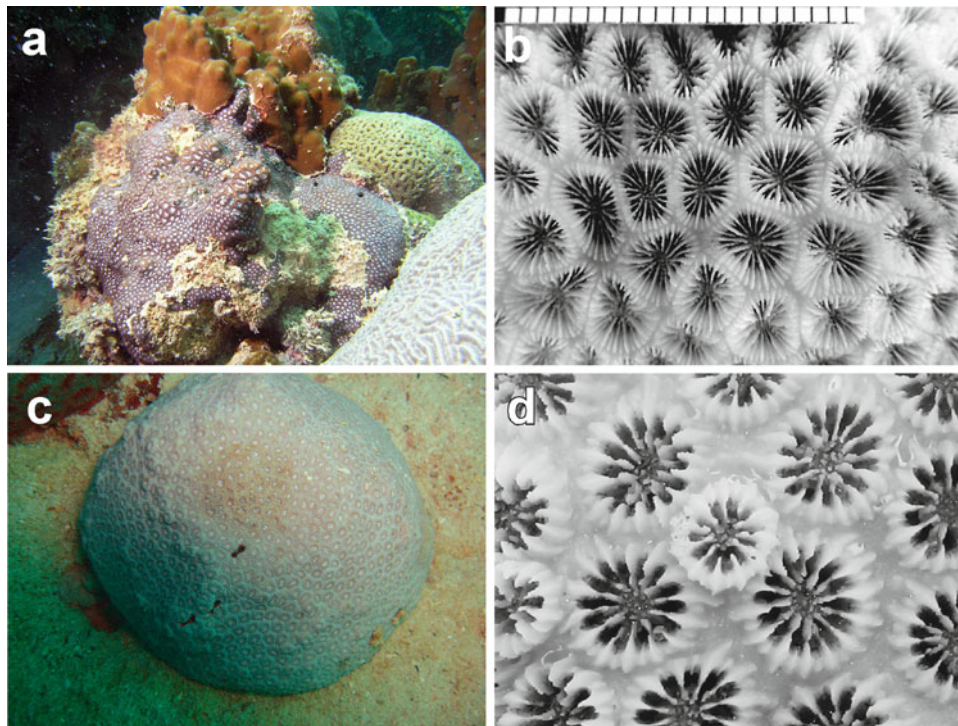


Fig. 11.19 (a, b) *Leptastrea purpurea*, (c, d) *Plesiastrea versipora* from Abu Dhabi

skeletal characters are obscured by living tissue, it is usually impractical to separate all but extreme forms of the two species, which are then distinguished by the shorter series in *P. daedalea*.

***Platygyra daedalea* (Ellis and Solander, 1786)**

Corallum: massive, flat to hemispherical.

Corallites: meandroid; long deep valleys, marked centers only at the ends of valleys or in short series. The length of valleys can vary. Most Gulf specimens fall into the variability previously associated with *P. lamellina*.

Septa: in one or two orders, most septa more or less equal, exsert and fusing above the theca thus forming continuing septa between two valleys, above the theca and at the bases of the septa a fine trabecular linkage exists between the septa; dentations very well developed; paliform lobes usually absent.

Columella: well-developed, trabecular, spongy, development varies within the colony.

Distribution: one of the most common corals. In all habitats throughout the Gulf (Figs. 11.20 and 11.21).

***Platygyra lamellina* (Ehrenberg, 1834)**

Corallum: massive, flat to hemispherical.

Corallites: meandroid; long deep valleys, marked centers only at the ends of valleys or in short series. The length of valleys can vary. The thecae are thicker than in *P. daedalea*, therefore the walls between the valleys appear more rounded and wider.

Septa: in one or two orders, most septa more or less equal, exsert and fusing above the theca thus forming continuing septa between two valleys, above the theca and at the bases of the septa a fine trabecular linkage exists between the septa; dentations very well developed; paliform lobes usually absent.

Columella: well-developed, trabecular, spongy, development varies within the colony.

Distribution: one of the most common corals. In all habitats throughout the Gulf.

Within the Faviidae, also *Favia matthai* Vaughan 1918, *Gonistrea retiformis* (Lamarck 1816), *Echinopora irregularis* Veron, Turak and DeVantier 200 and *Cyphastrea chalcidicum* (Forsk. 1775) are reported from Iranian islands in the Straits of Hormuz. *E. irregularis* is also reported from within the Gulf proper. No collected material was, however, available for review.

Genus *Hydnophora* Fisher de Waldheim, 1807

Generic synonymy

Hydnophora Fisher de Waldheim 1807

Monticularia Lamarck 1816; Dana 1846

Merulina Dana 1846 (*pars*)

Based on macro-morphologic characters such as wall and columella structure, and budding fashion, the genus *Hydnophora* has been part of the Faviidae (together with *Favites* and *Montastraea*) according to, among the others, Vaughan and Wells (1943), and Veron et al. (1977). Then, Veron (1986,

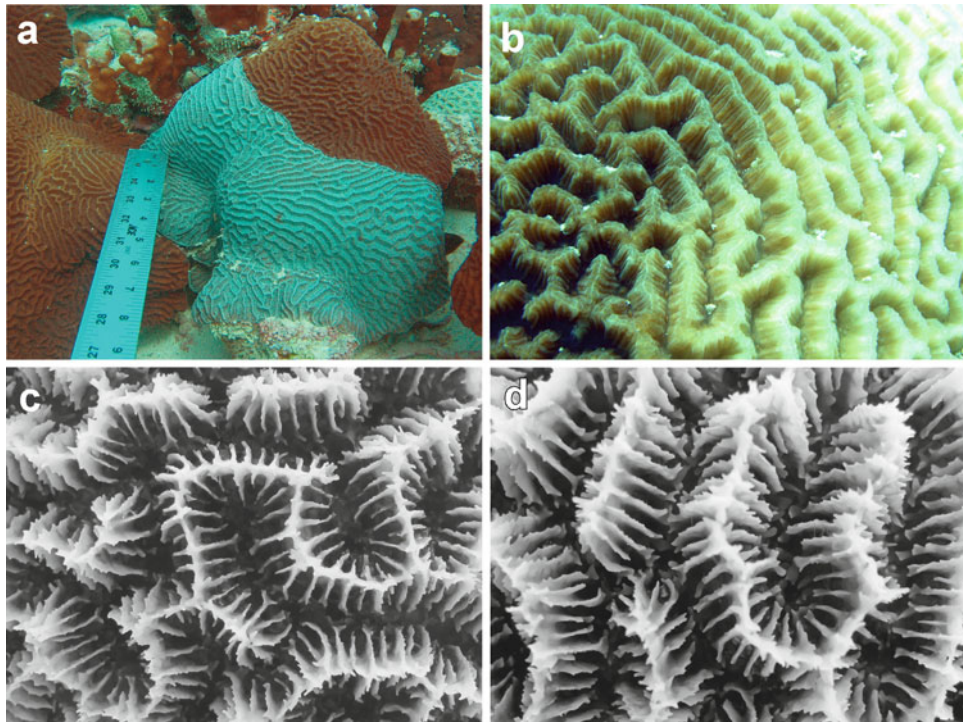


Fig. 11.20 *Platygyra daedalea* (a–d, From Ras Ghanada, Abu Dhabi, UAE)

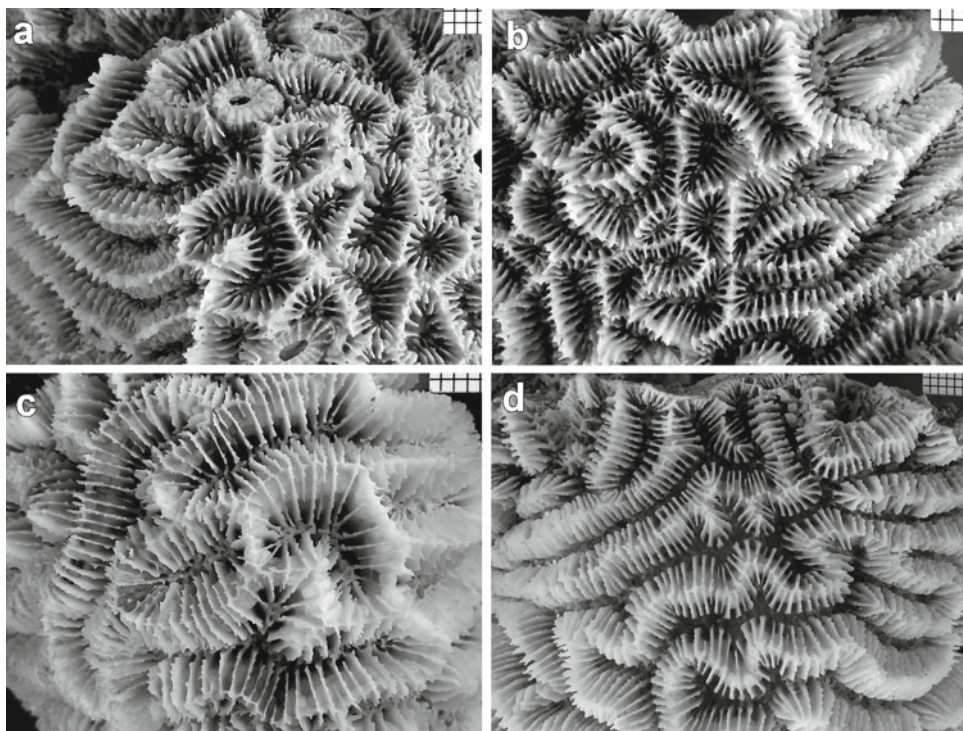


Fig. 11.21 (a, b) *Platygyra daedalea*; (c, d) *Platygyra lamellina*. Jebel Ali, Dubai

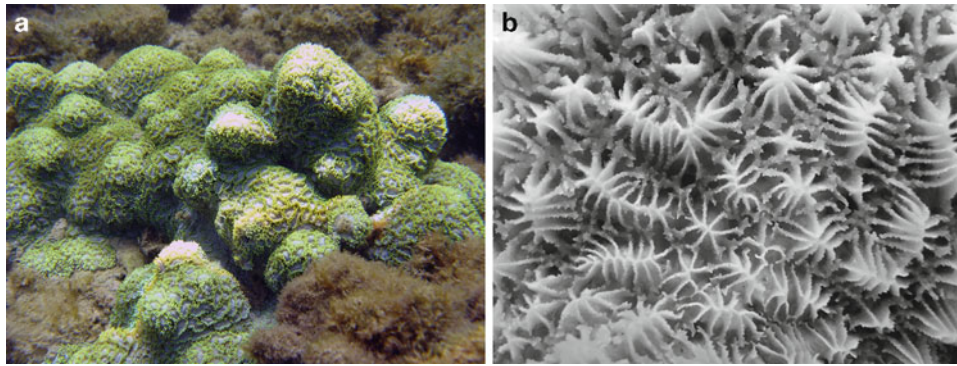


Fig. 11.22 (a, b) *Hydnophora pilosa* from Larak, Iran

2000) moved the genus into the Merulinidae. Molecular phylogenies have shown that this genus is actually closer to the other genera ascribed to the Faviidae than to any of those included in the Merulinidae (Fukami et al. 2008).

The genus was found at Larak and Abu Musa but is likely to also occur at other islands closer to the Strait of Hormuz. Also *Hydnophora exesa* (Pallas, 1766) has been reported, but only by a single specimen from Kuwait (Qaro Island, Carpenter et al. 1997).

Hydnophora pilosa Veron, 1985

Corallum: encrusting to sub-massive, with knobby protuberances.

Corallites: hydnochoroid; well developed monticules of different size and variable orientation can constitute single polyps or series. Thus the number of septa reaching the tips of monticules varies strongly. Monticule axis usually perpendicular to the surface of the corallum.

Septa: in only one size class that usually represents the first complete cycle. Small monticules therefore have six septa, longer, fused ones, tend to have a multiple of six. Secondary intermediate septa observed rarely. Septa mostly of uniform thickness throughout their length and bear well-developed teeth and denticular ornamentations.

Columella: usually present as a series of twisted trabeculae in the valleys inbetween monticules.

Distribution: Larak, likely to be found in other islands close to the Strait of Hormuz. If the Qaro specimen (assigned to *H. exesa* by Carpenter et al. 1997) is the same species, then occurrence is Gulf-wide (Fig. 11.22).

Family Mussidae Ortmann 1890

Genus *Symphyllia* Milne-Edwards and Haime, 1848

Generic synonymy

Symphyllia Milne-Edwards and Haime 1848.

Symphyllia radians Milne-Edwards and Haime, 1849

Corallum: massive, flat to hemispherical.

Corallites: meandroid; valleys irregularly sinuose and mostly long, with some short valleys irregularly interspersed.

Septa: Well developed, markedly spiny with strong dentations on upper margin. Not clearly arranged in orders but up to four size-classes distinguishable. Thin and thick septa alternate. Thicker septa have fewer, but better developed dentations.

Columella: variable. From a few twisted trabeculae to fully spongiose and clearly visible.

Distribution: Hengam, likely to occur in other islands close to the Strait of Hormuz (Fig. 11.23)

Family Psammocoridae Chevalier and Beauvais 1987

This family was described by Chevalier and Beauvais to accommodate the genus *Psammocora* on the basis of its distinctive corallite morphology. Although this decision was disregarded by others (Veron and Pichon 1976; Veron 2000) molecular phylogenies and a re-examination of polyp and corallite morphology confirmed the distinctiveness of the Psammocoridae and their close relationships with part of the genera once ascribed to the Siderastreidae (Fukami et al. 2008; Benzoni et al. 2007, 2010).

Genus *Psammocora* Dana, 1846

Generic synonymy

Madrepora (pars) Esper 1794; Esper 1798

Pavonia (pars) Lamarck 1816

Psammocora Dana 1846; *Porites* (pars) Milne-Edwards and Haime 1851

Maeandroseris Rousseau 1854

Stephanocora Verrill 1866

Stephanaria Verrill 1867

Plesioseris Duncan, 1884

Polyps in the genus *Psammocora* are characterised by concentric crowns of tentacles only the innermost of which is directly connected to the polyp gastrovascular cavity. In the calice, entosepta (bearing a tentacle) alternate with the exosepta (devoid of tentacles) and are connected to each other by synapticulae. The pattern of entosepta and exosepta furcation and fusion is described in detail in Benzoni et al. (2007). Entosepta and enclosed entosepta can be thicker than



Fig. 11.23 *Symphyllia radians* from Hengam Island, Iran

the exosepta and reach the typical “petaloid” shape and are characteristic of this genus.

Two species of *Psammocora* are found in the Gulf. *Psammocora albopicta*, recently described and confused for a long time with *P. superficialis*, and *P. stellata* whose small colonies, before attaining the typical branching morphology, may resemble *P. profundacella*. The genus taxonomy has been recently revised by Stefani et al. (2008) and by Benzoni et al. (2010).

Psammocora stellata (Verrill 1866)

The Kuwait population of this species has been shown to be a hybrid between *P. stellata* and *P. contigua* (Stefani et al. 2008) it is presently unclear if the other populations in the Gulf share this hybrid origin.

Corallum: Short, irregular branches arising from an encrusting to submassive base. Branch from 3 to 5 cm in length. Branches do not anastomose. Coralla are small, mostly of <15 cm diameter, with branches up to 5 cm in length, diameter around 1–1.5 cm. The surfaces of all coralla have small collines, which can develop into branches. This gives the surfaces of coralla a distinctly “uneven” appearance.

Corallites: Polygonal and shallow, and with a poorly defined wall. Calice diameter between 1.5 and 1.9 mm. Especially on branches, the walls are not of the same height on all sides of corallites, which leads to an arrangement of short series of corallites united by taller lateral walls separating them from the neighboring series of corallites, but low and fairly indistinct walls in between the corallites of the same series.

Septa: Eight to ten septa reach the fossa, and three to four of them are petaloid. Enclosed petaloid septa are 0.2 mm wide and 0.5–0.7 mm and have a rice-grain shape but they may be reduced to a dash-like shape. Septa side perforated.

Columella: Present in almost all corallites, typically made of five to eight round processes rarely even in size.

Color: beige to brown, sometimes greenish and typically paler on the tops of branches

Distribution: generally rare in the UAE, relatively common in Qatar and common on Kuwait reefs. Also occurs at some of the Iranian islands, such as Kish Island mainly as free living colonies (Fig. 11.24).

Psammocora albopicta Benzoni 2006

Corallum: Corallum encrusting to submassive, generally following the shape of the substrate.

Corallites: calice diameter from 0.9 to 1 mm, corallites can be locally arranged in short series, but are overall evenly distributed on the corallum surface. Shallow depressions delimited by rounded collines, or ridges can develop in parts of the corallum. These ridges are never acute as in *P. stellata*.

Septa: seven to nine septa reach the fossa, 3 or 4 are not fused with other septa, and can be petaloid or lamellar in shape. Enclosed septa form one or two complete series around the calice, mostly lamellar in shape, but can be petaloid. Septa side perforated.

Columella: present, made of a single process, round, oval or almost cross-shaped in section.

Color: brown to beige, with a typically white pattern

Distribution: generally rare. So far only reliably recorded from Kuwait and Saudi Arabia (Benzoni 2006), elsewhere likely to have been called *P. superficialis*. But since the species also occurs in the W-Indian Ocean, it likely occurs throughout the Gulf (Fig. 11.25).

Genus *Coscinaraea* Milne Edwards and Haime 1848

Generic synonymy

Madrepora Forskål 1775

Coscinastrea Milne Edwards and Haime 1848

Common and easily identified corals with massive skeletons and large, cerioid polyps. Thecae well-developed, but generally indistinct. Tentacle bearing septa alternate with exosepta. Although exosepta seem to continue over the wall and become septocostae, they actually stop on top of the wall where they meet their counterparts from the adjacent corallites. Corallites can form short series. Polyps often extended during the day.

Coscinaraea monile (Forskål 1776)

Corallum: encrusting, massive, hillocky, in shaded or turbid environments corallum margins may be free.

Corallites: cerioid, variable in shape going from oval, to polygonal, or irregular, between 5 and 15 mm diameter.

Septa: numerous (around 40) number variable between corallites, paddle-shaped ornamentation (Benzoni et al. 2007) on the upper edge. No clear distinction into different orders or cycles; not all septa reach the columella, many fuse along various positions; more than two septa can fuse. Septa are connected by synapticulae. Septal sides perforated.

Columella: present, a tangle of trabeculae.

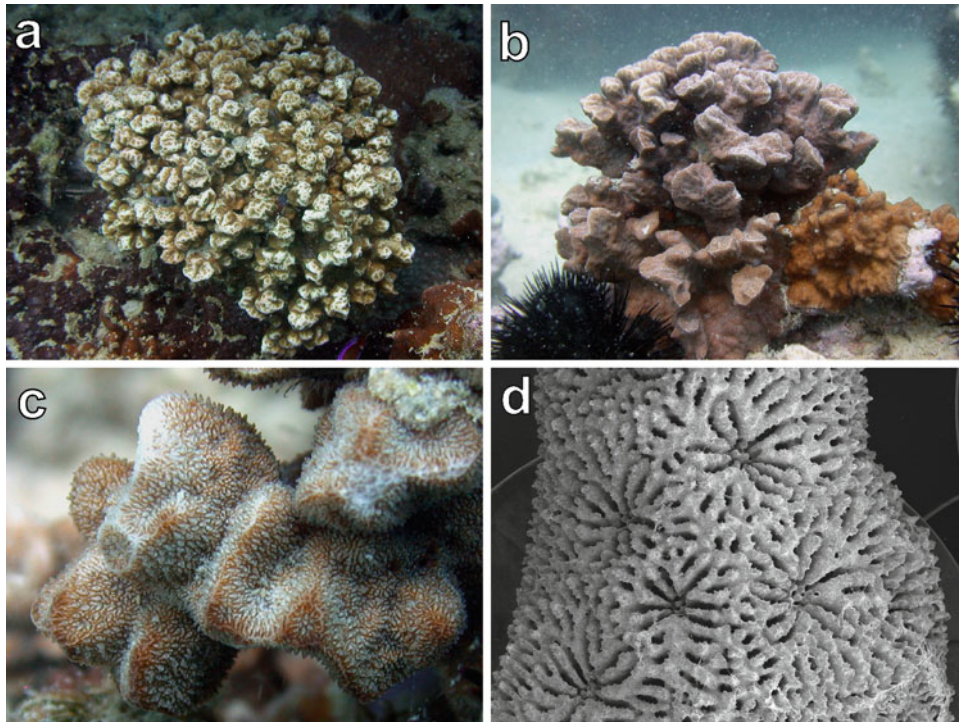


Fig. 11.24 *Psammocora stellata*: (a, b) from Kubbar Kuwait; (c) close up of the polyps usually expanded during the day; and (d) SEM image of corallites showing the typical petaloid and enclosed petaloid septa

Distribution: uncommon to common, mainly in sandy habitats throughout the Gulf (Fig. 11.26).

Differences Between *Coscinaraea monile* and *C. columna*:

Both *Coscinaraea monile* and *C. columna* have been recorded from the Gulf (Table 11.1). The examination of the holotype of *Psammocora columna* (USNM COE00188), as originally described by Dana (1846), has shown that this species displays, *de facto*, the typical psammocorid characters (e.g. enclosed petaloid septa) and its corallites are much smaller than in *C. monile* (3–4 mm in diameter) and septa less numerous (20–30). Images of the holotype are publicly available and can be found at <http://collections.nmnh.si.edu/search/iz/>. None of the *Coscinaraea* specimens examined from the Gulf share these characters although some colonies can have small corallites. *Coscinaraea monile* is highly variable both in shape of the corallum and in corallite arrangement. This plasticity is most likely at the base of the record of two distinct taxonomic entities instead of one.

Genus *Anomastrea* von Marenzeller 1901

Generic synonymy

Anomastrea von Marenzeller 1901;

Anomastrea irregularis von Marenzeller 1901

Corallum: encrusting, submassive or massive.

Corallites: cerioid, between 3 and 6 mm in diameter, never forming series. Irregularly polygonal in outline, tending to become elongated in certain parts of the colony.

Septa: between 15 and 30 depending on the size of the corallite. No clear distinction into different orders or cycles; 1–6 septa may reach the columella without fusing with others, the others fuse along various positions and more than two septa can fuse. Septa are connected by synapticulae. Septal sides perforated (Figs. 11.27 and 11.28).

Columella: present but sitting deep in the fossa, made of processes departing from the septa.

Distribution: common in reef and sandy habitats throughout the Gulf, though never abundant (Figs. 11.27 and 11.28).

Differences and confusion between *Anomastrea* and *Pseudosiderastrea*:

The genus *Pseudosiderastrea* was described for the first time by Yabe and Sugiyama (1935) and its morphologic affinities with *Siderastrea* on the one hand (Chevalier and Beauvais 1987) and *Anomastrea* on the other hand (Vaughan and Wells 1943; Veron and Pichon 1980; Veron 2000) were noted. *Pseudosiderastrea* and *Anomastrea* share several macromorphologic characters such as the size of corallites, their polygonal outline, and the fusion of septa. However, the former is characterized by a solid columella (*cf* figures in

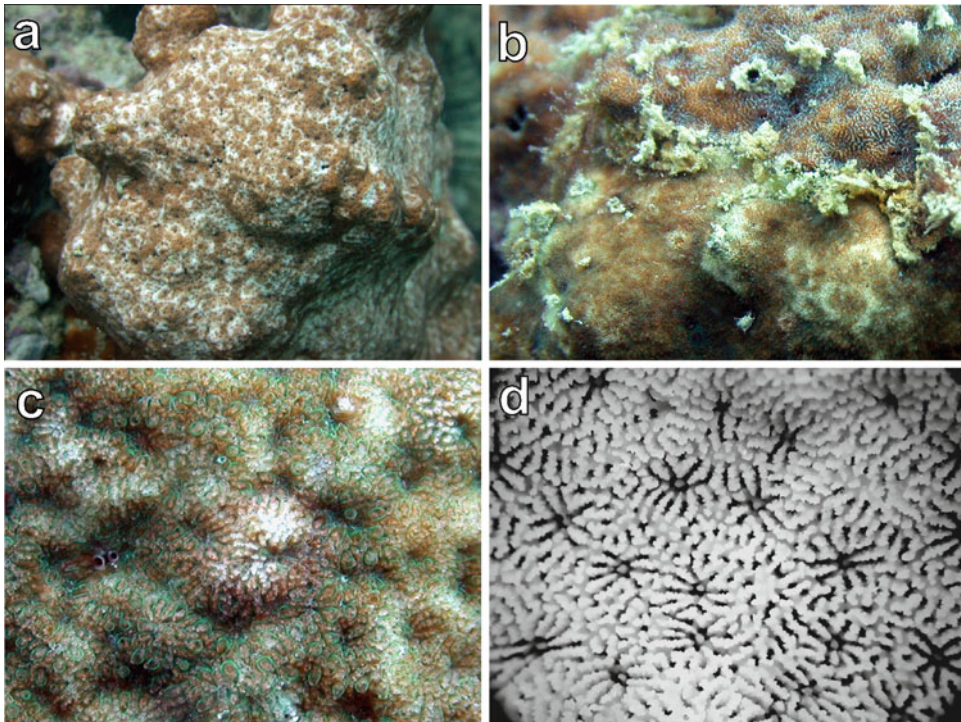


Fig. 11.25 *Psammocora albopicta*: (a) from Umm Al Maradem Kuwait; (b) *P. albopicta* (bottom) and *P. stellata* (top) showing the difference in calice diameter between the two species; (c) close up of the

transparent polyp tentacles expanded during the day; (d) close up of the corallites (F. Benzoni, coll.)

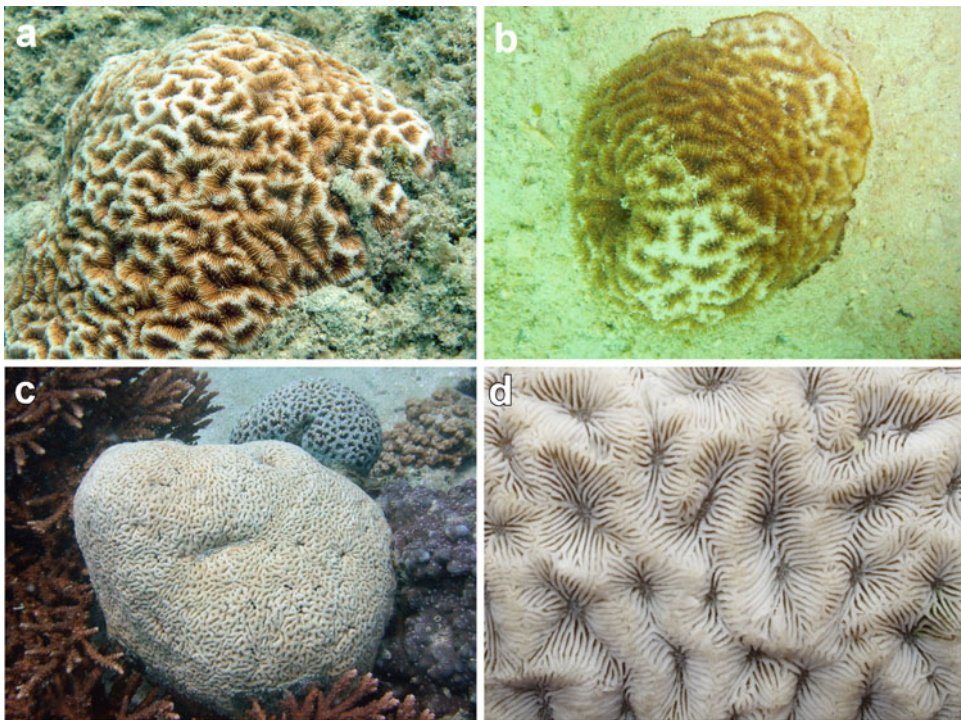


Fig. 11.26 (a, b, d) *Coscinaraea monile*, from Abu Dhabi, (c) from Umm al Maradem, Kuwait (F. Benzoni, coll.)

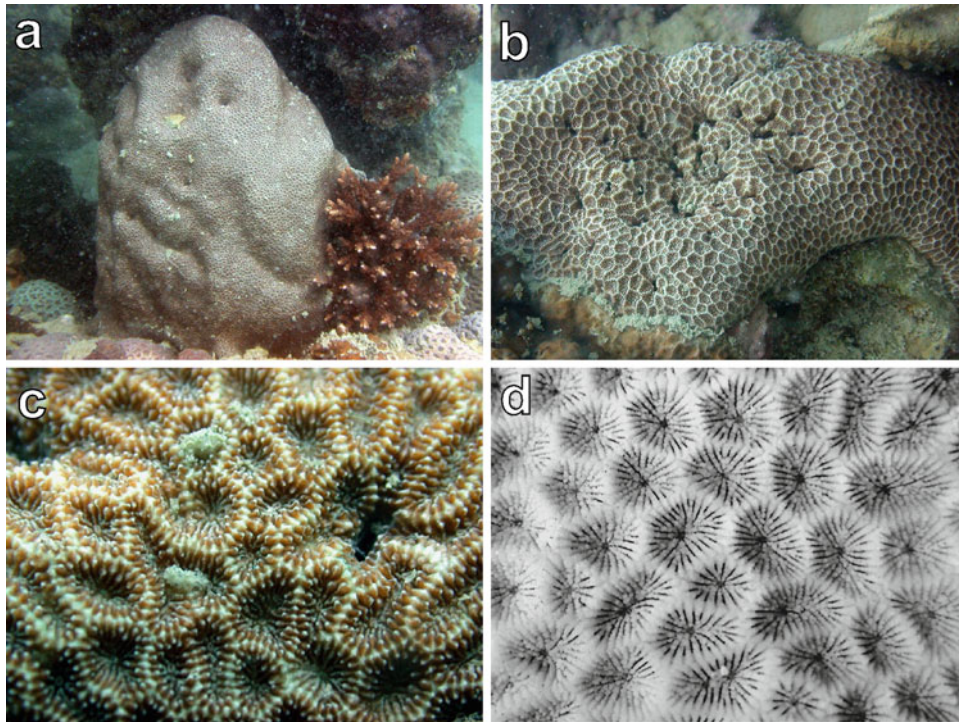


Fig. 11.27 *Anomastreaa irregularis*: (a) massive colony from Kubbar Kuwait; and (b, c) encrusting colony from Umm Al Maradem Kuwait; (d) close up of the corallites in a specimen from Karan Island Saudi Arabia (NHM 1978.2.2.115)

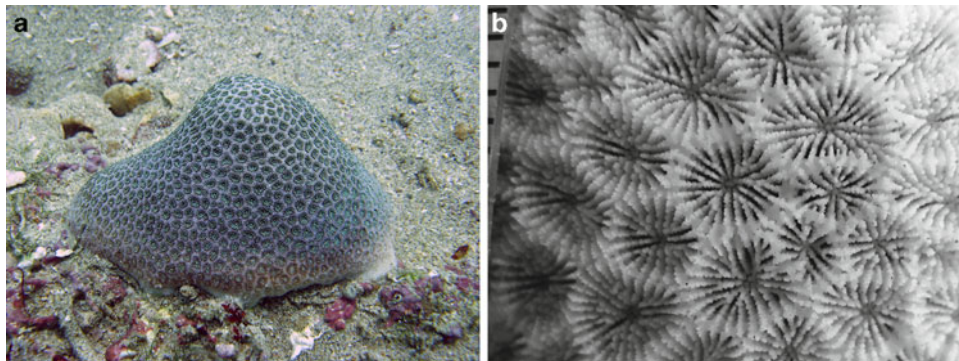


Fig. 11.28 *Anomastreaa irregularis*: (a) massive colony from Kish Island, Iran; (b, c) close up of the corallites in the same specimen

Veron and Pichon 1980), compact septa and solid corallite wall, while in *Anomastreaa* the columella is papillose, made of processes departing from the septa and sitting deep in the fossa, and septa and corallite wall are perforated. Overall, the pattern of fusion of septa is more irregular in *Anomastreaa* and the corallite outline can be more elongate. Finally, in *Anomastreaa* budding is intratentacular, in *Pseudosiderastrea* extratentacular. The two taxa have been confused, also with other genera formerly included in the Siderastreidae (Sheppard and Sheppard 1991; Veron 2000). A study of the specimens of both genera deposited at the Natural History

Museum (London) including the material depicted in Sheppard and Sheppard (1991) and a collection from South Africa (type locality for *Anomastreaa*) revealed that *Anomastreaa* has been extensively collected in the Gulf, but not *Pseudosiderastrea*. To date, no substantiated record of *Pseudosiderastrea* in the Gulf is known.

Family Agariciidae Gray 1847

Genus *Pavona* Lamarck 1801

Generic synonymy

Madrepora Forskål 1775

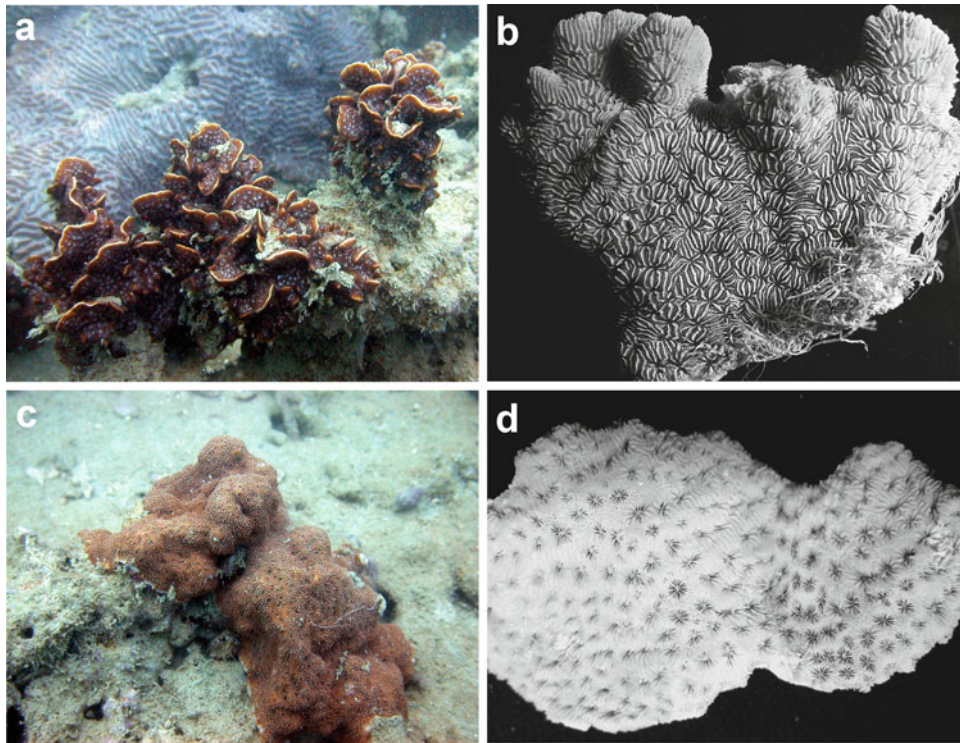


Fig. 11.29 *Pavona decussata*: (a) at Qaro, Kuwait; (b) from Ras Ghanada, Abu Dhabi, UAE; (c, d) *Pavona cf. explanulata* from Kubbar, Kuwait (M. Pichon. Coll)

Lophoseris Milne Edwards and Haime (1849)

Pavona Lamarck 1801

Generally uncommon in the Gulf but easily identified due to their contorted, “salad-like” appearance with bifacial fronds. Colonies are frond-like to laminar, submassive in some parts. Walls are poorly defined and septocostae well developed, making an intricate flower-like pattern in their passage among corallites. Distribution charts in Veron (2000) show more species in the Gulf than actually occur there. Sheppard and Sheppard (1991) list *Pavona cactus*, but not *P. decussata*. We here interpret specimens as *P. decussata* due to the irregular, deep-seated corallites with granulated septa.

Pavona decussata (Dana 1846)

Corallum: interconnecting and contorted, bifacial, relatively thick (0.5–1 cm) upright plates originating from an encrusting, sub-massive, or even massive center. Fronds have no lobed horizontal margins.

Corallites: thamnasterioid, 2–3 mm diameter, often highly irregular in size, Cerioid, often in short to medium-long series, including up to ten corallites; corallites generally deep with septa descending relatively abruptly towards the center. Between 3 and 7 mm in diameter, but highly variable.

Septa: two alternating orders, first order always reach the calyx center and fuse with the columella, second order usually

shorter and do not always reach columella, second order septa may split between calices. Septal sides of first order with regular, strong granulations and serrated upper margins, second order usually smooth. Septocostae well developed.

Columella: mostly present, usually developed as a vertical boss or plate.

Color: brown to beige, the typically white tentacles can be extended during the day.

Distribution: Common in western Gulf (Kuwait, Carpenter et al. 1997) and throughout northern Gulf but rare in eastern Gulf (UAE) (Fig. 11.29).

Pavona cf. explanulata (Lamarck 1816)

Pavona explanulata seems to be a very variable species currently recorded throughout the Indo-Pacific from the Red Sea to French Polynesia. The examined material from the Gulf seems to have intermediate morphology between *P. explanulata* (*sensu* Veron and Pichon 1980) and the holotype of *Pavona diffluens* (MNHN 18) in the National Museum of Natural History in Paris (MNHN). The holotype of *P. explanulata* could not be located at the MNHN, and, hence, the identification of the Gulf material remains uncertain.

Corallum: flat, encrusting colonies following the substratum shape.

Corallites: circular in outline, thamnasterioid, 3–7 mm diameter but highly variable. Corallites tend to be arranged in rows parallel to the corallum margin.

Septa: two alternating orders, first order often thicker and more exsert and always reaching the columella, second order usually shorter and not reaching columella. Septocostae well developed and alternating.

Columella: present and well developed as a solid vertical boss.

Color: brown to beige, with a typical white pattern

Distribution: rare, recorded from Kuwait.

Family Poritidae Gray, 1842

Genus *Porites* Link, 1807

Generic synonymy

Porites Link, 1807;

Neoporites Duchassaing and Michelotti, 1860

Cosmoporites Duchassaing and Michelotti, 1860

Napopora Quelch, 1886

Synaraea Forskal 1775

Porites is one of the most important genera on Indo-Pacific coral reefs and has been an important reef-builder since its emergence in the Eocene. Closely-related poritids have been building reefs since the Cretaceous. The growth form is typically massive, although in the Gulf two species with nodular to branching morphology are found. One of them, *Porites harrisoni*, is a characteristic and common species of most Gulf environments. This genus is characterized by the distinct pattern of septal arrangement: a short directive dorsal septum is opposite a ventral triplet, formed by the ventral directive and two adjacent septa. The arrangement and fusion pattern of this ventral triplet is an important species-specific character. Thecae and septa are reduced into arrangements of vertical spines with trabecular linkages, thus it can be very difficult to impossible to identify species from thin-sections. For unequivocal identification usually well-preserved colony surfaces are needed. The reduction in skeleton also causes high morphological variability, since patterns of septal fusion are easily modified. Thus, characteristics given in the following refer to what is typically seen in the majority of corallites, but much variability exists. Typically, several regions of the corallum have to be investigated.

Porites lobata Dana 1846

Corallum: in the Gulf, massive to (sub) columnar with clear lobes on large colonies (hence the name). Most colonies develop more or well developed columns or lobed protuberances. Generally rare, observed and collected in the UAE.

Corallites: mostly round to polygonal where crowded, deeper, with better developed walls than in the other local *Porites* species.

Septa: Despite remarkable corallum variability, septal patterns are stable and Gulf specimens are remarkably similar to

specimens from the eastern Pacific (Glynn et al. 2007). A fairly large dorsal directive septum ranges in size from ½ the length of the lateral pairs to the same length. Ventral triplet is characteristically free. Rarely is one of the lateral septa in the triplet fused to the ventral directive septum. Never full, trident-shaped fusion. The ventral directive septum is frequently shorter than the two attendant lateral septa in the triplet. Four complete lateral pairs of septa that are fused at their tips. A distinct, strongly ornamented, palus is found at the point of fusion of the lateral septal pairs and usually also on the directive septa, however, frequently not all septa of the ventral triplet are in possession of a palus. Also one ornamented spicule in the middle of the septum. Lateral dentation usually present but of variable prominence. Well-developed palar ring.

Columella: always present and well-developed, oval, compressed in the direction of the directive septa (i.e. the broad side facing the lateral. Usually strong trabecular linkage to the palar ring.

Thecae: well-developed and acute, with between three and one row of ornamented, large spines. On wide thecae (when corallites are not crowded) the two lateral rows of spines are low, leaving the central row to be prominent and vertically oriented. Spines have a tendency to fuse in their distal parts and thus form an acute ridge.

Distribution: collected in SE Gulf (Dubai, locality lost due to coastal reclamation), but ranging widely throughout the Gulf.

Porites lutea Milne Edwards & Haime, 1860

Corallum: in the Gulf, encrusting to massive to, in rare instances, (sub) columnar. Never forms clear lobes like *P. lobata*.

Corallites: diameter ~ 1 mm, mostly round to polygonal where crowded, fairly shallow, with septa clearly visible; distance between adjacent corallites < 1 corallite diameter.

Septa: Ventral triplet is characteristically fused in a “trident shape” (Veron and Pichon 1982); 5 large pali at the ends of septa and triplet (which usually has only a single palus, if more than one are present, the palus on the middle directive septum tends to be the largest). Pali fused to columella by synapticalae (radii) and a lower synaptical ring (palar ring) is complete while the outer synaptical ring is incomplete. Septa often bifurcate or become wedge-shaped between the outer synaptical ring and the theca. Only one denticle on the septa.

Columella: small, but mostly present. Absent in some corallites.

Thecae: Thin, with a row of spicules on thecal upper edge. Where theca is wide, it takes a spongy appearance.

Distribution: common in most habitats throughout the Gulf.

Porites cf. nodifera Klunzinger, 1879

Corallum: columnar, usually chocolate to light brown in color. Columns thicker and smoother than in *P. harrisoni*.

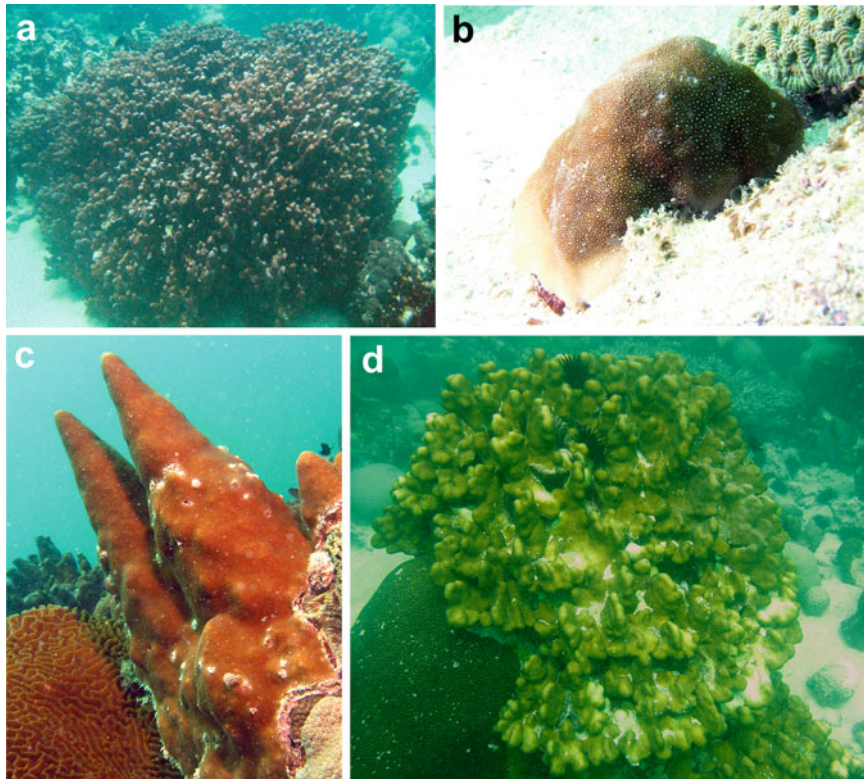


Fig. 11.30 (a) *Porites harrisoni*, (b) *Porites lutea*, (c) *Porites cf. nodifera*, (d) *Porites lobata* (All from Ras Ghanada, Abu Dhabi)

Corallites: diameter ~1–1.15 mm, mostly polygonal and crowded, deeper than in *P. harrisoni*; distance between adjacent corallites usually much less than 1 corallite diameter. Frequent immature corallites visible.

Septa: Ventral triplet is characteristically unfused. The other septa are mostly of a similar size. Up to eight large pali at the ends of septa and on each septum of the triplet. Lateral septa usually fused just before the palus to form a couplet, but sometimes remain free. Lower synapticular ring (palar ring) is usually complete. Typically none, or only very low denticles on the septa. *P. harrisoni* has one to two tall denticles.

Columella: small, styliform, not always present.

Thecae: Thin, with a row of spicules on thecal upper edge.

Distribution: rare, occurs only in good coral habitats (offshore islands, exposed coasts) (Fig. 11.30).

Porites harrisoni Veron, 2002

Corallum: the most obvious and most commonly encountered *Porites* in the Gulf. Nodular, columnar to branching, usually chocolate to light brown in color. Only similar *Porites* in the area is *P. nodifera* that makes much thicker columns and is rare.

Corallites: diameter ~1–1.15mm, mostly polygonal and crowded, fairly shallow, with small septa that are not very obvious to the naked eye; distance between adjacent corallites

usually much less than 1 corallite diameter. Frequent immature corallites visible.

Septa: Ventral triplet is characteristically unfused, although in some cases it can be fused by a synapticular rod. The other septa are mostly of a similar size. Up to eight large pali at the ends of septa and on each septum of the triplet. If triplet is fused, only one palus may be present. Lateral septa usually free, but in some instances fused at the palus to form a couplet. Lower synapticular ring (palar ring) is usually complete while the outer synapticular ring is incomplete. Typically one, sometimes two, denticles on the septa. Septa linked to columella by synapticulae.

Columella: small, styliform, not always present.

Thecae: Thin, with a row of spicules on thecal upper edge. Where theca is wide, it takes a spongy appearance.

Distribution: common in most habitats throughout the Gulf. One of the most common corals (Figs. 11.31 and 11.32).

Genus *Goniopora* de Blainville, 1830

Generic synonymy

Goniopora de Blainville, 1830; *Litharaea* Edwards and Haime, 1850.

Rhodaraea Edwards and Haime, 1849; Quelch (1886).

Trichopora Quelch, 1886.

Goniopora is a close relative to *Porites* and is easily recognized by its long, fleshy polyps that are usually extended during the

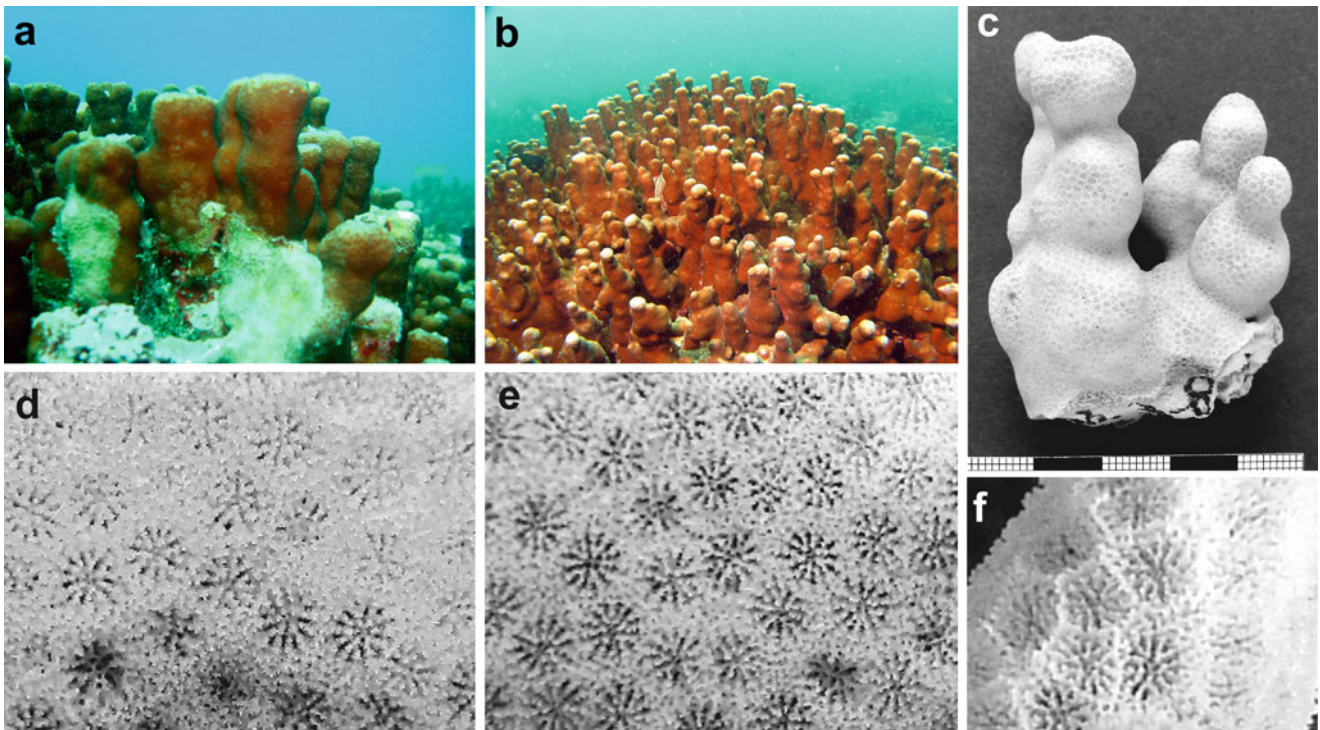


Fig. 11.31 Overall aspect and details of *Porites harrisoni* (a–f, All from Abu Dhabi)

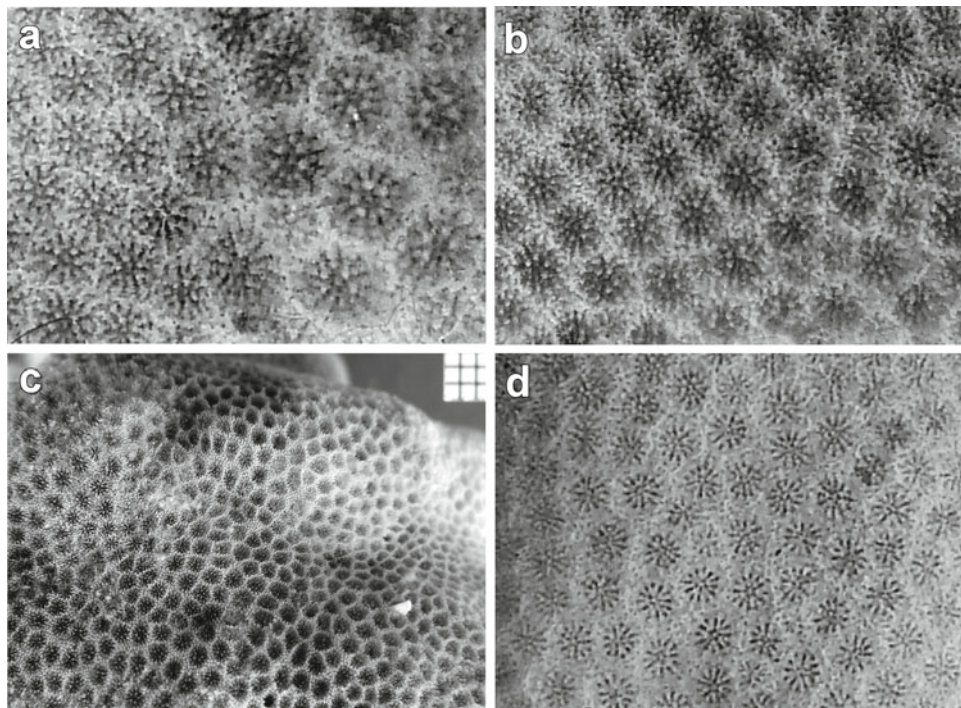


Fig. 11.32 Close-ups of skeletal structures of (a) *Porites lutea*, (b, c) *Porites lobata*, (d) *Porites harrisoni* (All from Jebel Ali, Dubai)

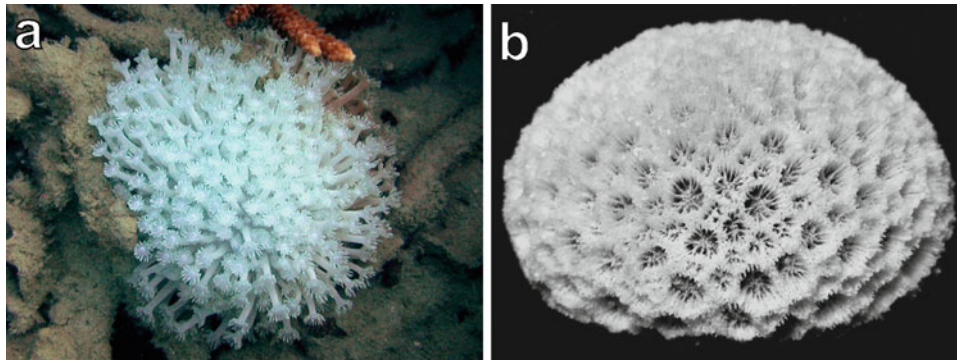


Fig. 11.33 (a) Bleached colony of *Goniopora lobata* at Umm Al Maradem Kuwait and (b) picture of a free living specimen (M. Pichon coll.) from Kuwait

day. It has the biggest corallites in the poritid family and a distinct septal pattern. Septa are basically in three orders, but these are not always discernible (Veron and Pichon 1982). Septal fusion does not follow a fixed pattern as in the genus *Porites*. Only a single species has been recorded in the Gulf (Kuwait, Carpenter et al. 1997). More species seem to exist in Iran, however requiring detailed study and proper identification.

***Goniopora lobata* Edwards and Haime, 1860**

Corallum: columnar, extended polyps usually yellow or light brown in color. Polyps large (several cm when extended).

Corallites: either rounded or polygonal, shallow, usually 2.5–4 mm in diameter.

Septa: 18–24 septa, irregularly developed but mostly three size classes, gonioporoid pattern of fusion generally well-developed. First order septa may bear large spines that may appear like pali; all septa with spines of variable development; septal sides granulated, only the two largest septal cycles fused to columella. Third cycle can be abortive and only developed as a ridge along the theca.

Columella: consists of fused trabeculae and synapticulae.

Thecae: Porous, 1–2 mm thick.

Color: brown to beige.

Distribution: apparently rare. Only recorded from Kuwait (Carpenter et al. 1997) where it can locally form small monospecific stands and Iran (Fig. 11.33).

Goniopora planulata (Ehrenberg 1834) is reported from Iranian Islands in the Straits of Hormuz but no collected material was available for review.

Family Siderastreidae Vaughan and Wells 1943

Until recently this family included besides the type genus *Siderastrea*, the genera *Coscinaraea*, *Anomastraea* (both found in the Gulf), *Horastrea*, *Psammocora*, and *Pseudosiderastrea*. However, molecular phylogenies have shown that *Siderastrea* and *Pseudosiderastrea* are not closely related to the others (Fukami et al. 2008). The genus *Siderastrea* is present and common in the Gulf while

previous records of *Pseudosiderastrea* actually refer to *Anomastraea* (see previous discussion). *Siderastrea* is one of the few genera found in the Atlantic as well as in the Indo-Pacific.

Genus *Siderastrea* Blainville 1830

Generic synonymy

Madrepora (pars.) Pallas 1766

Astrea (pars) Lamarck 1801

Siderastrea Blainville 1830

Siderina Dana 1846

***Siderastrea savigniana* Milne Edwards and Haime, 1850**

This species seems to be one the most resistant scleractinian coral species to the extreme environmental conditions in the Gulf (Sheppard et al. 1992).

Corallum: flat encrusting colonies, often partially buried in sediment, to massive. It can form free-living colonies on rubble beds in shallow water (1–3 m).

Corallites: cerioid, between 4 and 5 mm in diameter, polygonal in outline and never arranged in series.

Septa: numerous (around 40) and typically fusing, they are ornamented on the upper edge. Generally 6 septa reach the columella without fusing with other septa. All septa are connected by one row of synapticulae regularly occurring between the corallite wall and the fusion of septa. Septa compact.

Columella: present and styliform.

Color: walls are typically white and polyp colour varies between brown and green.

Distribution: common in reef and sandy habitats but also found in algal beds. It can be locally abundant (Fig. 11.34).

Family Mussidae Ortmann, 1890

Genus *Acanthastrea* Milne-Edwards and Haime 1848

Generic synonymy

Acanthastrea Edwards and Haime (1848c); Vaughan and Wells (1943), Wells (1956); Chevalier (1975); Veron and Pichon (1980);

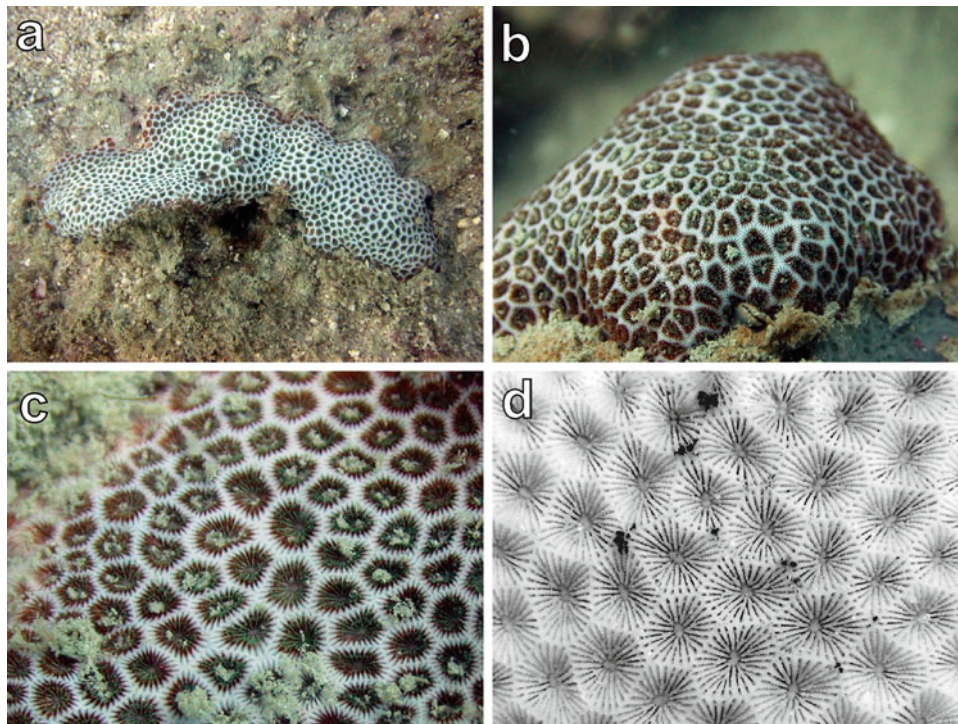


Fig. 11.34 *Siderastraea savignyana* from Qaro (a) and Kubbar (b, c) Kuwait. A close up of the corallites in a specimen from Kuwait (M. Pichon coll.) (d) skeleton from Jebel Ali, Dubai

Usually submassive to massive corals with monocentric, ploicoid to cerioid corallites and thick, fleshy polyps of usually several colors. *Acanthastrea echinata* can superficially resemble *Favites*, were it not for the different septal dentations and columella. *A. maxima* is unique and cannot be confused with any other species.

Acanthastrea echinata (Dana 1846)

Corallum: encrusting or massive.

Corallites: Cerioid, round to oval, diameter ~10 mm often more, intratentacular budding.

Septa: one order only, but number varies with the size of corallites; almost all septa reach the columella, some fuse on their inner margins; septa are regularly spaced, upper edges with long irregular and echinulate dentations. Septocostae well-developed, those of neighboring corallites join together.

Columella: well-developed, consists of twisted septal dentations.

Color: brown to green.

Distribution: uncommon but widely distributed throughout the entire Gulf.

Acanthastrea maxima Sheppard and Salm 1988

Corallum: submassive to massive.

Corallites: Cerioid, round to oval, diameter ~10 mm often more, intratentacular budding, but at the periphery of corallites, so as to appear almost extratentacular (Sheppard and

Salm 1988); corallites always monocentric; diameter up to 50 mm, depth up to 10 mm (largest corallites of any coral in the Gulf).

Septa: at least three orders, first order reach columella, second order to about ½ radius, third order thin ridges or abortive; large calices with up to 80 septa, upper septal margins with large dentations, only weakly exsert (1–3 mm).

Columella: well-developed, consists of twisted septal dentations.

Thecae: well developed with thick, vesicular endotheca. A ridge runs along the top.

Color: brown to green.

Distribution: uncommon but apparently widely distributed throughout the entire Gulf. Recorded from Oman (type locality), Iran and Kuwait (Carpenter et al. 1997) (Fig. 11.35).

Family Dendrophylliidae Gray, 1847

Genus *Turbinaria* Oken 1815

Generic synonymy

Turbinaria Oken 1815; (pars) Ehrenberg (1834); Edwards and Haime (1851), Bernard (1896); Veron and Pichon (1980); Sheppard and Sheppard (1991); Veron (2000);

Explanaria Lamarck 1816 (pars); (pars) Schweigger (1820); (pars) Ehrenberg (1832).

Gemmipora de Blainville 1830; Dana (1846).

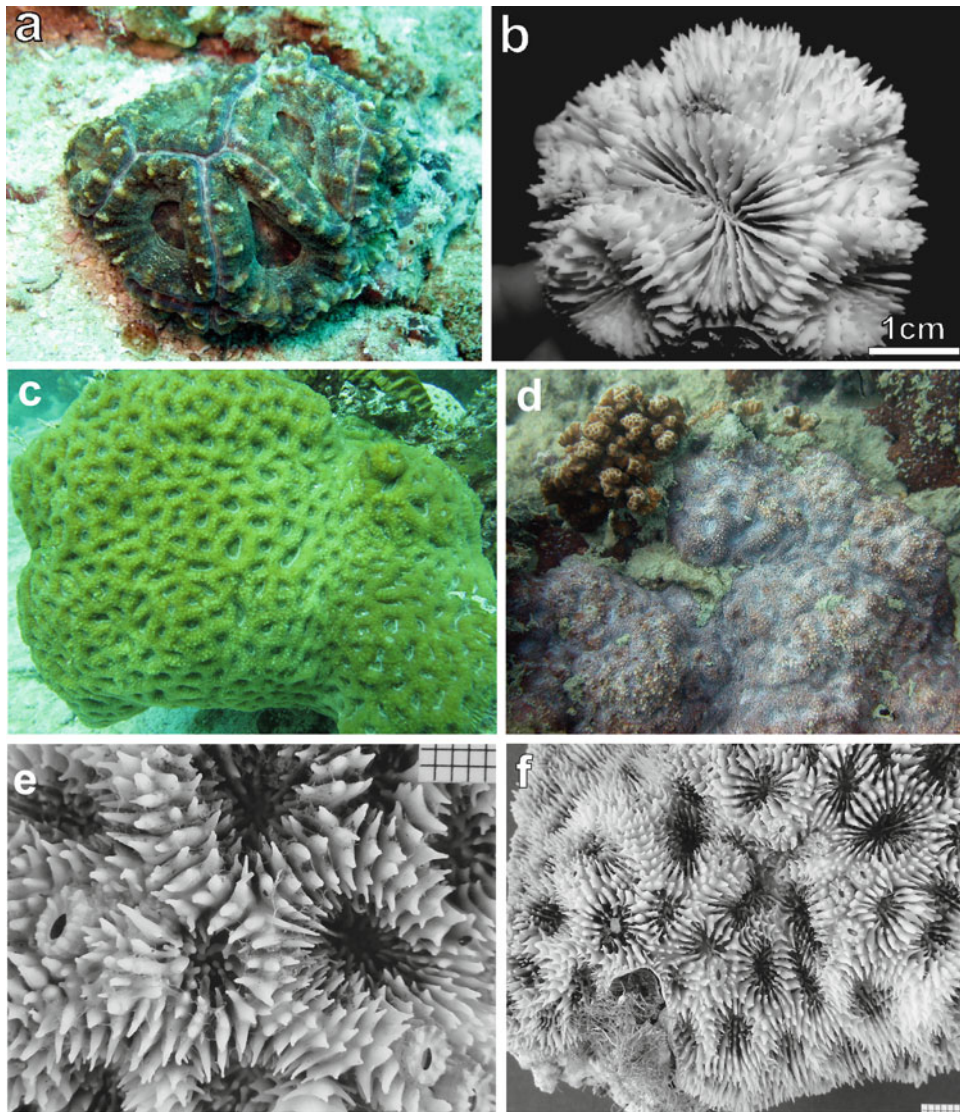


Fig. 11.35 (a, b) *Acanthastrea maxima*, (c–f) *Acanthastrea echinata* (a, from Abu Dhabi, b from Qaro, Kuwait, c–f from Jebel Ali, Dubai)

Small to large basically foliaceous colonies of irregular shape in shallow water, or small mushroom-shaped colonies in deep water. Clearly visible, large corallites that are united by an extensive coenosteum. Septa and columella usually well visible.

***Turbinaria peltata* (Esper 1794)**

Corallum: small, mushroom-shaped colonies. Large vasiform colonies can be formed, but this has not been reported from the Gulf. Soft tissues are usually brown with the oral disk white or gray, giving a striking color contrast. Polyps usually open during the day.

Corallites: Well spaced, regular, circular, little inclined, diameter 3–5 mm.

Septa: three orders, first two orders very similar, projecting inwards for about half corallite radius, third cycle reduced, sometimes absent, septal sides granulated.

Columella: well-developed, consists of twisted septal dentations.

Thecae: well developed, spongy.

Color: typically brown to beige with paler polyps.

Distribution: rare in shallow water <15 m, but a characteristic, albeit uncommon coral in deeper water.

***Turbinaria reniformis* Bernard 1896**

Corallum: large, irregularly foliate colonies, that can form sheets in several layers; usually light brown to yellowish in color.

Corallites: more crowded, smaller and irregular than in *T. peltata*; sometimes arranged in irregular rows.

Septa: 12–20, number variable, mostly in a single order without much differentiation. Finely dentate margins and heavily granulated sides.

Columella: barely visible deep inside the calice and often not present at all, consists of vertical elements.

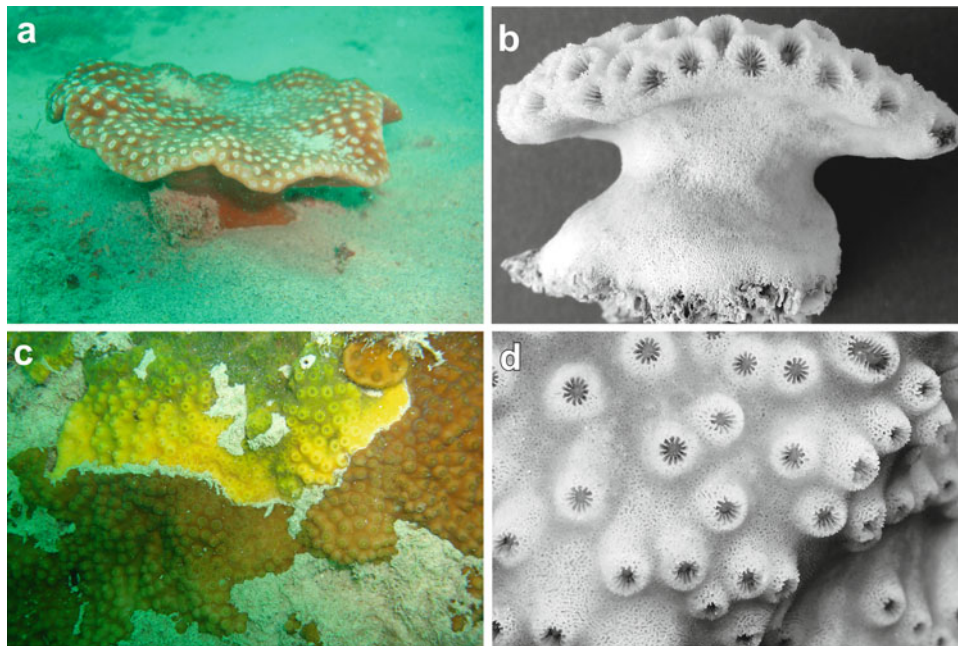


Fig. 11.36 *Turbinaria peltata* (a) (from Umm al Arshan, Qatar), (c, d) *Turbinaria reniformis* with yellow-band disease in (c) (from Ras Ghanada, Abu Dhabi, UAE), (b, d from Jebel Ali, Dubai)

Thecae: well developed, spongy.

Color: typically light brown to orange

Distribution: common in all shallow habitats. Color and gross morphology make it distinct and easy to identify (Fig. 11.36).

Family Fungiidae Dana, 1846

Genus *Cycloseris* Milne Edwards & Haime, 1849

Cycloseris curvata (Hoeksema, 1989)

Corallum: Solitary and free-living, the immature coralla regularly discoidal, but later folded. Coralla relatively thick, small ones relatively flat while they become highly arched when larger. Diameter varies between 1.5 and 8.5 cm.

Corallites:

Septa: Densely packed, straight except where they fuse at the corallum margin. Unequal in thickness and height. The margins are ornamented with fine, sharp dentations which become indistinct on the thickened lower order septa.

Costae: Almost equal in size; distinct at the corallum margins. Ornamented with small and acute, granular spines.

Columella: formed by mingled mass of loosely packed, partly fused trabeculae and paliform lobes with the tips pointing in various directions.

Thecae: Solid wall is not granulated and may still show a detachment scar at the aboral side of small specimens.

Distribution: Uncommon, so far recorded in Kuwait and from Hendorabi, Farur, Abu Musa islands, Iran; found at depth of about 18–25 m on sand.

Remark. Previously *C. cyclolites* has been reported by Burchard (1979) from Saudi Arabia. However, Hoeksema (1989) designates *C. curvata* nom. nov. for a species which includes the Gulf specimen (Fig. 11.37).

Family Dendrophyllidae Gray, 1847

Genus *Tubastrea* Lesson, 1829

Tubastrea aurea (Quoy and Gaimard, 1833)

Corallites: corallites rise from basal cushion, without any budding, orange-red; and corallites can reach 1.5 cm height and 10 mm width.

Distribution: Common at least throughout the northern Gulf in shaded habitats (Fig. 11.38)

Figure Credits and Acknowledgements All specimens figured in this chapter were collected (coll.) and photographed by the authors unless indicated so in the figure legends. For fieldwork which allowed *in situ* images from the U.A.E. R. Al-Mubarak, A. Al-Cibahy, Emirates Wildlife Society and the Environment Agency-Abu Dhabi are acknowledged. Some of the images are a result of the WWF/Dolphin Energy coral project. For fieldwork in Halul Island, Qatar we are grateful to E. Dutrieux (Creocean), Dr. A. Abdel-Moati and the Supreme Council of Environment & Natural Reserves (SCENR). For research in Kuwait S. Sartoretto (Safege) and the Kuwait Institute for Scientific Research (KISR) are thanked. The image from Bir Ali, Yemen, was taken during the Coral Biodiversity study for which C.H. Chaineau (Total EP) and E. Dutrieux (Creocean), and the Yemen Environment Protection Authority (EPA) are acknowledged. Images and sample of *Madracis*

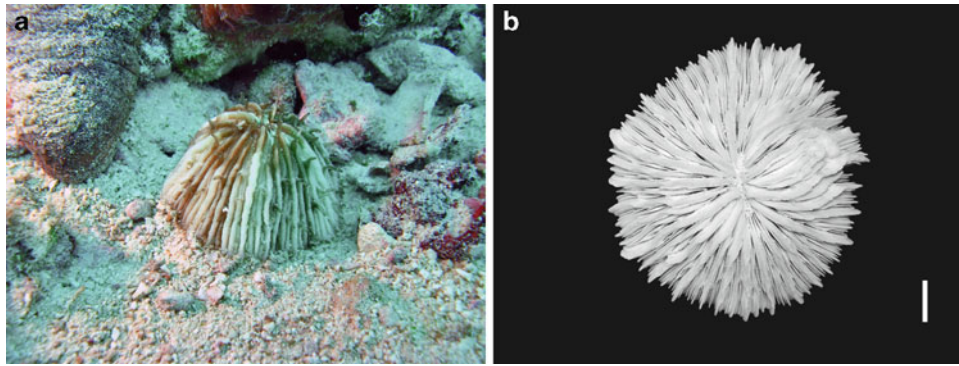


Fig. 11.37 (a) *Cycloseris curvata* from Abu Musa Island, Iran; (b) a close up image of another *C. curvata* sample from Farur Island, scale bar=1 cm

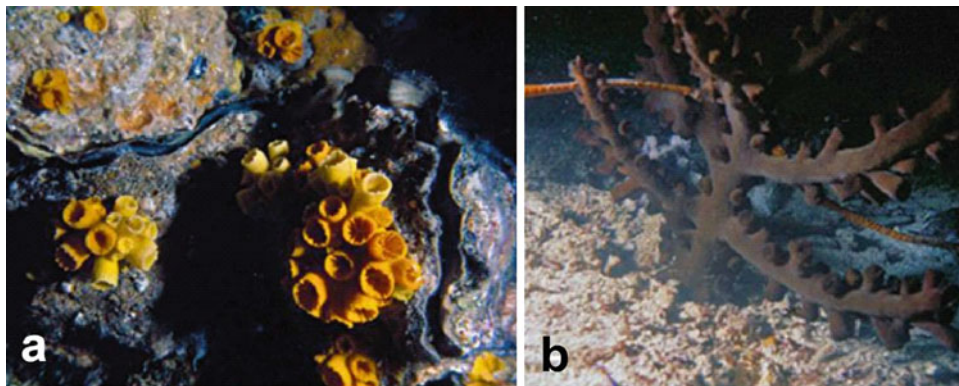


Fig. 11.38 (a) *Tubastraea aurea* from Farur Island, Iran; (b) a *Dendrophyllia* species from Farur Island, Iran

kirby from Mayotte Island were collected during the Tara Oceans expedition, E Karsenti (EMBL) and the Oceans Consortium are acknowledged. Specimens collected in Kuwait by M. Pichon (Museum of Tropical Queensland) and depicted in this review are currently deposited at the University of Milan-Bicocca. W.E. Piller at Karl-Franzens University Graz took pictures of skeletons and has been curating a collection of Gulf corals from Jebel Ali.

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12.1 Introduction

Approximately 3,000 species of Octocorallia are distributed worldwide (Williams and Cairns 2005; Daly et al. 2007). New species, even genera and families, continue to be described especially from the deep-sea environment and the Indo-Pacific. A total number of 46 octocoral families (van Ofwegen and McFadden 2010) are described of which 29 (excluding sea pens) are in the order Alcyonacea; and 23 of them are found in the warm, shallow waters of the Red Sea, Indian, and Pacific Ocean. The subclass octocorallia (Alcyonaria) has three major orders: Helioporacea (blue coral), Alcyonacea (soft corals and gorgonians) and Pennatulacea (sea pens), only the two latter have been recorded in the Persian Gulf (Samimi-Namin and van Ofwegen 2009a).

Octocorals are sessile, mostly colonial Anthozoa with polyps containing eight pinnate tentacles and skeleton consisting of numerous microscopic structures made of calcium carbonate called sclerites. The sclerites are produced by cells in the mesogloea, the so-called scleroblasts. The sclerites remain in the mesogloea, and are incorporated in the connective tissue grid. In this respect these sclerites are not different from the internal skeletal elements of other animals. Many taxa also have an axis of horn-like substance called gorgonin, often more or less calcified.

K. Samimi-Namin (✉)
Netherlands Centre for Biodiversity Naturalis,
P.O. Box 9517, 2300 RA Leiden, The Netherlands
e-mail: kaveh_s_n@yahoo.com; kaveh.samimi@ncbnaturalis.nl

L. van Ofwegen
Netherlands Centre for Biodiversity Naturalis,
P.O. Box 9517, 2300 RA Leiden, The Netherlands
e-mail: Leen.vanOfwegen@ncbnaturalis.nl

12.1.1 Morphological Characteristics

The polyp is the individual zooid in octocorals and it is a tubular structure with a mouth opening with tentacles at one end. The polyps are responsible for all the vital functions of the colony such as growth, food capture, nutrient transportation, water circulation, defence and reproduction. Most of the species have only one type of polyp, the autozooid, and are therefore called monomorphic. Few alcyonacean species have a second type of polyp, the siphonozooid, and are hence called dimorphic. The latter polyp type has one rudimentary tentacle or none at all and its primary function is to circulate sea water into the colony to support hydroskeleton system. Usually, the term polyp refers to the autozooids, the sexual individuals.

The lower part of the polyp is embedded in gelatinous material, the coenenchyme. Part of the polyp that is able to contract extends above the colony surface (anthocodia) and has a central mouth opening surrounded by eight tentacles. Tentacles have finger-like extensions along each side (the pinnules) which enhance the surface area of the polyp (Fig. 12.1). The number of pinnules per row, and the number of rows on each side of the tentacle, varies between species. Only one genus has been described as having no pinnules, *Acrossota* Bourne, 1914 (Alderslade and McFadden 2007). Tentacles are contractile and contain sensory cells and stinging capsules; in some zooxanthellate genera like *Sinularia* and *Sarcophyton* they are filled with symbiotic algae. The polyp mouth extends into a gastrovascular cavity through a tubular pharynx. The gastrovascular cavity has eight radially arranged protruding tissue plates (mesenteries) which have an important function in the polyp hydraulic system, contain digestive gland cells and in most genera, produce the gonads.

12.1.2 Biology and Ecology

The reproductive structures in most octocorals separate colonies into male and female; however, some species are hermaphroditic. Octocorals have two reproductive

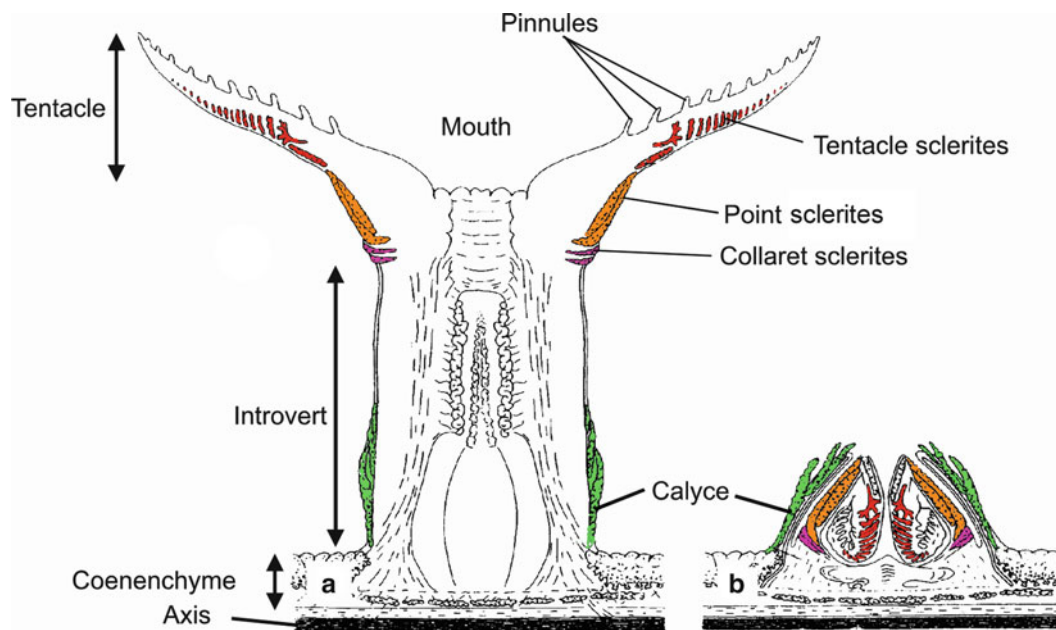


Fig. 12.1 Typical polyp structure. (a) An extended polyp. (b) A retracted polyp, showing the position of different sclerites (Modified from Grasshoff and Bargibant 2001, by permission of IRD)

strategies: sexual reproduction and asexual propagation. Three types of sexual reproduction occur: (1) broadcasting of eggs and sperm (the release of large numbers of eggs and sperm into the water where fertilisation takes place); (2) internal brooding of larvae (sperm but not the eggs, are released into the water, fertilisation takes place within the females); (3) external brooding of larvae (fertilised eggs remain attached to the mother colony and develop to larvae in mucus pouches on the surface of the colony) (Fabricius and Alderslade 2001). The result of fertilization is a planula larva which settles on the appropriate substrate type and then metamorphoses to a founder polyp starting a new colony by budding. Asexual propagation is common in soft corals and is achieved by stolons, colony fragmentation, fission or budding (Fig. 12.2). The physical fragmentation of the branches is another way to propagate in some gorgonians.

The colony growth depends on the environmental conditions and ecological setting. Most of the octocorals are suspension feeders, therefore, growth and feeding is related to current flow. They can take small organic particles (<20 mm), or capture larger particles such as zooplanktons and larvae when intercepted by the tentacles. As the nematocysts (stinging capsules) are simple, the food is restricted to small and weakly swimming plankton.

Octocorals are usually abundant components of shallow-water, rocky wall and coral reef environments of the world. They are a widespread group, occurring from the littoral down to the deep-sea abyss and from the Arctic to the Antarctic oceans (Fabricius and Alderslade 2001). Their zonation and densities are depending on different physical

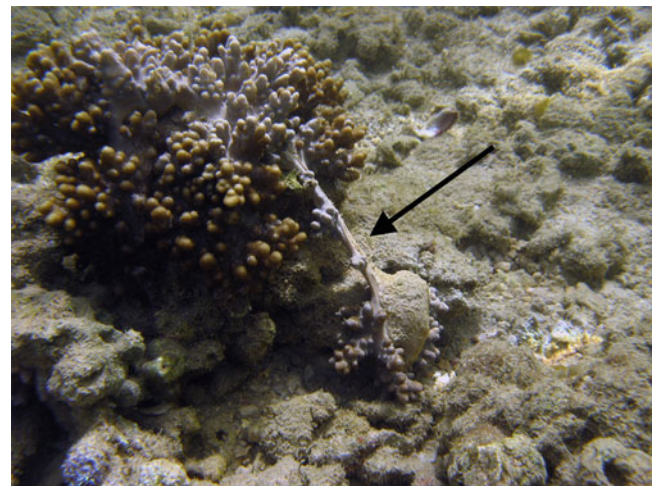


Fig. 12.2 Asexual reproduction in *Sinularia* species at north of Larak Island in the Strait of Hormuz

environmental parameters such as light, sedimentation, depth, wave exposure and especially water motion, though the impact of these conditions varies between species (Fabricius and Déath 1997). While all these gradients are related, it is difficult to discern which of them is most important in controlling the abundance and distribution of species. Studies have demonstrated that the octocorals are distributed along a wide depth gradient, and that water currents and wave action are the more influential factors determining their abundance, diversity and distribution. Even though octocorals are susceptible to abrasion, dislodgement and other kinds

of damage produced by strong swell and strong currents, many species of gorgonians are well adapted to these conditions and can be the most abundant faunal component on steep to vertical rocky walls.

Octocorals often host a conspicuous and important fauna, including sponges, molluscs, polychaetes, echinoderms and fish (Reijnen et al. 2011). Furthermore, they are significant sources of natural products of real or potential importance in biomedical research, pharmacology and cancer therapy (i.e. prostaglandins, inflammatory and antitumor activity, antibacterial and secondary metabolites) (Sammarco and Coll 1996; Fabricius and Alderslade 2001). Research in the Great Barrier Reef suggests that octocorals are suitable indicators of environmental degradation because the abundance of species is determined by the physical environment and the water quality (Cooper et al. 2009); many are long-lasting when environmental conditions do not change; they have low levels of predation; they do not show seasonality. Octocorals have also been used as bio-indicators of environmental changes (Sherwood et al. 2005).

12.1.3 Collection and Identification

Formalin is not recommended for storage purposes as with time it will dissolve sclerites and eventually destroy them completely. Preferred preservation medium is ethanol, which can be used diluted 70%, or pure for molecular studies. Octocoral identification is not easy, as many species or even genera have identical colony shapes. Therefore, unequivocal identification of species under water is often not possible. However, most genera or in some cases species can be recognized under water after some years of training, especially in the Gulf where the diversity is much lower than in the Indian Ocean. Specimens need to be collected for investigating the sclerites in the lab using light microscopy and Scanning Electron Microscopy. Underwater photos of the same colony are helpful for identification or gaining knowledge about the species (For more details see Fabricius and Alderslade 2001).

Often older literature provides little information about shape and detailed structures of sclerites. Therefore, most genera are in need of revision, and many species need to be re-described. Also, often old type material is not available or lost. Therefore, identification to species level is impossible in many cases.

12.1.4 Note on the Ongoing Changes in Octocorallia Taxonomy

Molecular phylogenetic studies support the monophyly of Octocorallia, and a sister relationship to Hexacorallia, although the ordinal and subordinal relationships within the

clade are not established yet (McFadden et al. 2010). Molecular reconstruction of phylogenetic relationships between octocoral taxa does not support traditional taxonomy and traditional ordinal level and family level taxonomy seems not to reflect phylogeny; however, the characters currently used for taxonomy (skeletal features and gross morphology) are evolutionarily reliable (McFadden et al. 2010). The root of Octocorallia phylogeny is unclear, though few studies suggested *Erythropodium* and *Briareum* as located at or near the base (McFadden et al. 2006; Berntson et al. 2001). Knowledge of octocoral evolution improved considerably during recent years, however, we are still far from a complete understanding of their cladogenetic patterns and morphological evolution (McFadden et al. 2010). Reconciling the results of molecular phylogenies with traditional taxonomy is an ongoing process and needs to be expanded to species level (McFadden et al. 2010) as many unsolved questions remain. The next generation sequencing technologies together with development of markers offer promise for species-level studies.

12.2 Octocorals of the Gulf

Thomson and Simpson (1909) were the first to publish about octocorals from the Gulf describing a collection in the Indian Museum, Calcutta, collected by the Royal Indian Marine Survey Ship "Investigator" in the Indian Ocean (and Arabian Sea, Andaman Sea and Indo-Pacific). They reported four species occurring in the Gulf, *Solenocaulon tortuosum* (Gray, 1862), *Echinogorgia ramulosa* Gray, 1870 (an *Echinogorgia* species, but probably different from Gray's species), *Versluysia ramosa* (Thomson & Henderson, 1905), and *Parisis fruticosa* Verrill, 1864, and described one new species from the same region, *Nicella reticulata* (a species belonging to *Verrucella*). No precise localities were mentioned in the publication. Later on, Stiasny (1940) described material in the alcyonarian collection of the Museum of Natural History in Paris. Part of this material was re-examined by us. Stiasny reported two new records, *Echinogorgia macrospiculata* Thomson & Simpson, 1909, and *Junceella fragilis* Ridley, 1884, (= *Junceella juncea*, wrong identification of Stiasny) from stations close to the Strait of Hormuz. This author also described two new species from the Gulf, *Subergorgia perezii* (= *Subergorgia suberosa*) and *Echinogorgia bahrelfarsi* (according to us belonging to *Menella*). In 1979 Burchard, surveying the coral fauna of Saudi Arabia and the western Gulf, mentioned that there are several soft corals but did not record any particular species. In 1992 Sheppard et al. mentioned that absence of soft corals in the Gulf has been commonly asserted, with only some species (including *Dendronephthya*) occurring just west of Musandam while being rare and not reaching the central part

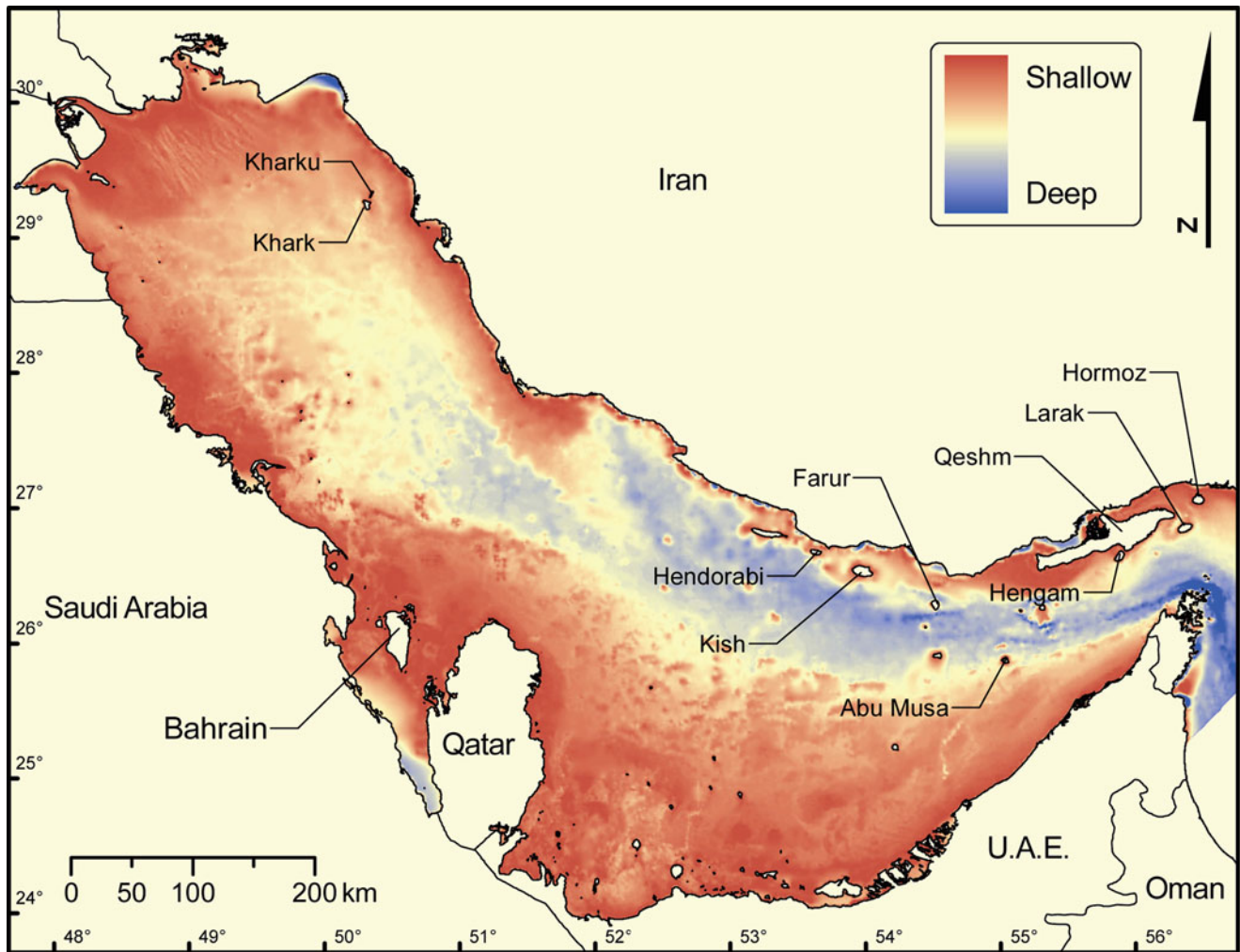


Fig. 12.3 Geographical location of the Gulf and the depth gradient. For more detailed bathymetry information, see Chaps. 2 and 3

of the Gulf. In 1995 Rezaei reported *Sarcophyton* sp. and *Dendronephthya* sp. from Larak and Lesser Tonb islands. He also reported some gorgonians around Bani Farur and Lesser Tonb Island, and some Pennatulacea around Lavan and Hendorabi Island. His material does not exist anymore. Rezaei et al. (2004) reported *Subergorgia suberosa* (Pallas, 1766) from Lesser Tonb Island. It seems that this report was based on the specimens that he collected in 1995, but he only mentioned them as gorgonians in that paper. Samimi-Namin & van Ofwegen (2009a) identified 31 different species, in 21 genera from material collected from the coast of Iran (Fig. 12.3). Adding the previous reported species, the total number of the genera in the Gulf rises to 24, and the number of species to 35. Recent studies added some more species and genera to the known Octocoral faunal knowledge (Table 12.1). Undoubtedly, the number of species and genera will increase in future as there are still locations that have

not been surveyed and even some of the collected material is still under study.

12.2.1 Distribution and Zonation

Octocorals are not limited to small areas in the Gulf, they occur along its Iranian side from the Strait of Hormuz to Khark and Kharku Islands in the western part and also have been recorded from some places in the southern Gulf. Diversity and density of octocorals in the northern part is markedly richer than the southern part of the Gulf, where only few records are available (Riegl 1999; Rezaei et al. 2004; Sheppard et al. 1992; Samimi-Namin and van Ofwegen 2009a, b). Due to the counter-clock wise pattern of water circulation in the Gulf, the northern part and the Iranian coastline have better environmental condition (lower

Table 12.1 List of Octocorallia species known from the Gulf

Order	Family	Species
Alcyonacea	Clavularidae	<i>Carijoa</i> sp.
	Alcyoniidae	<i>Sarcophyton minusculum</i> Samimi-Namin and van Ofwegen, 2009a <i>Sinularia erecta</i> Tixier-Durivault, 1945 <i>Sinularia compressa</i> Tixier-Durivault, 1945
Nephtheidae		<i>Dendronephthya</i> sp. a <i>Dendronephthya</i> sp. b <i>Umbellulifera</i> sp.
	Subergorgiidae	<i>Subergorgia suberosa</i> (Pallas, 1766)
	Briareidae	<i>Briareum</i> cf. <i>hamrum</i> (Gohar, 1948)
Anthothelidae		<i>Solenocaulon</i> spp.
Acanthogorgiidae		<i>Acanthogorgia spinosa</i> Hiles, 1899 <i>Muricella</i> sp.
	Plexauridae	<i>Astrogorgia fruticosa</i> Samimi-Namin and van Ofwegen, 2009a <i>Echinogorgia</i> sp. a <i>Echinogorgia</i> sp. b ? <i>Echinogorgia macrospiculata</i> Thomson and Simpson, 1909 <i>Echinomuricea</i> sp. a <i>Echinomuricea</i> sp. b <i>Euplexaura plana</i> Samimi-Namin & van Ofwegen, 2009 <i>Euplexaura</i> sp. a <i>Euplexaura</i> sp. b <i>Menella</i> sp. a <i>Menella</i> sp. b <i>Menella</i> sp. c <i>Menella</i> cf. <i>kanisa</i> Grasshoff, 2000 <i>Menella bahrelfarsi</i> (Stiasny, 1940) <i>Paraplexaura</i> sp. <i>Trimuricea</i> aff. <i>reticulata</i> (Thomson and Simpson, 1909)
Ellisellidae		<i>Junceella juncea</i> (Pallas, 1766) <i>Verrucella</i> cf. <i>reticulata</i> (Thomson and Simpson, 1909)
	Veretillidae	<i>Cavernularia</i> sp. <i>Veretillum</i> sp.
Pennatulacea	Virgulariidae	<i>Virgularia</i> sp.
	Pteroeididae	<i>Pteroeides</i> sp.

temperature, lower salinity, better aragonite saturation, greater depth, see Chaps. 2 and 3) which has its expression in increasing species richness towards the Straits of Hormuz. This has been seen in octocorals (Samimi-Namin and van Ofwegen 2009a) and the same trend exist for hard corals (Samimi-Namin, unpublished data). In general, octocoral diversity decreases from east to west and from north to south. The main species boundaries are not clear yet and therefore further studies are necessary to fully reveal octocoral diversity in the Gulf and adjacent seas.

Vertical zonation as expected is different in zooxanthellate and azooxanthellate species. The zooxanthellate genera like *Sinularia*, *Sarcophyton*, and *Briareum* are light dependant and therefore limited to 10–12 m depth in most of the Gulf (in few places like Abu Musa Island, where the water is very clear, they can extend deeper). Soft corals can form carpets and dense monospecific, or monogeneric, stands. For example, NW of Larak Island, several *Sinularia* species make up a stand with very high surface cover (up to 90%) at 1–2 m depth. Azooxanthellate species mostly occur below 10–12 m depth where hard substratum can be found.

12.3 Taxonomic Account

Class Anthozoa Ehrenberg, 1831

Subclass Octocorallia Haeckel, 1866

Order Alcyonacea Lamouroux, 1812

Family Clavularidae Hickson, 1894

Genus *Carijoa* Müller, 1867

***Carijoa* sp.**

Diagnosis: Tall, thin, axial polyps, which bud off lateral polyps and are united by a network of anastomosing stolons. Colonies can be up to 20 cm high, and in most cases are overgrown by encrusting sponges or ascidians (Fig. 12.4).

Habitat: Predominant in turbid and dark places, usually as fouling organisms on wrecks, oil rigs. Usually in deep waters.

Distribution: So far recorded from Iran, Kuwait. Likely to occur throughout the Gulf.

Remarks. Without thorough revision of *Carijoa* we consider it impossible to identify species of this genus.

Family Alcyoniidae Lamouroux, 1812

Genus *Sarcophyton* Lesson, 1834

Diagnosis: Colonies with noticeable stalk which supports a wider, fleshy, disk shape polyparium that can be folded or wavy around the periphery. Polyps are dimorphic, retractile. The surface layer of the polyparium and stalk have well-formed clubs; the interior contains sticks and spindles. Sclerites are colourless. Zooxanthellate. Widespread from the Red Sea to Polynesia (Fabricius and Alderslade 2001).

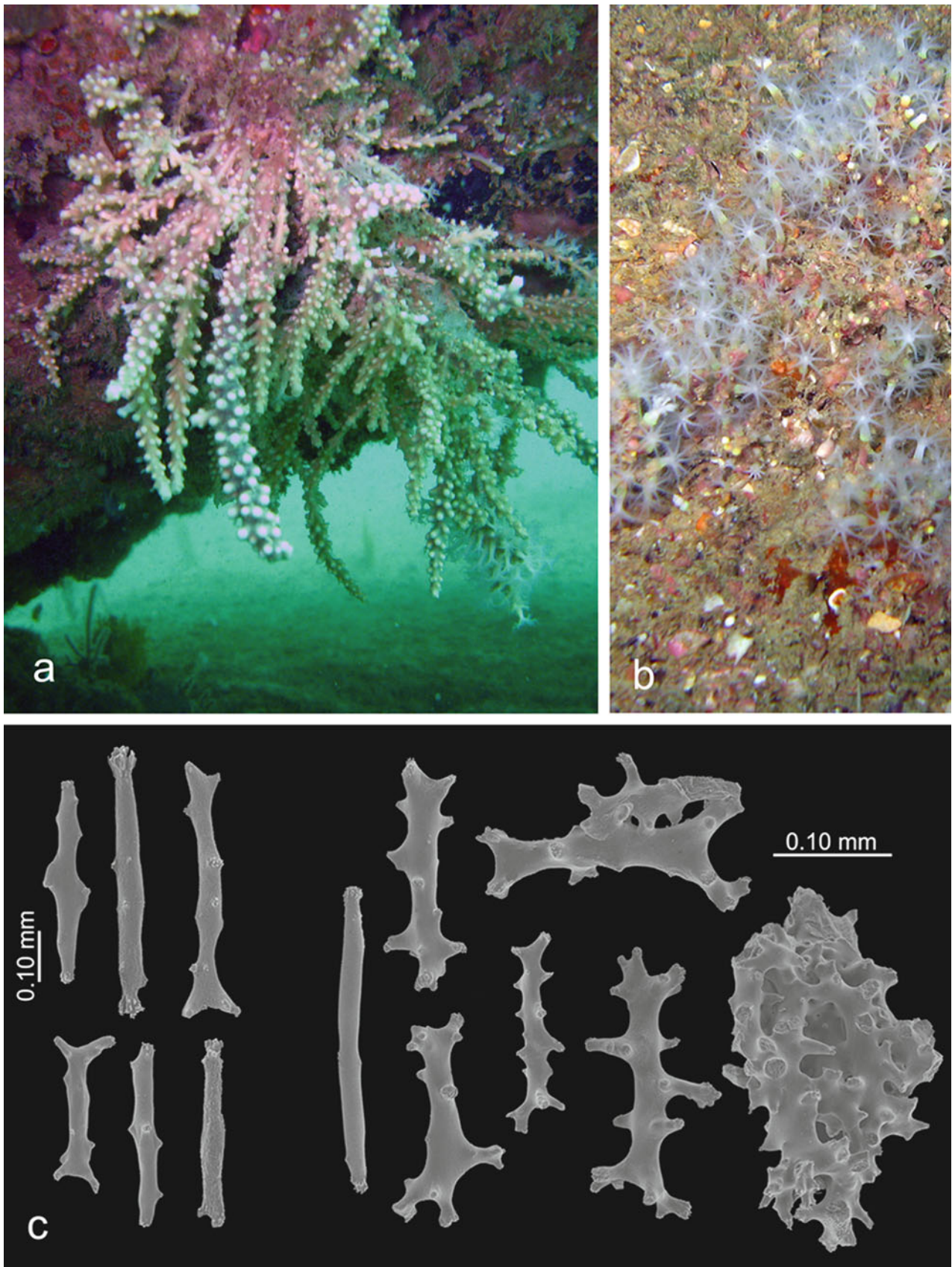


Fig. 12.4 (a) In situ image of *Carijoa* colonies from Chabahar, in the Gulf of Oman; (b) *Carijoa* colonies at Kish Island, 20 m depth, (c) SEM image of the sclerites in *Carijoa* species from Farur Island. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

***Sarcophyton minusculum* Samimi-Namin & van Ofwegen, 2009a**

Diagnosis: Live colonies are bluish to greenish, with brown polyps. Preserved they are light brown.

Sclerites: The polyps have eight points with many sclerites; these are flattened rods, up to 0.35 mm long, with a few simple tubercles. The tentacles also have many rods, similar to those of the points, but smaller in size, the largest being 0.10 mm long. Surface layer of the polyparium has many small capstans, about 0.05 mm long and clubs with poorly developed heads; these clubs are 0.07–0.25 mm long. The interior of the polyparium has slender spindles, with simple tubercles or spines; these spindles are up to 0.45 mm long. The surface layer of the stalk has capstans and clubs, similar to those of the polyparium. The capstans are somewhat longer than those in the polyparium, the clubs somewhat shorter. The interior of the stalk has spindles with spines, or simple or complex tubercles. These spindles have the same length as those of the interior of the polyparium, but are distinctly wider (Fig. 12.5).

Distribution: Recorded only from Larak Island and possibly can be found in Lesser Tonb Island (Fig. 12.6).

Remarks: This species can cover fairly large areas on the seafloor and sometimes forms dense monospecific stands. The completely expanded colonies underwater might look fairly large, however they will shrink dramatically after physical disturbances or removal from the water.

Genus *Sinularia* May, 1898

Diagnosis: The colony form can be highly variable, encrusting, tall and abundantly lobed, branched, flat and leaf-like and almost everything in between. Polyps are monomorphic, retractile. The surface of the colonies contains clubs, rods and spindles. The surface of the stalk contains clubs; interior with warted spindles, occasionally branched. Sclerites are colourless. Zooxanthellate. Several species of *Sinularia* occur in the Gulf, however, so far only two of them were identified and the rest is under further examination.

Distribution: Widespread, from Africa and the Red Sea to Hawaii.

***Sinularia compressa* Tixier-Durivault, 1945**

For the description of the sclerites see Verseveldt 1980.

Distribution: Common around Larak Island in the Strait of Hormuz, also recorded in Hengam, and Farur islands (Fig. 12.7 c, d).

***Sinularia erecta* Tixier-Durivault, 1945**

For the description of the sclerites see Verseveldt 1980.

Distribution: Common around Larak Island in the Strait of Hormuz, also can be found in Farur, and Hengam islands (Fig. 12.7 a, b).

Family Nephtheidae Gray, 1862

Genus *Dendronephthya* Kükenthal, 1905

Diagnosis: Highly branched or bushy colonies, end branches generally arranged as divaricate, glomerate, umbellate (Fabricius and Alderslade 2001). Polyps predominantly on the terminal twigs forming small bundles. Spindles occur on the surface of the twigs, branches and in most parts of the colony. Azooxanthellate.

Distribution: widespread, from Africa to Micronesia and Polynesia.

Remarks: The genus has about 275 nominal species and is badly in need of revision. The genus is likely to occur in most of the places and so far two different species were collected from the Gulf (Samimi-Namin and van Ofwegen 2009a), however, the sp. b is more common in the area (Fig. 12.8).

***Dendronephthya* sp. a**

Distribution: So far recorded from Hengam Island

***Dendronephthya* sp. b**

Distribution: It can be found in most of the Iranian Islands.

Genus *Umbellulifera* Thomson & Dean, 1931

Diagnosis: Colonies with a long stalk ending in an umbellate polyparium. Polyps monomorphic, not retractile, and single. Polyps with numerous spindles arranged in eight points. Stalk surface with capstans and derivatives of those; interior with six radiates. Azooxanthellate

Distribution: Indo-Pacific. The genus is rare, probably because it occurs below diving depth. So far only recorded from washed up specimens on Hengam Island.

Family Briareidae Gray, 1859

Genus *Briareum* Blainville, 1830

Diagnosis: Colonies encrusting or forming finger-like lobes, mostly with calyces. Polyps monomorphic and retractile. Sclerites are spindles with tubercles arranged in girdles. Polyps without sclerites. The deeper layer of the colony normally has magenta coloured sclerites. Surface layer often with colourless sclerites. Zooxanthellate.

Distribution: Indo-Pacific.

***Briareum* cf. *hamrum* (Gohar, 1948)**

For description see Gohar 1948.

Distribution: So far recorded in Larak, Farur, Kish Islands. Likely to occur in other Iranian Islands close to the Strait of Hormuz (Fig. 12.9).

Remarks: The specimens found in the Gulf are in agreement with *B. hamrum*, but more detailed sclerite information should be made available to ascertain this. Alderslade, 2000, referred *Clavularia hamra* Gohar, 1948, to *Briareum*, consequently the species name had to be changed to *hamrum*.

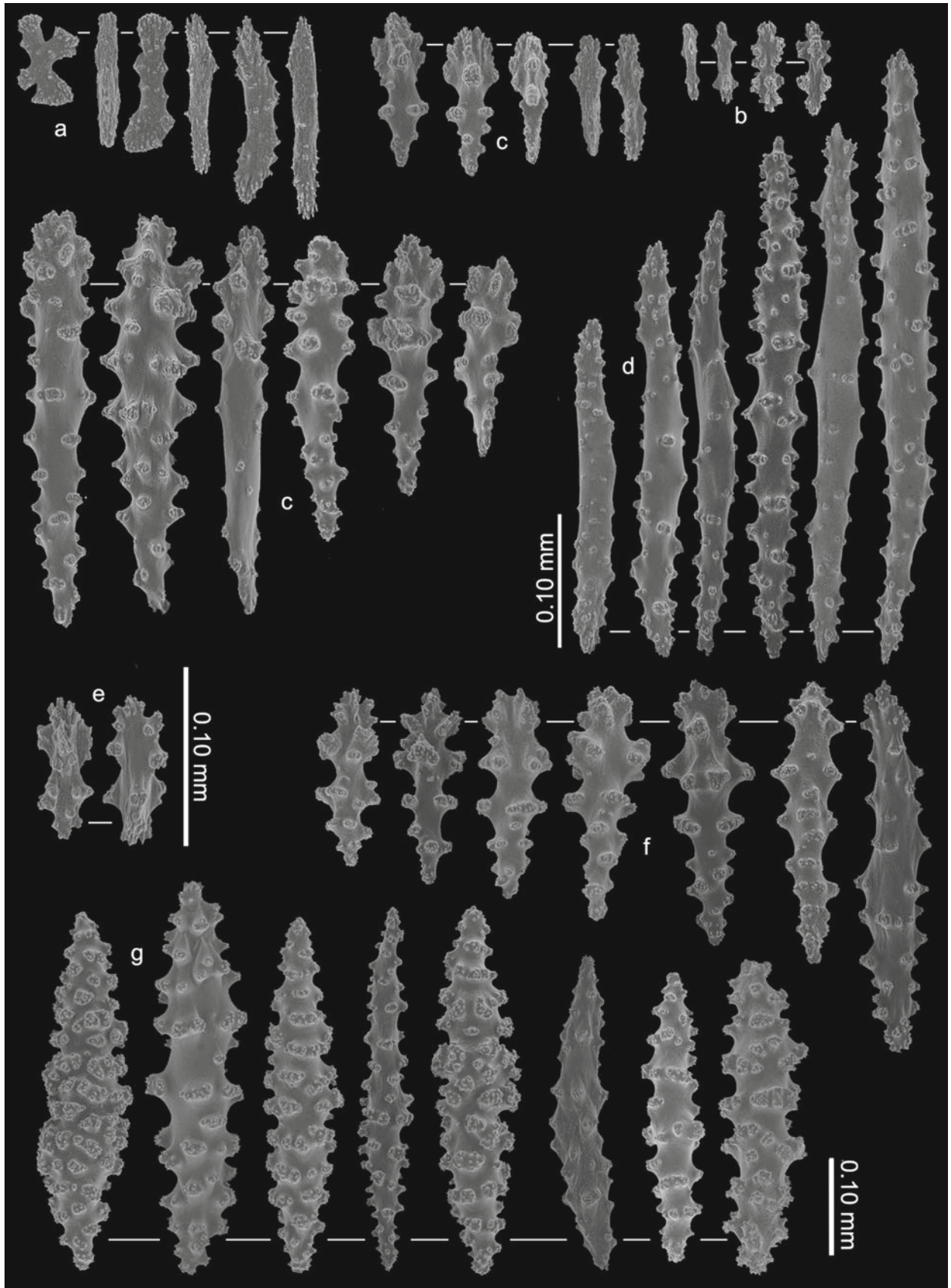


Fig. 12.5 Sclerites of the *S. minusculum* at Larak Island. (a) polyp rods; (b) capstans of the polyparium surface; (c) clubs of the polyparium surface layer; (d) spindles of the polyparium interior; (e) capstans of the base surface layer; (f) clubs of the base surface; (g) spindles of the base interior. Scale at e also applies to a, b, c, and f. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

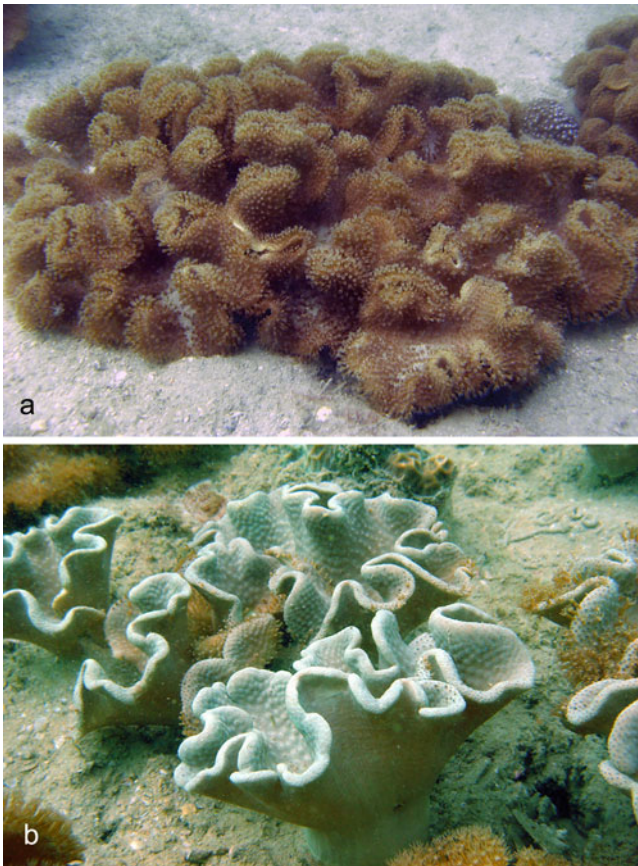


Fig. 12.6 Colonies of *Sarcophyton minusculum* at Larak Island, 12 m depth. (a) Colonies with fully expanded polyps. (b) Colonies with retracted polyps

Family Anthothelidae Broch, 1916

Genus *Solenocaulon* Gray, 1862

Diagnosis: Colonies with hollow branches, forming fans. End of the branches can be gutter-like. Polyps monomorphic and retractile. Interior sclerites are needles. Surface layer with spindles and ovals. Polyps with a collaret and points arrangement. Sclerites colourless and/or coloured. Mostly growing in muddy environments or on sandy slopes (Fig. 12.10a, b). Often the basal part of the colony flattened to anchor the colony in the substrate. Azooxanthellate

Distribution: Indo-Pacific.

Remarks: It is considered a rare genus probably, because it occurs below diving depth. So far two species have been found washed up on Hengam Island's shore (Fig. 12.10c). More detailed taxonomic work is necessary for the identification and a revision of the genus is being undertaken by the authors.

Family Subergorgiidae Gray, 1859(a)

Genus *Subergorgia*, Gray, 1857

Diagnosis: Colonies growing in one plane, laterally or dichotomously branched without forming nets. Monomorphic

polyps which are usually arranged on the lateral sides of the branch (Fig. 12.11). Polyps with flattened spindles. Sclerites branching and fusing in the axis; warty spindles or ovals occur on the outer surface. Azooxanthellate.

Distribution: Indo-Pacific.

Subergorgia suberosa (Pallas, 1766)

For references see Grasshoff, 1999: 15; 2000: 6. *Subergorgia pérezi* Stiasny, 1940: 132.

Distribution: It is not a common species and so far recorded from Farur, and Qeshm Islands.

Remarks: *S. suberosa* has ovals in the coenenchyme while the only other known species *S. rubra*, Thomson, 1905, has spindles.

Subergorgia pérezi Stiasny, 1940, described from the Gulf, shows all the characteristics of *S. suberosa*, and therefore Samimi-Namin & van Ofwegen (2009a) synonymised it with that species.

Family Acanthogorgiidae Gray, 1859(b)

Genus *Acanthogorgia* Gray, 1857

Diagnosis: Colonies are mostly planar and reticulate, bushy, fans. Monomorphic polyps, non retractile, even when contracted often tall (Fig. 12.12a, b). The polyps have warty boomerang-shaped spindles. Surface has small warty spindles, thorn stars or capstan derivatives. Azooxanthellate.

Distribution: Indo-Pacific, Atlantic.

Acanthogorgia spinosa Hiles, 1899

Diagnosis: Colony form is a tangled three dimensional network. Polyps less than 1 mm tall, tips of polyp wall sclerites protruding, tentacle bases with a conspicuous crown of spines, and coenenchyme with thorn stars (Fig. 12.12c).

Distribution: So far recorded from off Bahrain.

Remark: The genus mostly can be found on slopes, and steep walls, however, it is uncommon throughout the Gulf.

Genus *Muricella* Verrill, 1869 (1868a)

Diagnosis: Planar fans, often net-like, usually up to one half meter tall (Fig. 12.13a, b). Polyps are monomorphic, non-retractile and dome shape and contain small rods and spindles. The coenenchyme has small capstans and large spindles. Azooxanthellate

Distribution: Indo-Pacific.

Muricella sp.

Diagnosis. Branched in one plane. The main branches are flattened perpendicular to the plane of branching. The polyps have spindles, up to 0.25 mm long, with simple tubercles. The same sclerite form occurs in the coenenchyme of the branches but these spindles are longer, up to 0.50 mm, and somewhat more tuberculate. The interior has capstans and rods, up to 0.10 mm long (Fig. 12.13c). All sclerites are colourless.

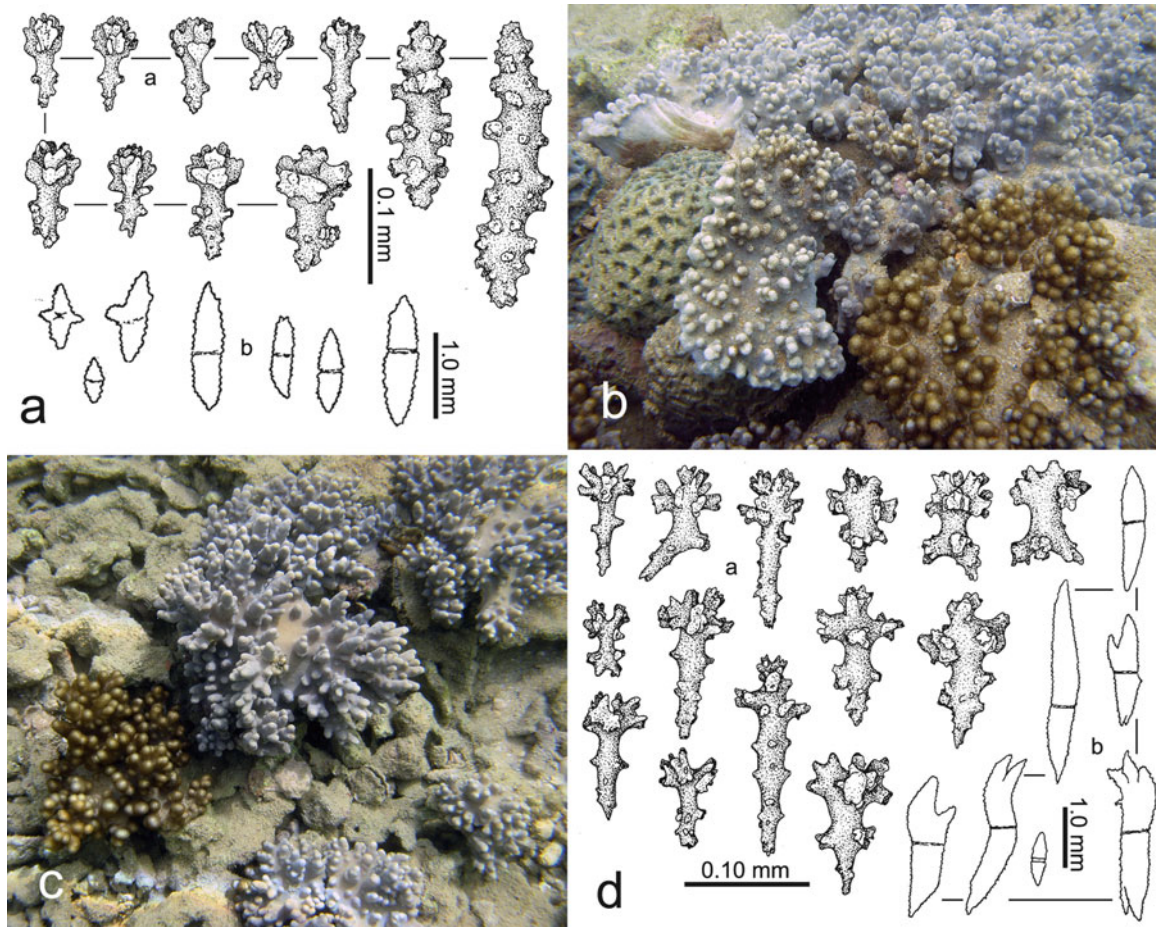


Fig. 12.7 (a) Sclerites of the *S. erecta* type material (a, sclerites of the surface; b, sclerites of the interior). (b) Colonies of *Simularia erecta* at Larak Island. (c) Colonies of *Simularia compressa* at Larak Island.

(d) Sclerites of *S. compressa* of the type material (a, surface sclerites; b, interior sclerites) (Figures a and d are modified from Verseveldt (1980))

Distribution: Uncommon in the Gulf, so far recorded from the south of Hengam Island. Likely to occur at islands around the Strait of Hormuz in deep areas.

Remarks. Without thorough revision of the genus *Muricella* we consider it impossible to identify species of this genus. Probably because of the almost complete lack of coenenchyme of the examined specimens we were unable to observe tentacle sclerites, which normally are present in species of *Muricella*.

Family Plexauridae Gray, 1859(b)

Genus *Astrogorgia* Verrill, (1868b)

Diagnosis: Colonies grow in one plane as fans without having a net structure; also bushy forms exist (Fig. 12.14a, b). Polyps are monomorphic, retractile and contain spindles and rods. The surface has spindles with different sizes and ornamentation from complex tuberculation to small prickles. Azooxanthellate.

Distribution: Indo-Pacific.

***Astrogorgia fruticosa* Samimi-Namin & van Ofwegen, 2009a**

Diagnosis: Bushy colony shape with anastomoses, the latter mostly situated in the lower part of the colony. Polyps are situated all around the branches; calyces are about 1 mm high. Polyp collaret has 6–7 rows of spindles and the points have many sclerites. These sclerites do not differ much from those of the calyx, and are up to 0.25 mm long, with simple tubercles or spines. Tentacle sclerites are similar to those of the points but slightly shorter, more flattened and less tuberculate. The surface layer of the coenenchyme has spindles up to 0.60 mm long; with simple or complex tubercles. The interior of the coenenchyme has capstans and rods, up to 0.10 mm long, with simple tubercles (Fig. 12.14c). Colony red, tentacle sclerites yellow, point sclerites partly yellow partly reddish; all other sclerites are reddish.

Distribution: So far only recorded from Hengam Island, washed ashore.

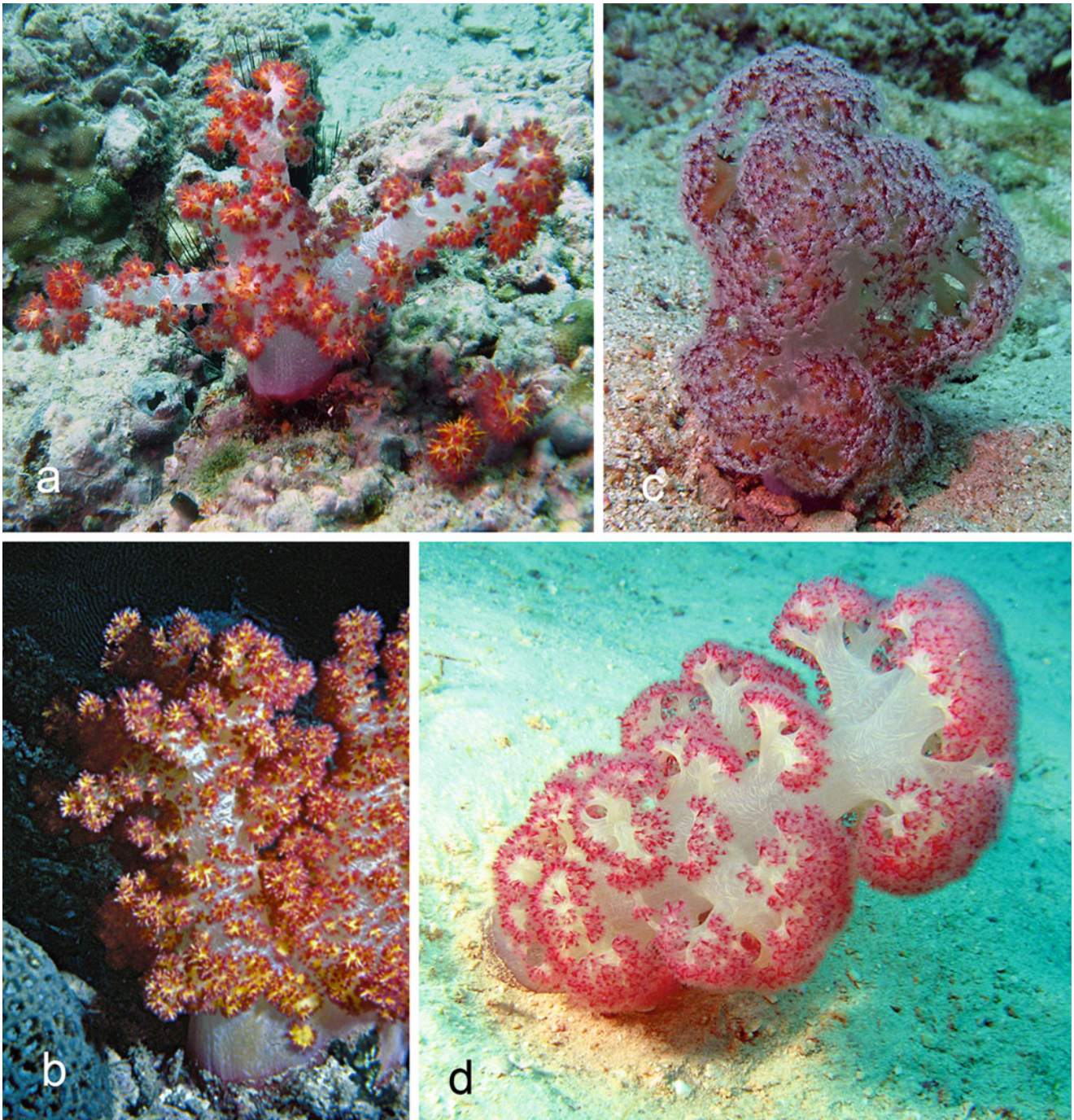


Fig. 12.8 (a, b) *Dendronephthya* sp. a from Oman and Farur Island, respectively; (c, d) *Dendronephthya* sp. b from Oman and Kish Island, respectively

Remarks: This is the first *Astrogorgia* species described having both a bushy colony form and anastomoses.

Genus *Echinogorgia* Kölliker, 1865

Diagnosis: Colonies usually grow in one plane, often net-like, with very short side branches. Polyps are monomorphic,

retractile and contain spindles. The surface has thorn-scales, spindles and capstans. Azooxanthellate.

Remarks. Without thorough revision of *Echinogorgia* we consider it impossible to identify species of this genus with any certainty. At present we recognize four different species from the Gulf, three of which are mentioned below

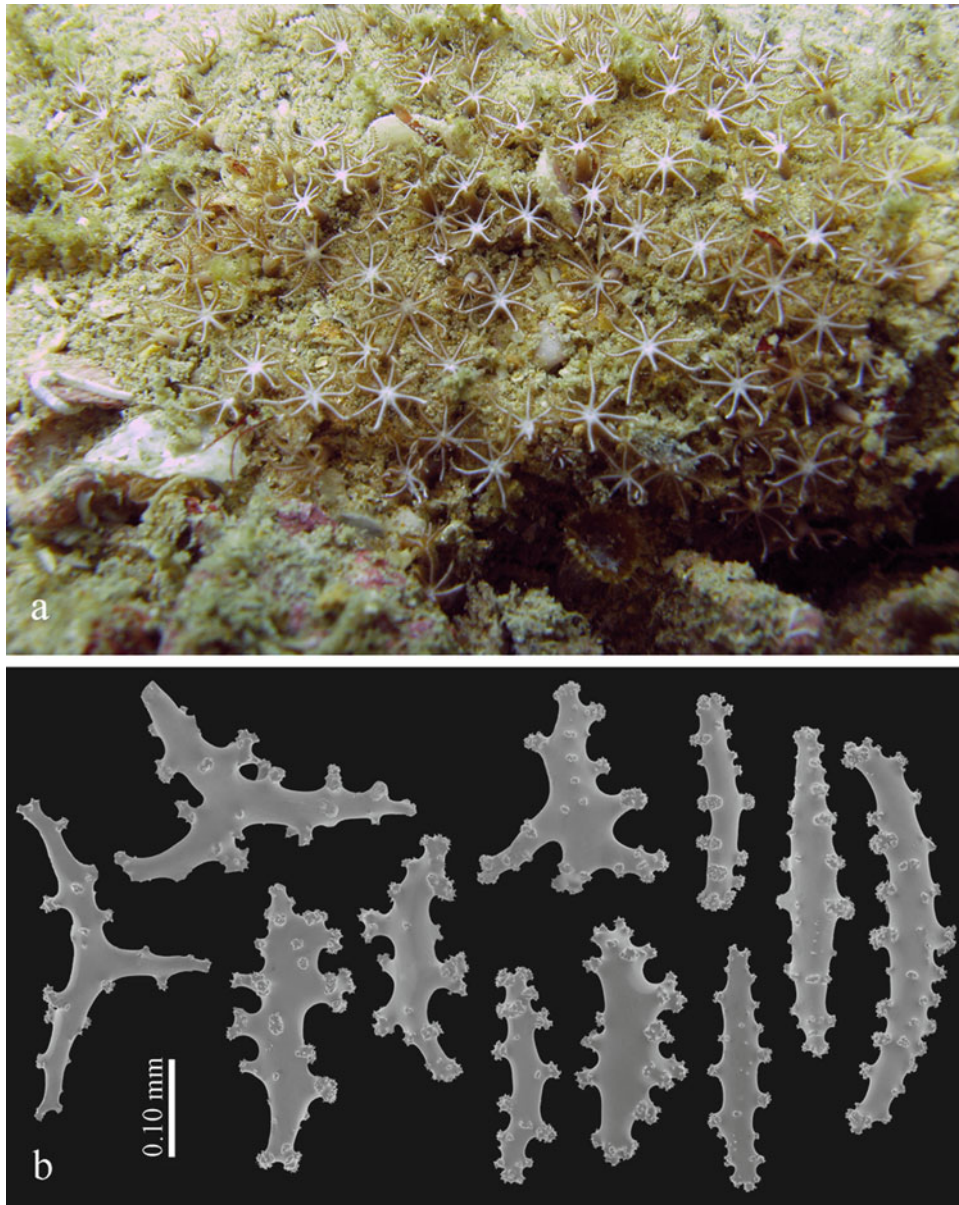


Fig. 12.9 (a) A colony of *Briareum* cf. *hamrum* at Larak Island, (b) Sclerites of the *B.* cf. *hamrum* from the Gulf

(see Samimi-Namin & van Ofwegen 2009a, for detailed sclerite characteristics of each species). Thomson & Simpson (1909) identified *E. ramulosa* (Gray, 1870) from the Gulf, a species originally described from an unknown locality. It is doubtful Thomson & Simpson really had Gray's species but from the information given by them it is obvious they indeed had a species belonging to *Echinogorgia*. Their Gulf specimen differs from the three species below in being almost black and having its branches flattened in a plane perpendicular to the plane of branching.

Distribution: Indo-Pacific.

***Echinogorgia* sp. a**

Diagnosis: Branching is in one plane, anastomoses are frequent, forming a network. Alive colony purple in colour, preserved it is brown. Sclerites are colourless.

Distribution: Farur Island, likely to occur at Iranian Islands around the Strait of Hormuz.

***Echinogorgia* sp. b**

Diagnosis: Colony branches loosely, more or less in one plane, without anastomoses. Colony ochre, sclerites yellow.

Distribution: Farur Island, Qeshm Island, likely to occur at Iranian Islands around the Strait of Hormuz..

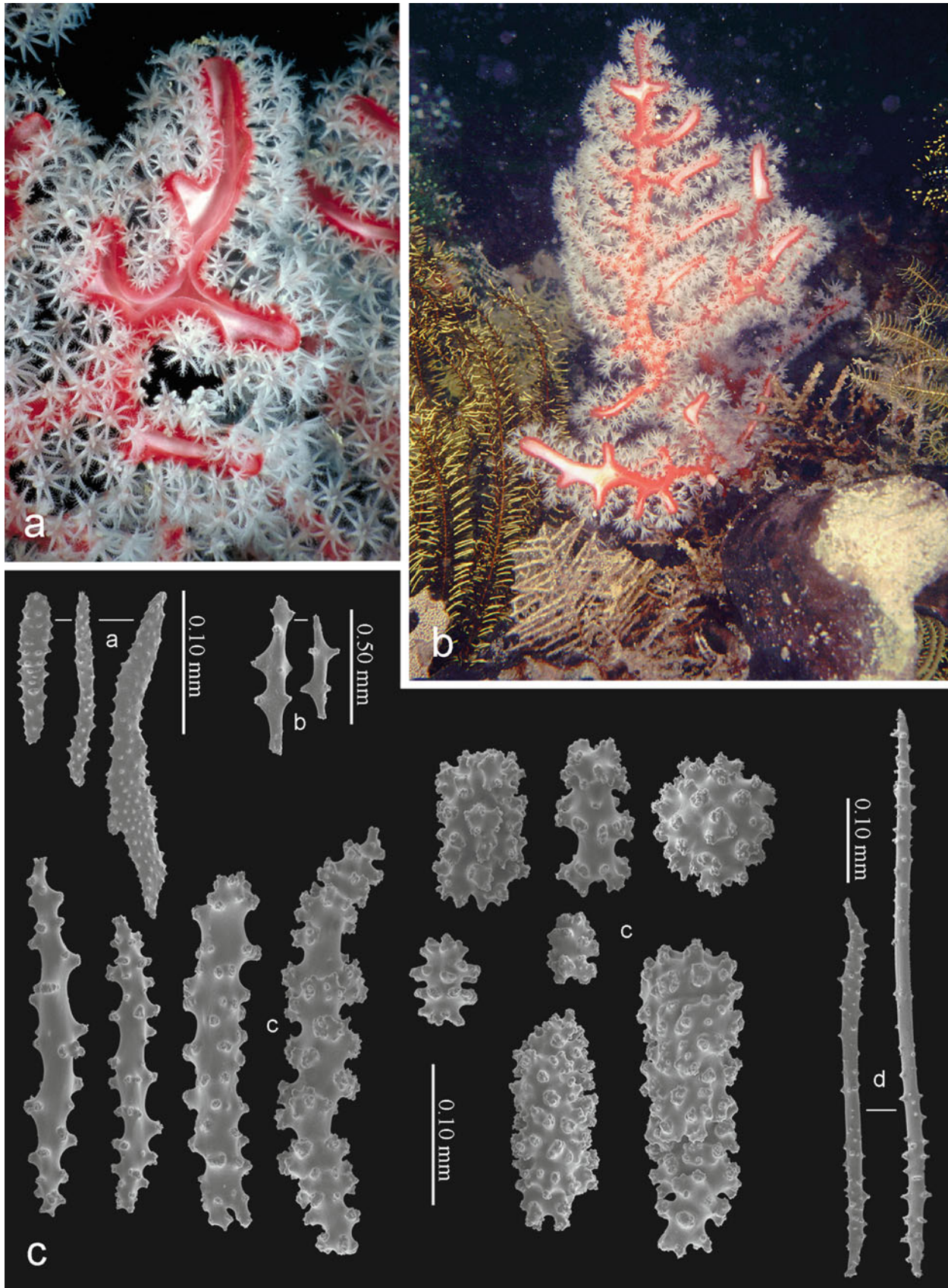


Fig. 12.10 (a) A close up of *Solenocaulon* polyps; (b) A *Solenocaulon* species colony from Indonesia (Photos: B.W. Hoeksema); (c) Sclerites of the *Solenocaulon* species from Hengam Island (a, polyp sclerites; b,

pharynx; c, sclerites from the cortex; d, sclerites from the medulla). Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

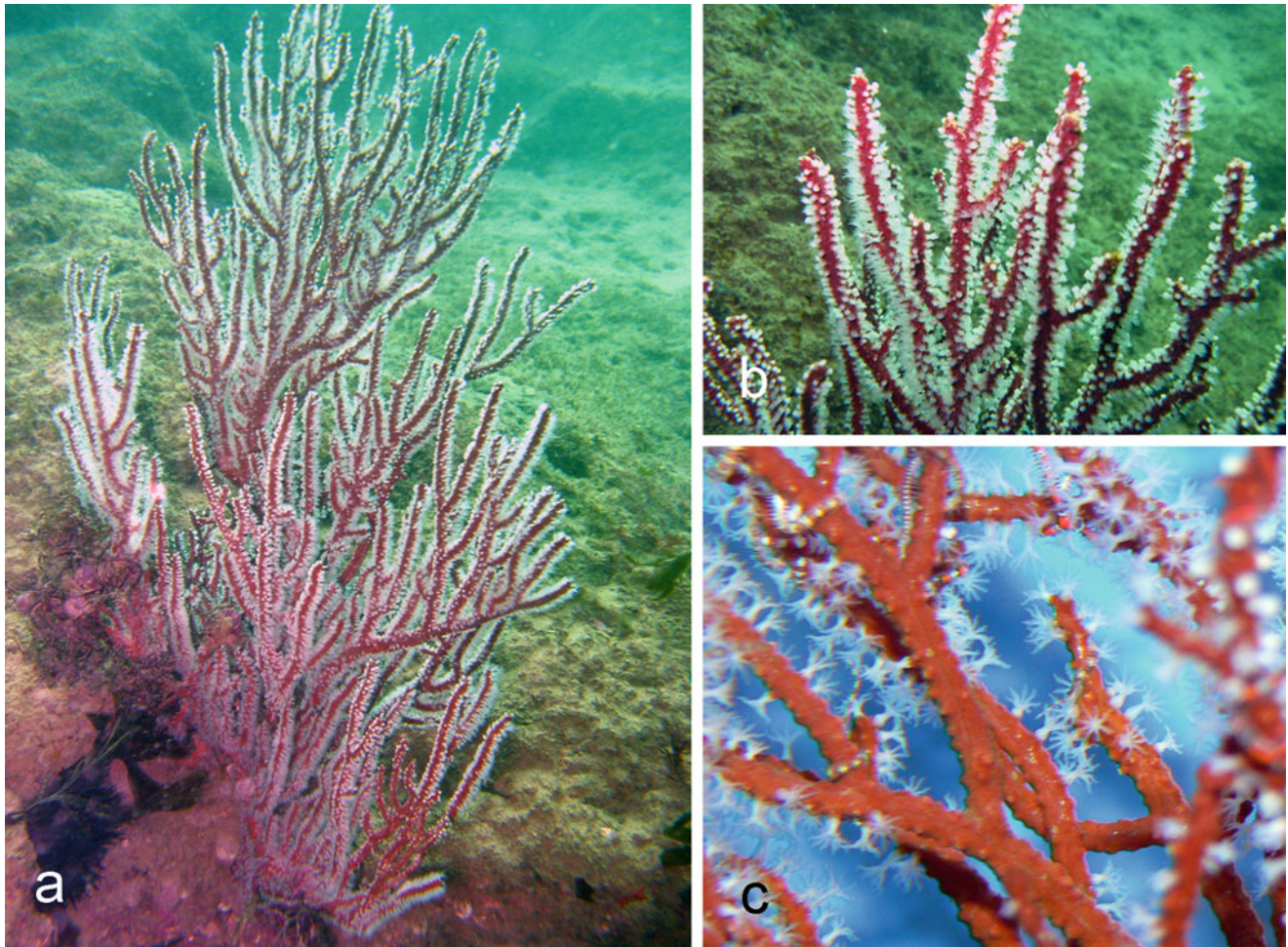


Fig. 12.11 (a) Colonies of *Subergorgia suberosa* from Chabahar, in the Gulf of Oman; (b) A close up of *S. suberosa* from Chabahar; (c) a close up of a specimen from Farur Island. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

? *Echinogorgia macrospiculata* Thomson & Simpson, 1909

Remarks. As with most species described by Thomson & Simpson, *E. macrospiculata* also needs re-description before one can identify material as belonging to this species.

Genus *Echinomuricea* Verrill, 1869

Diagnosis: Colonies up to about half a meter high, usually with few, long and slender, whip-like branches; growing in one plane or bushy. Monomorphic, retractile polyps which contain spindles and rods. The characteristic sclerites are thornscales, which usually have a single spine arising from a warty base. Azooxanthellate.

Remarks: Although only a small number of *Echinomuricea* species have been described, Kükenthal (1924: 186) lists only 16. However, most descriptions lack sufficient detail to appreciate what are the characters of the species concerned. Therefore we consider it impossible to identify species of

this genus with any certainty (see Samimi-Namin & van Ofwegen 2009a, for detailed sclerite characteristics of each species).

***Echinomuricea* sp. a**

Diagnosis: Branches are slender, 1–2 mm wide. Alive, the colony was red with yellow polyps, preserved it is red. Most sclerites are reddish; the interior radiates pinkish to colourless.

Distribution: Farur Island; likely to occur at most of the Iranian Islands.

***Echinomuricea* sp. b**

Diagnosis: Branches up to 4 mm wide. Alive, the colony was red with yellow polyps, the preserved colony and the sclerites are reddish.

Distribution: Hengam Island, Kish Island, Kharku Island, Farur Island, off Kuwait.

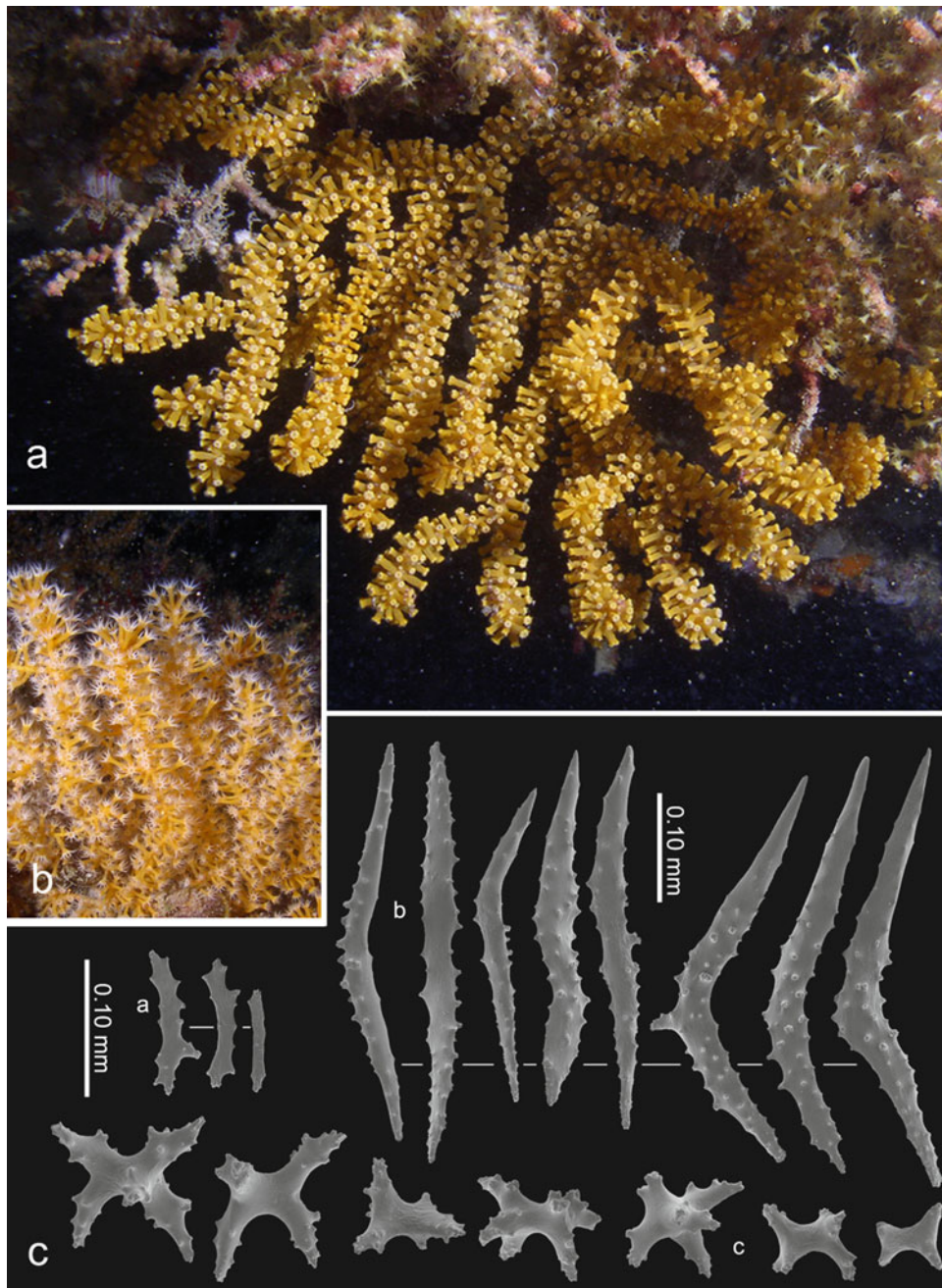


Fig. 12.12 (a) An *Acanthogorgia* species from Oman, overhang on a cliff; (b) A close up of the same species from Oman; (c) sclerites of *Acanthogorgia spinosa* from the Gulf (a, tentacle rods; b, spindles of

the polyps; c, thornstars of the surface layer; scale at a also applies to c). Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

Remarks: The two *Echinomuricea* species differ not much from each other. *Echinomuricea* sp. b has thicker branches while the colonies are all much smaller. This striking difference in colony shape is the main reason we consider them to be different species as the sclerites of the two species do not differ much.

Genus *Euplexaura* Verrill, 1869

Diagnosis: Colonies are fan-shaped in one plane or bushy. Polyps are monomorphic, retractile and contain spindles and rods. Calyces may be present or completely absent. The surface has ovals, subspheroidal and plump spindles. Azooxanthellate.

Distribution: Indo-Pacific.

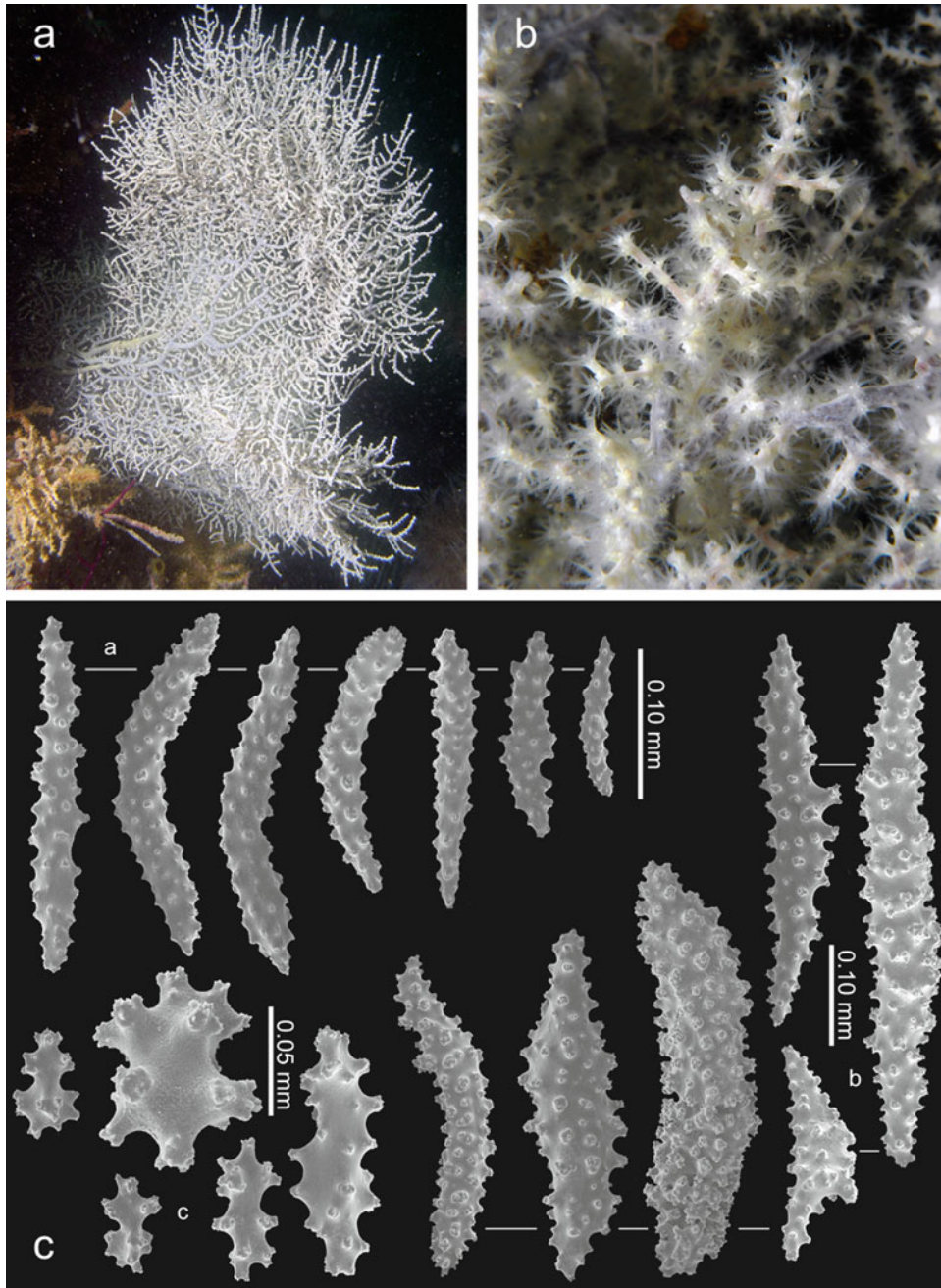


Fig. 12.13 (a) A *Muricella* colony from Oman; (b) Close up image of a *Muricella* species from Oman; (c) Sclerites of *Muricella* sp. from the Gulf (a, polyp sclerites; b, capstans and rods of the subsurface

layer; c, sclerites of the coenenchymal surface). Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

Remarks. According to Grasshoff (1999: 35) species of *Euplexaura* are distinguished only by differences in the size of the sclerites in combination with different growth forms. The findings of Samimi-Namin & van Ofwegen (2009a) suggest that the shape of the interior sclerites could be another useful character to discriminate between species in this genus. This genus is one of the most common genera throughout the Gulf (Fig. 12.15c, d) and

several species occur inside the Gulf some of which are mentioned here.

***Euplexaura plana* Samimi-Namin & van Ofwegen, 2009a**

Diagnosis: Colonies branched in one plane and the end branches especially are flattened in the plane of branching (Fig. 12.15a). The surface layer of the branch has blunt ellipsoids and spindles, up to 0.35 mm long, with complex

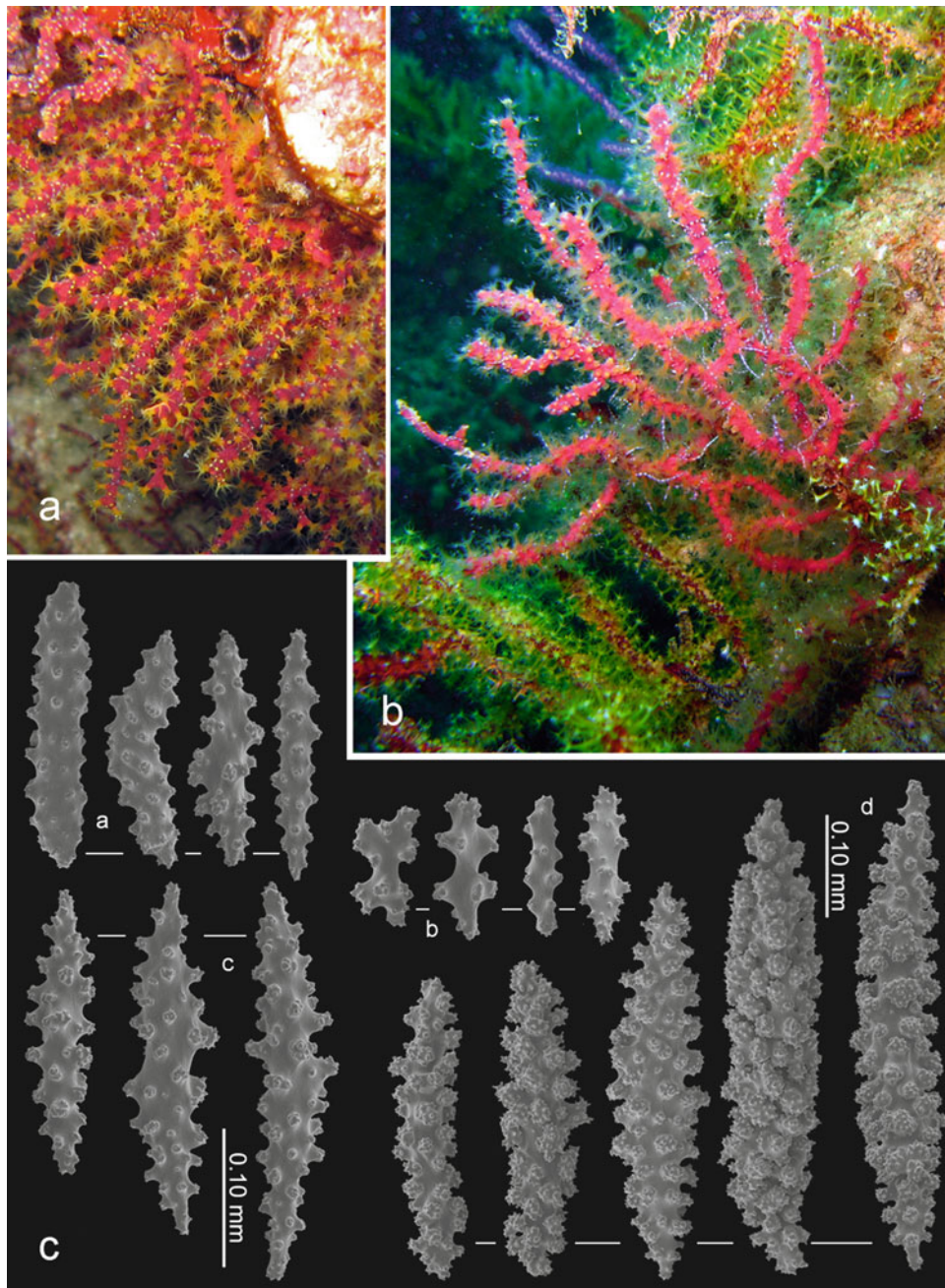


Fig. 12.14 (a) *Astroorgia* species overhang a cliff at Daymaniyat Islands, Oman; (b) Another *Astroorgia* species from Oman; (c) Sclerites of *Astroorgia fruticosa* (a, polyp spindles; b, capstans and

rods of the subsurface layer; c, d, coenenchymal spindles; scale at d only applies to d). Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

tubercles. Several of them with one side less tuberculate. Interior has sclerites similar to those of the surface layer, but they are less tuberculate, and smaller, up to 0.25 mm long (Fig. 12.15b).

Distribution: So far recorded from Farur Island inside the Gulf, also observed in Musandam.

Euplexaura sp. a

Diagnosis: Colonies branched in one plane with cylindrical branches. The surface layer of the coenenchyme has blunt ellipsoids and spindles, up to 0.25 mm long, with complex tubercles. Several of them with one side less tuberculate. The calyces have spindles with smaller

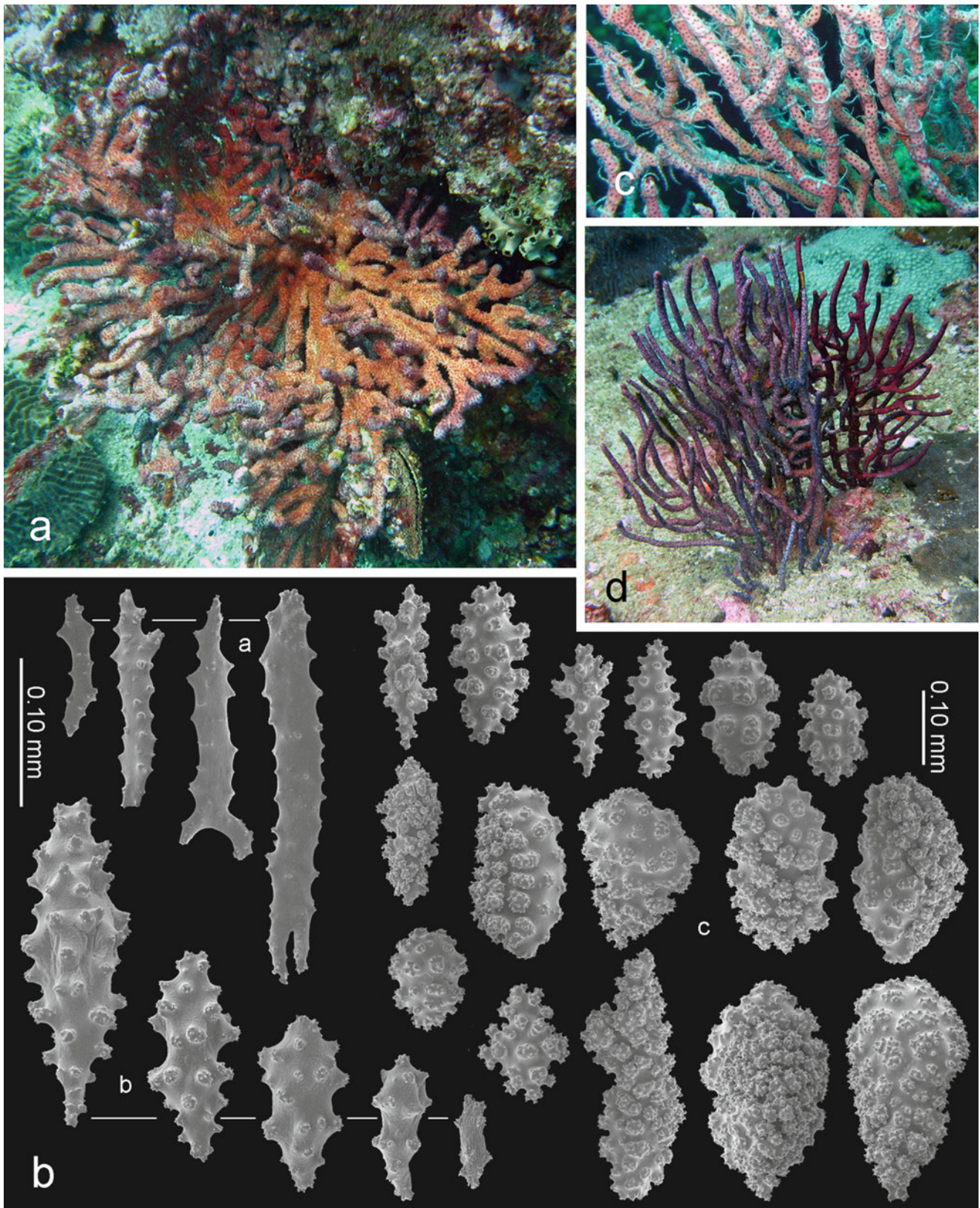


Fig. 12.15 (a) *Euplexaura plana* at Musandam; (b) Sclerites of *E. plana* (a, polyp spindles; b, spindles of the subsurface layer of the coenenchyme; c, ellipsoids and spindles of the coenenchyme surface layer); (c) most of the time *Euplexaura* species are covered with many

brittlestars; (d) Another *Euplexaura* species from Musandam. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

tubercles. The interior has small spindles and rods, up to 0.15 mm long.

Distribution: So far recorded from Kharku Island, off Kuwait.

***Euplexaura* sp. b**

Diagnosis: Colonies branched in one plane with cylindrical branches. The surface layer of the coenenchyme has blunt ellipsoids and spindles, up to 0.25 mm long, with complex tubercles. The calyces have spindles with simple tubercles and spindles with one end being less tuberculate. The interior has small spindles and rods, up to 0.20 mm long.

Distribution: So far recorded from Qeshm Island.

Remarks: This species differs from *Euplexaura plana* and *Euplexaura* sp. a in having uniformly tuberculated surface sclerites.

Genus *Menella* Gray, 1870

Diagnosis: Colonies usually sparsely branched or unbranched and whip-like, without forming nets. Polyps are monomorphic, retractile, and contain spindles and rods. The surface has leaf scales which are a leaf attached to a tuberculated root; small spindles and capstans. Azooxanthellate.

Distribution: Indo-Pacific.

Remark: This genus is one of the most common genera throughout the Gulf (Fig. 12.16a) and several species occur inside the Gulf of which few mentioned here. Further studies are necessary for identification of the different species (see Samimi-Namin and van Ofwegen 2009a for detailed characteristics of the species).

***Menella* sp. a**

Diagnosis: Alive, the colony was red, and preserved it retains this colour. Polyp sclerites are colourless, all others orange. Inner layer of coenenchyme with spindles, up to 0.35 mm long, with rather simple tubercles; several with side branches. Furthermore, sparsely ornamented capstans and derivatives of capstans are present, up to 0.15 mm in length.

Distribution: Kish Island, likely to occur at most of the Iranian Islands.

***Menella* sp. b**

Diagnosis: Colony brown, polyp sclerites colourless, all others yellow. Inner layer of coenenchyme with capstans, derivatives of capstans and spindles, the latter up to 0.30 mm long and often branched.

Distribution: Larak Island, likely to occur at most of the Iranian Islands.

Remarks: This species is similar to the previous one, having similarly shaped rooted leaves. It differs in having a different colour, and different interior sclerites

***Menella* sp. c**

Diagnosis: Alive, colonies purple, preserved they are brown. The polyp sclerites are colourless, all others are red. Inner layer

of coenenchyme with capstans, derivatives of capstans and spindles, the latter up to 0.50 mm long. Several spindles with side branches and rather complex tubercles (Fig. 12.16b).

Distribution: Farur Island, likely to occur at most of the Iranian Islands.

Remarks: The species differs from the others in lacking leaf spindles, having many rooted leaves with dentate leaf margin, and possessing interior branched spindles with rather complex tubercles.

***Menella* cf. *kanisa* Grasshoff, 2000**

Diagnosis: Colonies reddish, polyp sclerites are colourless, all others dull red. Inner layer of coenenchyme with capstans, derivatives of capstans, spindles, and branched bodies, the latter up to 0.40 mm long.

Distribution: Off Kuwait.

Remarks: The sclerites of this species mostly resemble those of *Menella* sp. c but the species differs in having mostly rooted leaves with a smooth leaf, and different colony shape and colour. Grasshoff (2000: 91–93) described only one paratype of *Menella kanisa* being red like the present specimen, most of his specimens had a yellow colour. The present material fits Grasshoff's description, although the somewhat schematic drawings of sclerites given by him still leave some doubts about the identity of the Gulf material.

***Menella bahrelfarsi* (Stiasny, 1940)**

Diagnosis: See Stiasny (1940: 135).

Distribution: Close to the Strait of Hormuz.

Remarks: The description was based on material stored in formalin and therefore the exact shape of its sclerites is unknown. It differs from the above four species in being yellowish red, and apparently having very thick branches, up to 8 mm in diameter. It mostly resembles *Menella* sp. a.

Genus *Paraplexaura* Kükenthal, 1909

Diagnosis: Colonies sparingly to richly branched with often thick branches; colonies do not form nets (Fig. 12.17a). Monomorphic, retractile polyps which mostly contain spindles and rods but never in a collaret and points arrangement. The characteristic sclerites are unilaterally spiny or foliate spheroids. Azooxanthellate

Distribution: Indo-Pacific.

Remarks: Without thorough revision of the genus *Paraplexaura* we consider it impossible to identify species of this genus with any certainty. The genus is rare and so far recorded from Qeshm Island.

***Paraplexaura* sp.**

Diagnosis: The colony and sclerites are yellow. The polyps have no sclerites. Surface layer of coenenchyme with thorn-scales and unilateral spinose bodies, up to 0.50 mm long. Inner layer of coenenchyme has spindles, capstans, and capstan derivatives; the capstans and derivatives are up to 0.10 mm long, the spindles up to 0.35 mm (Fig. 12.17b).

Distribution: So far recorded from Qeshm Island.

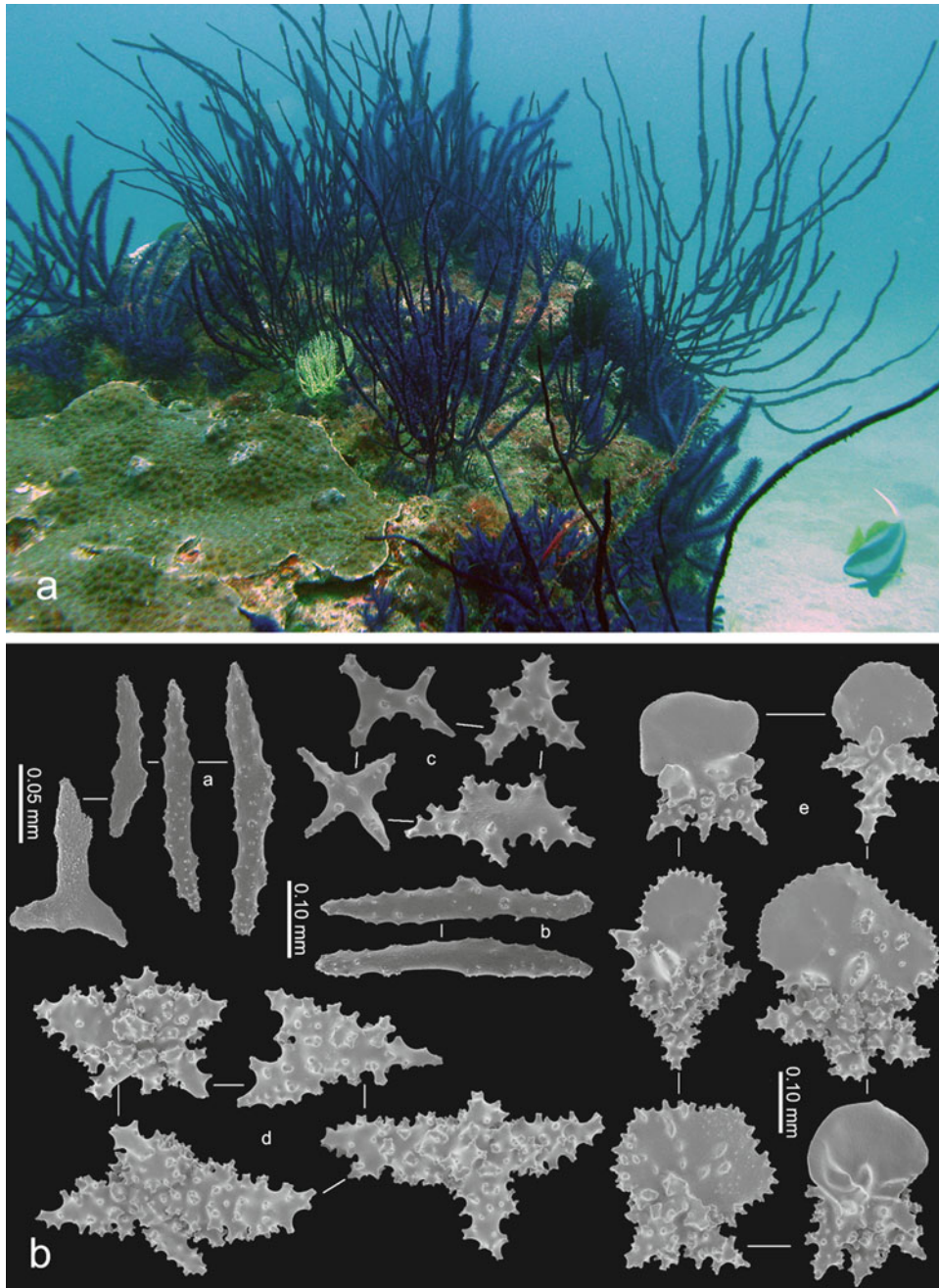


Fig. 12.16 (a) *Menella* colonies at Musandam, Oman; (b) Typical sclerites of the *Menella* sp. c from the Gulf (a, polyp sclerites; b, collar sclerites; c, d, capstans and spindles of the subsurface of the

coenenchyme; e, rooted leaves of the coenenchyme). Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

Genus *Trimuricea* Gordon, 1926

Diagnosis: Colonies forming net-like fans with polyps crowded on the branches; polyps with well developed calyces. Polyps having triradiate sclerites next to point and collar sclerites. Calyces with thorn-scales and coenenchyme between the calyces with spindles. Zooxanthellate.

Distribution: Indo-Pacific. The genus is not common.

Trimuricea aff. *reticulata* (Thomson & Simpson, 1909)

Diagnosis: Alive, reddish-purple (Fig. 12.18a), preserved brown. The coenenchyme has thorn-scales, up to 0.40 mm long, and spindles up to 0.60 mm long; occasionally one of these spindles has a short spine. The smallest spindles have simple tubercles, the larger ones also complex tubercles (Fig. 12.18b).

Distribution: Farur Island.

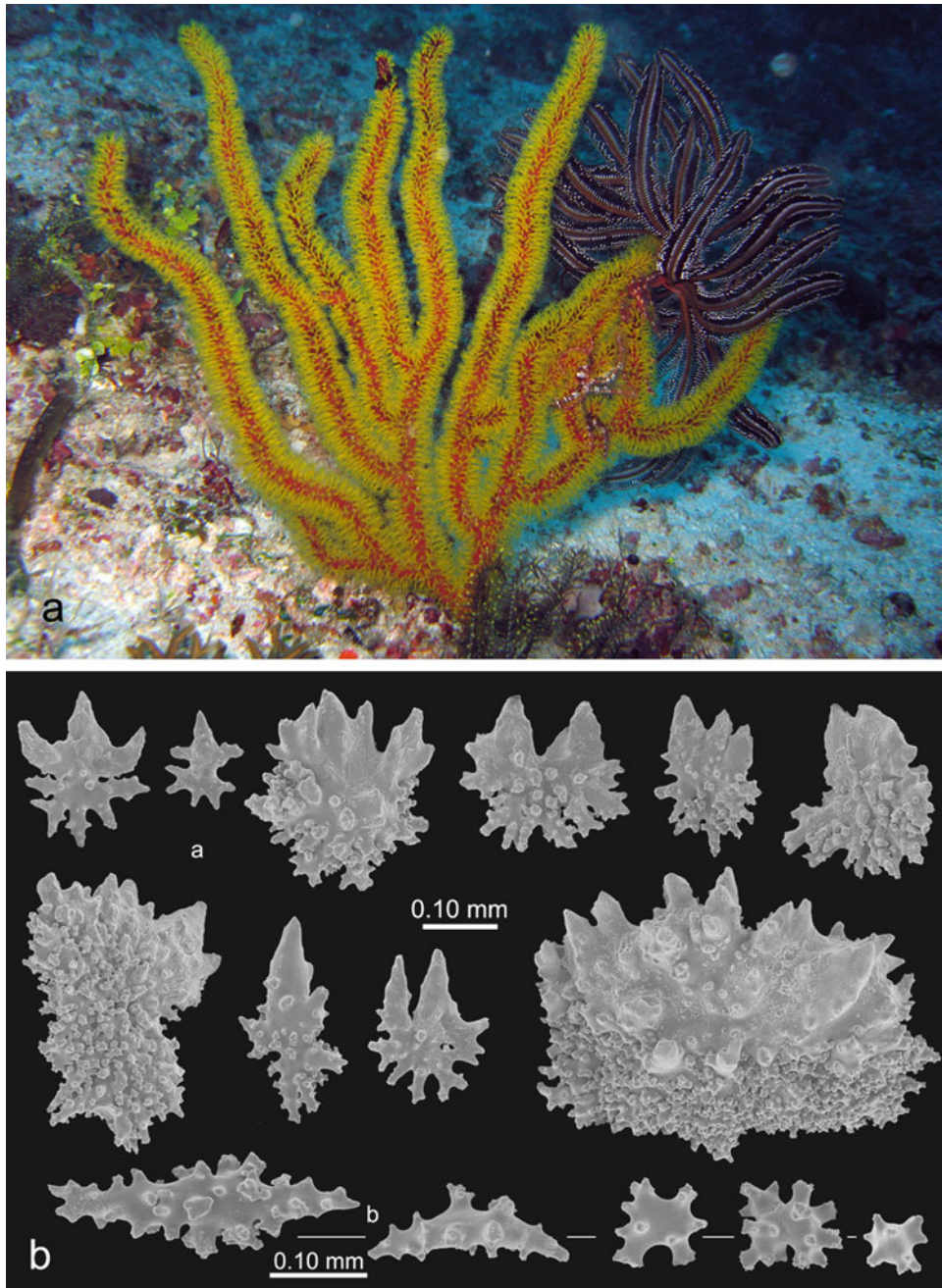


Fig. 12.17 (a) *Paraplexaura* colony from Indonesia; (b) Sclerites of the *Paraplexaura* sp. from the Gulf. a, Thornscales and unilateral spinose bodies of surface layer b, spindles, capstans, and capstan

derivatives of the subsurface layer. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

Remarks: Examining the recent material from the Gulf and Gulf of Oman showed that several species of this genus occur in the region. Therefore, a revision of the genus is currently being undertaken by the authors.

Family Ellisellidae Gray, 1859a
Genus *Junceella* Valenciennes, 1855

Diagnosis: Colonies usually unbranched, whip-like that can grow to over 2 m tall. Polyps are monomorphic and contractile. The surface contains clubs and subsurface usually symmetrical capstans. Azooxanthellate.

Distribution: Indo-Pacific.

***Junceella juncea* (Pallas, 1766)**
 For references see Grasshoff (2000: 106).

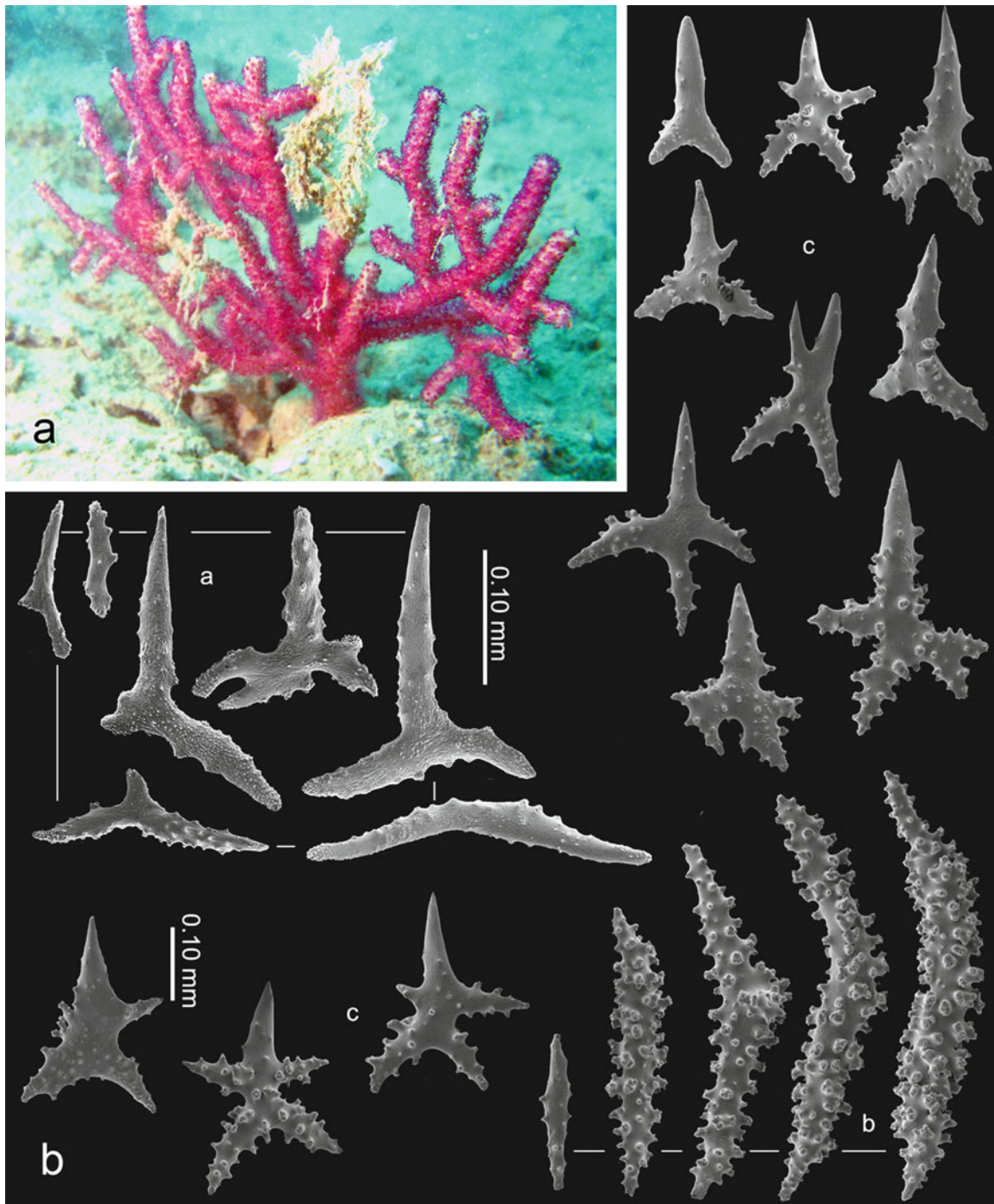


Fig. 12.18 (a) In situ image of a *Trimuricea* species at Larak Island, the second in situ image of the genus (Samimi-Namin and van Ofwegen 2009b); (b) Sclerites *Trimuricea* aff. *reticulata* from the Gulf (a, polyp

sclerites; b, spindles of the surface layer; c, thorn-scale sclerites). Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

Distribution: Common along Iranian coastline and islands (Fig. 12.19); So far recorded from Kish Island, Kharku Island, Hengam Island, Farur Island, Qeshm Island, and also off Dubai. Large stands also occurs at E of the Qatar peninsula.

Genus *Verrucella* Milne Edwards & Haime, 1857

Diagnosis: Colonies at least up to half a meter tall, branched in one plane or bushy, they can form net-like fans (Fig. 12.20a). Polyps are monomorphic and contractile. The surface has double headed, narrow and plump spindles. Azooxanthellate

Distribution: Indo-Pacific.

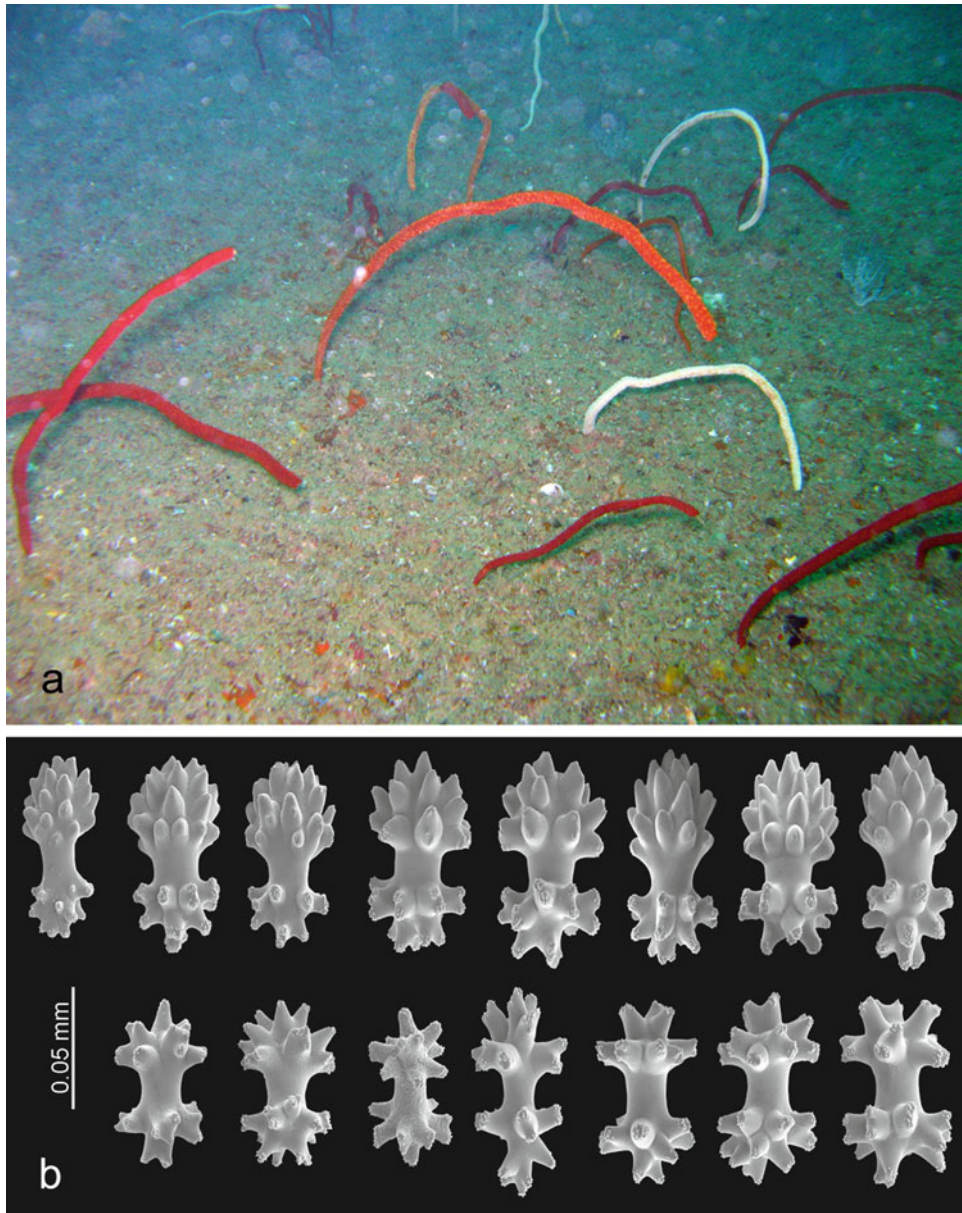


Fig. 12.19 (a) Colonies of *Junceella juncea* at Kish Island; (b) Sclerites of *J. juncea* from Indonesia. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

***Verrucella cf. reticulata* (Thomson & Simpson, 1909)**

Diagnosis: Colonies form a network, orange-red; coenenchymal sclerites are pink, those of the polyps colourless. Sclerites are mostly double heads, but several longer ones are spindle-like; length of these sclerites is 0.04–0.08 mm. The polyps have small spindles, 0.04–0.07 mm long, and the pharynx has double stars, about 0.04 mm long (Fig. 12.20b).

Distribution: It is rare throughout the Gulf. So far only recorded from Qeshm Island.

Remarks: The material examined is in agreement with the description of *Nicella reticulata*, if we assume to have a red part of a mixed coloured colony or a completely red specimen, as the one from the Laccadives mentioned by Thomson & Simpson. However, because of the rather poor original description and images it is impossible to obtain certainty about the correct identification without comparison with the type material, probably stored in the Indian Museum Calcutta, but at present unavailable to us.

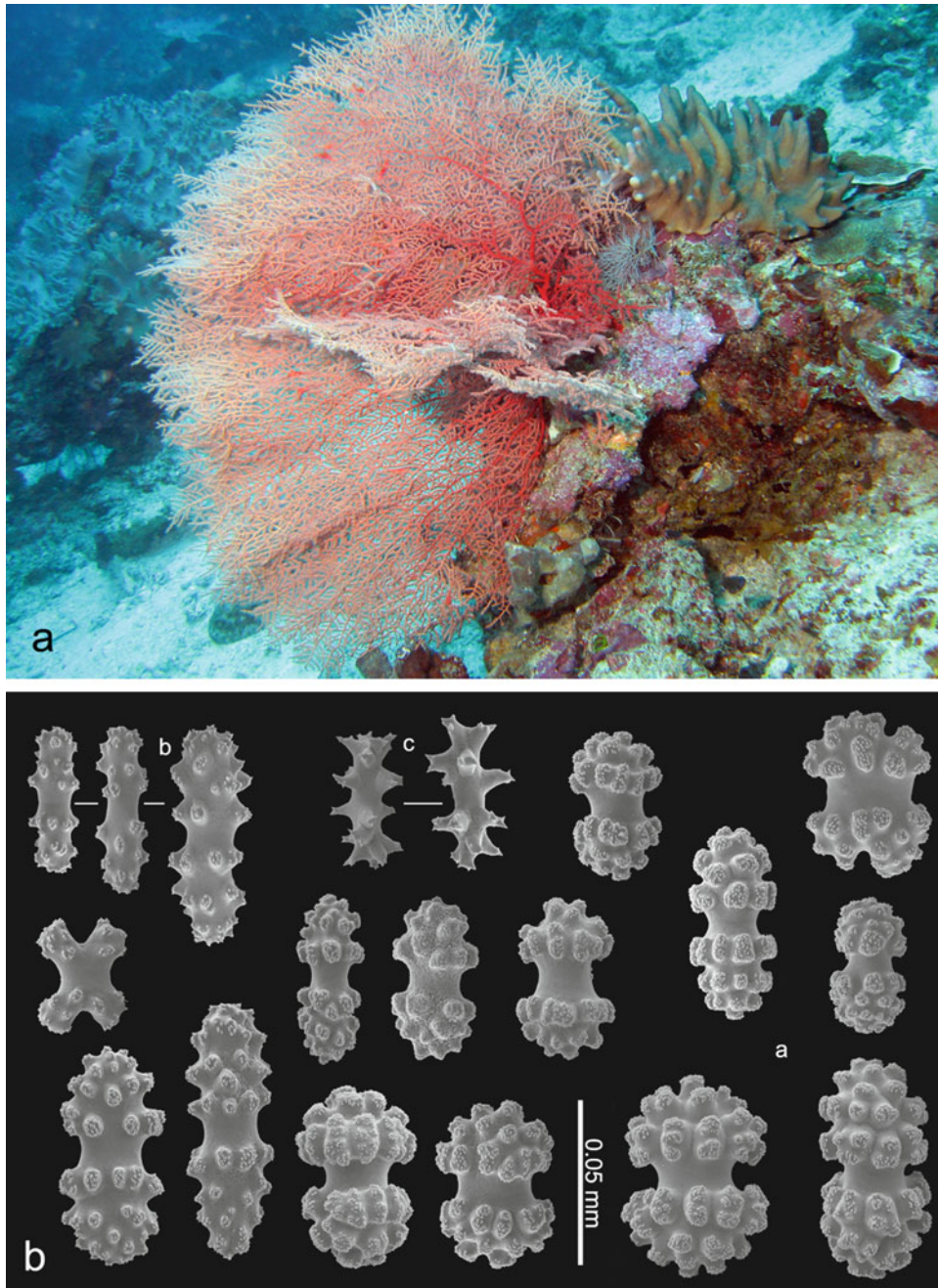


Fig. 12.20 (a) A *Verrucella* colony from Indonesia; (b) Sclerites of *Verrucella* cf. *reticulata* from the Gulf. Reproduced from Samimi-Namin and van Ofwegen (2009a) by permission of Magnolia Press

Order Pennatulacea Verrill, 1865

The sea pens or Pennatulacea are a diverse and poorly known group of octocorals containing 16 families (Williams 1995). The majority live in the deep sea but many species can be found in shallow waters of the Indo-Pacific (Fabricius and Alderslade 2001). Living on soft substrate and often withdrawn into the substrate during daylight, they are rarely

encountered by divers. Unlike other octocorals they are formed from a single large polyp, called oozoid. Lateral budding of the body wall of the oozoid make the secondary zooids which comprise the colony. They are usually dimorphic with large well developed tentacle autozooids and smaller siphonozooids, with or without tentacles. As the emergent part of their body looks like a feather, they are

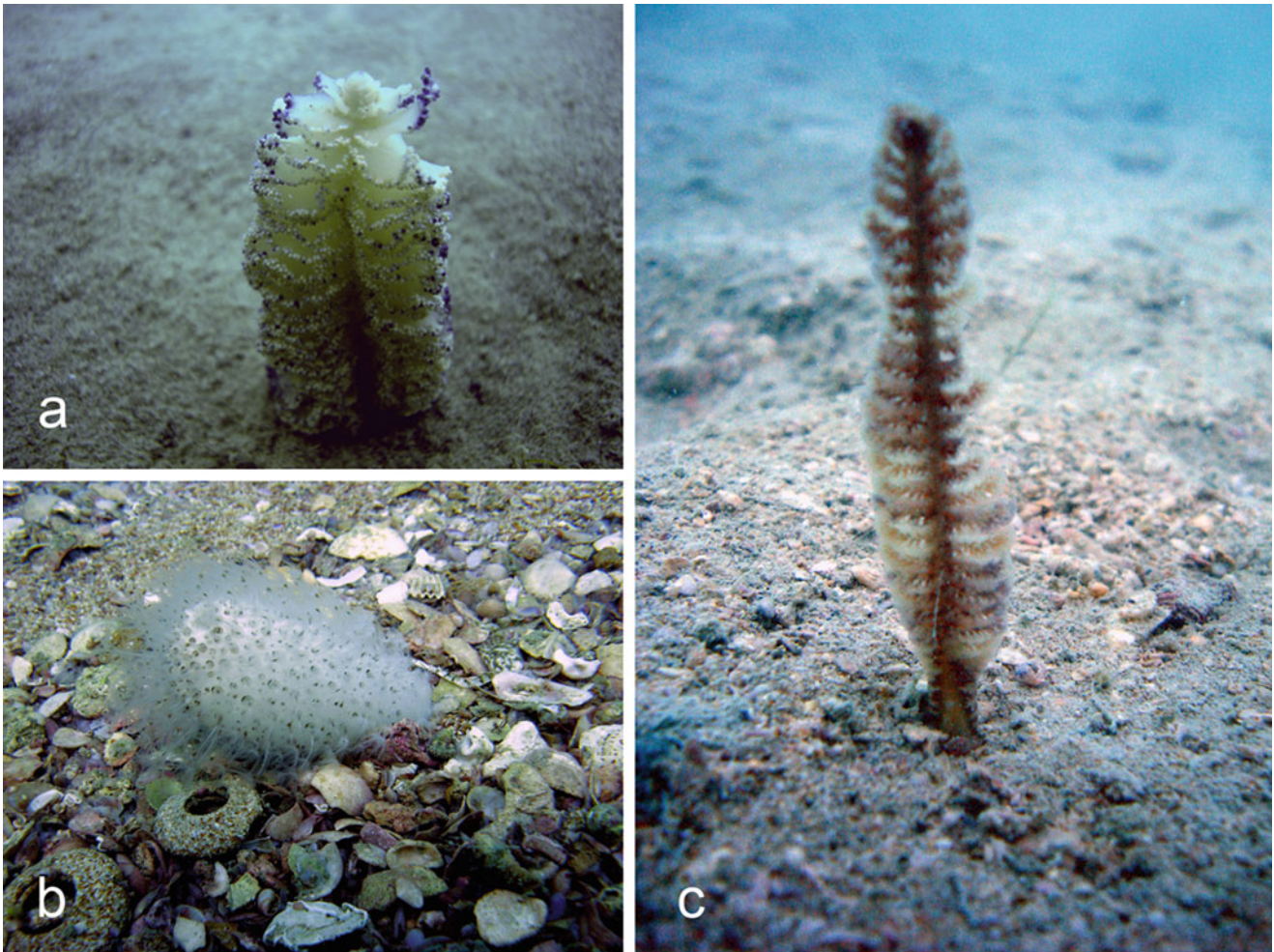


Fig. 12.21 (a, c) *Virgularia* colonies from Hengam Island at 12–18 m depth; (b) *Cavernularia* colony from Hengam Island at 14 m depth

called sea pens, but the shape and colour of the colony are largely variable. It has been suggested that sea pens arose from alcyonacean ancestors in the shallow-water tropics, and subsequently diversified and spread to temperate and polar latitudes and deeper waters (Williams 1993). Their fossil record is restricted to the Cretaceous and Tertiary with some questionable records from earlier periods (Williams 1995). For taxonomic reviews see Williams (1992, 1995, 1999).

So far, four genera have been found inside the Gulf; *Cavernularia*, *Veretillum*, *Virgularia*, and *Pteroeides* (Fig. 12.21). These occur on sandy-muddy substrates and in deeper areas (more than 10 m depth). It is likely that other genera occur in the Gulf region, especially in shallow areas (less than 10 m depth). Not many records and collected

specimens exist for the Gulf, hence their distribution pattern is not known.

Family Veretillidae Herklots, 1858

Genus *Cavernularia* Valenciennes in Milne Edwards & Haime, 1850

***Cavernularia* sp.**

Diagnosis: Radial colony symmetry; polyps arise directly from the surface of the rachis. Polyps without calyces; Polyps are dimorphic. Sclerites are smooth spindles, ovals, or rods; Interior sclerites of the peduncle are often ovals. For further information about the species and identification refer to Williams (1989) and Williams (1995).

Distribution: Eastern Atlantic and Indo-Pacific; in the Gulf collected from Hengam Island.

Genus *Veretillum* Cuvier, 1798***Veretillum* sp.**

Diagnosis: Colonies cylindrical or slightly clavate with radial symmetry throughout the length of the rachis. Axis can be present or absent. Polyp leaves absent. Polyps are dimorphic. Surface sclerites are small (>0.15 mm) irregularly-shaped plates with variable shape of denticulations. Interior sclerites of the peduncle are minute ovals (>0.03 mm). Polyp sclerites present or absent.

Distribution: Eastern Atlantic and Indo-West Pacific. In the Gulf collected from Farur Island.

Family Virgulariidae Verrill, 1868a**Genus *Virgularia* Lamarck, 1816*****Virgularia* sp.**

Diagnosis: Colonies long, slender, and vermiform or more stout, robust, and rigid with bilateral symmetry throughout the body. Polyp leaves present. Polyps are dimorphic. Sclerites are absent except for minute oval bodies in the interior of the peduncle.

Distribution: Widespread distribution in the Atlantic, Indian and Pacific Ocean. In the Gulf collected from Hengam Island.

Family Pteroeididae Kölliker, 1880**Genus *Pteroeides* Herklots, 1858*****Pteroeides* sp.**

Diagnosis: Colonies mostly stout and featherlike with bilateral symmetry throughout the rachis. Axis is present. Polyps are dimorphic, Polyp leaves well developed and rigid. Sclerites are smooth needles, spindles or rods in polyp leaves, rachis and peduncle.

Distribution: Eastern Atlantic, Mediterranean Sea, and Indo-West Pacific. In the Gulf collected from Kharku Island.

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J. David George

13.1 Introduction

In many ways the Southeastern region of the Gulf is a uniquely difficult area physiologically for macroinvertebrates to flourish in because of the extreme conditions of sea temperature and salinity that prevail in these predominantly shallow waters, particularly during the summer months. For this and other reasons linked to the Gulf's recent geological history, the biodiversity of the macrobenthic biota in the Gulf is considered by most to be relatively low compared with that existing outside the Strait of Hormuz in the north-western Indian Ocean (Sheppard et al. 1992; Khan et al. 2002).

Of particular interest is that many groups of macroinvertebrate that would not necessarily be recognised as associated in quantity with the coral reef ecosystem or coral assemblages elsewhere in the world are found in abundance on shallow SE Gulf reefs due to the average low percentage cover (<20%) of living coral there. This situation has been recently exacerbated by the well-documented higher-than-normal prolonged summer seawater temperatures in the summers of 1996 and 1998 (e.g. see George and John 1998, 1999, 2004, 2005a, b; Riegl 1999, 2002; Al-Qaseer and Uwate 2005; Sheppard and Loughland 2002; Vogt and Al Shaik 2005) that left new large areas of dead coral and limestone substratum available for colonization by non-coral macroinvertebrate groups as well as by calcareous algae.

Within the Gulf many of the reef-associated non-coral invertebrate groups (especially soft-bodied groups) are poorly known due to the concentration of limited research resources on the reef-building corals themselves, the food fishes associated with the reefs, and the few commercially important macroinvertebrate species living there. The majority of early ('historical') subtidal research was conducted by using

remote sampling techniques to capture bottom-dwelling specimens (hopefully intact) in and on sediment surfaces from vessels confined to the water surface and usually some distance away from shallow coral reefs due to the inherent danger of grounding as well as loss of expensive sampling equipment.

With the relatively recent advent of easily available SCUBA-diving techniques reef-dwelling invertebrates have become more readily accessible for *in situ* observation by diving scientists and enthusiastic amateur naturalists, and, if deemed necessary for laboratory-based identification procedures, collected by them undamaged and carefully preserved for further study by taxonomic specialists. Nevertheless, there is generally (with some notable exceptions) a lack of recent relevant published literature on the identification, biology and ecology of non-coral benthic macroinvertebrates inhabiting subtidal hard substrata in the Gulf (George 2007). This is due largely to the current lack of financial support for the relatively few taxonomically orientated Institutions in the world still able to employ marine invertebrate specialist staff capable of accurately identifying particular invertebrate groups present in the Gulf. Their ability to identify taxa is helped considerably by their frequently outstanding libraries of historical literature as well as by well-curated specimen reference collections from the Arabian region dating back many decades and in some cases for more than a century. These 'time-series' of specimens held in Museums and other related Research Institutions are of particular value when it comes to convincing senior officials of relevant authorities bordering this small shallow sea how much the marine biodiversity and abundance of species within the Gulf has rapidly deteriorated since the early 1990s (see Sheppard et al. 2010 for a review of the current poor health of the Gulf). Indeed it is likely to be the case that many of the marine species recorded as being present at the time of earlier pioneering work by SCUBA-diving scientists and others on subtidal hard substrata (Hughes Clarke and Keij 1973; Purser and Evans 1973; Basson et al. 1977; Titgen 1982) may no longer

J.D. George (✉)
Natural History Museum,
Cromell Road, London, SW7 5BD, UK
e-mail: d.george@nhm.ac.uk

be present at the sites they investigated, or those sites themselves may no longer exist as a marine habitat. In this regard much potentially useful biological information relating to the distribution, ecology and biology of non-coral macroinvertebrates in the stressed coral reef ecosystems of the SE Gulf obtained during investigations by Marine Environmental Consultants remains unpublished due to client confidentiality.

13.2 Reef Habitats of the SE Gulf Colonized by Non-coral Macroinvertebrates

Along mainland coastlines, where fringing coral reefs and coral assemblages still exist, low reef fronts rarely more than a metre or two high provide numerous microhabitats for a variety of non-coral macroinvertebrates with different requirements. For example the large number of available living spaces between individual corals on most coral reef fronts of the SE Gulf reefs provide areas for settlement of sessile macroinvertebrates that do not appear to have any obvious need for the presence of the scleractinian coral species themselves other than to provide them with some protection from the worst ravages of violent seas and predators that would assail them more easily if situated on open hard substrata. Other mobile macroinvertebrates need the space over which to forage whilst others are there because they are predators of the living corals or of the sessile invertebrates and slow moving invertebrates that have settled there. Large areas of coral skeletons exposed when corals die provide settlement space for the so-called 'fouling organisms' whilst others live within living coral or bore into soft calcareous skeletons to provide themselves with living space (Fig. 14.1a). Many other sessile invertebrates (especially encrusting species) are to be found established on the upper surfaces beneath rocky overhangs on the reef slopes and both mobile and sessile species make use of the multitude of microhabitats provided by many runnels, fissures, and small crevices and other 'nooks and crannies' that exist in the reef structure there.

Behind the reef front a more-or-less horizontal, generally low relief, shallow (<1 m at low water spring tides) and often very extensive back-reef of lithifying coral limestone mixed with other biogenic calcareous material is another habitat utilized by a surprising number of macroinvertebrate species. Relatively few sessile species are able to withstand settling in the open on this shallow, often apparently featureless, soft rock habitat. Frequently, however, near its junction with the reef front large stabilised coral boulders carried on to the back-reef initially during particularly bad storms provide a microhabitat for invertebrates beneath their bulk and other smaller coral rubble may accumulate in large dips and run-

nels across the back-reef providing a further habitat for colonization. Invariably there are also fissures and crevices in the back-reef platform providing another microhabitat colonized by invertebrates.

Most offshore islands also have fringing reefs of living coral and calcareous algae, but in contrast to the coastal fringing reefs are generally surrounded by deeper water with their fronts often extending to greater depths (>10 m depending on water clarity) before an interface with the calcareous sand. The species of hard and soft coral inhabiting these greater depths, which are somewhat different from those higher up reef slopes (see earlier chapters), along with the adjacent sand deposits often harbour macroinvertebrate species rarely seen in shallower waters (e.g. certain polychaetes and echinoderms).

In many areas of the SE Gulf, particularly offshore from the extensive north-facing coastline of Abu Dhabi Emirate, Pleistocene limestone rock and other pre-Holocene rocks do not always reach above sea level as islands, but instead form nuclei at their shallowest points for the development of more recent extensive shallow coral reef shoals. The reef fronts of these shoals facing the full force of the prevailing north-westerly winds have a varied selection of microhabitats under rock overhangs, in runnels, and in cracks and crevices available for occupation by a more species-rich selection of non-coral macroinvertebrates than on inshore mainland fringing reef faces due to the less polluted and less silt-laden water conditions that exist offshore. Other reef-slope areas around such shoals that do not directly face the prevailing winds have a wider range of coral species present, including in their shallows stands of branching acroporid corals that provide extra three-dimensional microhabitats for occupation by macroinvertebrates unable to withstand the physical rigours of life on reef fronts facing directly into the prevailing winds.

Behind the advancing coral reef fronts of the shoals vast areas of lithifying shallow reef rock platform are available for colonization by non-coral macroinvertebrates. These platforms have running over them an almost constant flow of wind- and tide-driven water currents often with a residual dominant direction of flow driven by the prevailing winds. This water flow carries coarse calcareous sand from unconsolidated offshore sediments during rough sea conditions up and over the coral reef front and deposits it as a thin unstable surface layer of sand on the shoal platform behind. Despite the reef-top of offshore shoals being a constantly changing habitat it is one in which a different range of primarily rock-dwelling sessile and mobile macroinvertebrates are able to survive successfully amongst stabilised coral rock boulders and coral rubble thrown up (and then sometimes regrowing) on to the shoal platform during storms, and in large fissures and crevices in the platform surfaces. Some sessile macroinvertebrate

groups appear able to live permanently on flat uncreviced shoal surfaces as long as these are far enough away from windward reef faces to ensure that they are not dislodged by wave action and remarkably are even able to survive periodic inundation by a covering of sand (see later for details of these groups). In other areas atop large surface area shoals where water movements are even less energetic, sand sometimes accumulates to such a depth that seagrass beds are able to establish themselves and stabilise the sand accumulations still further and to such an extent that yet another subtidal reef habitat for colonization by benthic macroinvertebrates is provided. This habitat will not be dealt with in detail in this chapter although references will be made to the non-coral macroinvertebrates found on and in seagrass beds on reef shoal platforms.

In sheltered nearshore shallow areas less than 2–4 m deep where a limestone substratum protrudes from the sand, patch reefs dominated by *Acropora* corals are a common feature in the SE Gulf (see earlier chapter), although in recent times severely degraded. These branching fast-growing *Acropora* corals form an open three-dimensional thicket of branches that provides sheltered microhabitats for numerous non-coral macroinvertebrate groups as well as fish and in which slow-growing poritid and faviid corals provide a less important role in terms of microhabitat for colonizing macroinvertebrates than they do in slightly deeper water where they dominate. This is exemplified by a situation at the wind-exposed eastern end of Abu Dhabi Emirate where isolated, but structurally substantial, offshore patch reefs often no more than 100 m across and composed predominantly of poritid and faviid corals protrude from the surrounding coarse sand at a depth of 6–8 m where the leading invertebrate microhabitat-providing roles of the corals is reversed as the branching acroporids struggle to survive in the often sediment-laden rough sea conditions that prevail there.

13.3 Non-coral Macroinvertebrate Groups Recorded on SE Gulf Reefs Between 1996 and 2008

In the following section attention will also be drawn to those macroinvertebrate groups whose ecology, biology and feeding behaviour has been generally overlooked in published research work on coral reef ecosystems of the Gulf. Notable amongst these are the sponges, most soft-bodied worm-like groups, sea mats, and sea squirts. Within each group treatment is a list or table of taxa of which a few easily recognised species were identified *in situ*, but mainly collected by myself with assistance on occasions of V.J.H. Pappin, C.J.H. Spurrier, and latterly C.W. Teasdale

for examination by specialist invertebrate taxonomists at the Natural History Museum, London (NHM). The collections now reside at the NHM, apart from a few specimens that have been retained by experts elsewhere for further examination.

13.3.1 Porifera

The Porifera (sponges) (Table 13.1, Fig. 13.1), a phylum of primitive multicellular invertebrates, is represented by a large number of species on the shallow coral/algal reefs in the region although often encrusting in cryptic microhabitats such as under rock overhangs and boulders and in crevices. The two classes of sponge present on the reefs are the Calcarea with skeletal spicules composed of calcite (Fig. 13.1b), and the Demospongiae whose skeletal elements are of silica and/or spongin fibres. The Demospongiae are by far the largest group on reefs and are known to play an important role in reef ecosystems elsewhere in the world (see Bell 2008; Sheppard et al. 2009 for the latest discussions on the functional roles of sponges). All are sessile suspension feeders, efficiently filtering large quantities of particulate organic debris and minute planktonic organisms from the water column. Water is drawn into the interior of the body through a large number of small pores (ostia) on the body surface by powerful inhalent currents generated by the beating in unison of whip-like flagellae of numerous specialised cells situated in chambers within the body and connected to the surface pores by intricate networks of canals. After filtration of food particles and diffusion of oxygen through the cells lining the canals and chambers the filtered water passes out of the body by means of exhalent canals leading to fewer but generally much larger pores (oscula) that are readily visible to the naked eye (Fig. 13.1c). Pumping of water through the body is not a continuous process but occurs in cycles probably dictated by the availability of food in the water column coupled with its own physiological needs. In addition many species gain extra nutritional supplements (e.g. fixed carbon) provided by endosymbiotic photosynthetic cyanobacteria, dinoflagellates or unicellular green algae (Trautman and Hinde 2001) (Fig. 13.1d). Certain species of sponge that contain phototrophic symbionts have been observed to bleach and some to die during episodes of unusually high water temperature stress that also cause bleaching in corals (Vicente 1990; Fromont and Garson 1999). It is not known, however, whether sponges containing phototrophic symbionts in the SE region of the Gulf were affected during the severe episodes of unusually high and prolonged water temperatures during the summers of 1996, 1998, 2002 and 2010 (see Chap. 1), although it is likely. Many of the more upright sponges in the Gulf provide a protective habitat and

Table 13.1 Porifera of the reefs of the Gulf Emirates. Identifications by M. Kelly, spicule preparations by C. Valentine

Class Calcarea	<i>Nara</i> cf. <i>nematifera</i> de Laubenfels, 1954	
Subclass Calcinia	<i>Sigmadocia</i> sp.1	<i>Sigmadocia</i> sp.2
Order Clathrinida	<i>Toxadocia</i> sp.	
Family Clathrinidae	Family Haliclونidae	
<i>Clathrina darwinii</i> (Haeckel, 1870)	<i>Haliclona</i> sp.1	<i>Haliclona</i> sp.5
Family Leucettidae	<i>Haliclona</i> sp.2	<i>Haliclona</i> sp.6
<i>Leucetta</i> sp.	<i>Haliclona</i> sp.3	<i>Haliclona</i> sp.7
Class Demospongiae	<i>Haliclona</i> sp.4	<i>Haliclona</i> sp.8
Subclass Homoscleromorpha	Family Adocidae	
Order Homosclerophorida	<i>Adocia atra</i> Pulitzer-Finali, 1993	
Family Plakinidae	<i>Gellius</i> sp.	
<i>Plakortis</i> sp.	Family Callyspongiidae	
Subclass Tetractinomorpha	<i>Callyspongia</i> sp.1	<i>Callyspongia</i> sp.4
Order Hadromerida	<i>Callyspongia</i> sp.2	<i>Callyspongia</i> sp.5
Family Suberitidae	<i>Callyspongia</i> sp.3	
<i>Suberites</i> sp.1	<i>Suberites</i> sp.2	<i>Dactylia</i> sp.1
<i>Laxosuberites</i> sp.1	<i>Laxosuberites</i> sp.3	<i>Dactylia</i> sp.2
<i>Laxosuberites</i> sp.2	Family Arenosclera sp.	
<i>Prosuberites</i> sp.	Family Niphatidae	
Family Tethyidae	<i>Amphimedon</i> sp.	
<i>Tethya robusta</i> (Bowerbank, 1873)	<i>Cribrochalina</i> sp.	
<i>Tethya seychellensis</i> (Wright, 1881)	<i>Niphates</i> cf. <i>cavernosa</i> Kelly and Berquist, 1988	
<i>Tethya</i> sp.1	<i>Tethya</i> sp.2	<i>Niphates</i> sp.
Family Clionidae	Order Dictyoceratida	
<i>Cliona</i> sp.	Family Spongiidae	
Family Timeidae	<i>Spongia</i> sp.	
<i>Timea</i> sp.	<i>Hippospongia</i> sp.	
Family Chondrosiidae	<i>Hyatella intestinalis</i> (Lamarck, 1914)	
<i>Chondrilla</i> cf. <i>nucula</i> Schmidt, 1862	<i>Hyatella</i> sp.	
<i>Chondrilla</i> sp.	Family Irciniidae	
Order Halichondrida	<i>Ircinia</i> sp.1	<i>Ircinia</i> sp.3
Family Axinellidae	<i>Ircinia</i> sp.2	
<i>Stylissa flabelliformis</i> (Hentschel, 1912)	Family Thorectidae	
Family Desmoxidae	<i>Fascaplysinopsis</i> sp.	
<i>Heteroxa</i> sp.	<i>Hyrtios</i> sp.	
Family Halichondriidae	<i>Laffariella</i> sp.	
<i>Halichondria</i> sp.1	<i>Halichondria</i> sp.3	<i>Petrospongia</i> n.sp.
<i>Halichondria</i> sp.2	<i>Halichondria</i> sp.4	Family Dysideidae
Order Poecilosclerida	<i>Dysidea chlorea</i> de Laubenfels, 1954	
Family Mycalidae	<i>Dysidea</i> (Eury spongia) sp.1	<i>Dysidea</i> sp.5
<i>Mycale</i> cf. <i>cecilia</i> de Laubenfels, 1936	<i>Dysidea</i> sp.2	<i>Dysidea</i> sp.6
<i>Mycale</i> (<i>Carmia</i>) sp.1	<i>Dysidea</i> sp.3	<i>Dysidea</i> sp.7
<i>Mycale</i> sp.2	<i>Dysidea</i> sp.4	<i>Dysidea</i> sp.8
Family Desmacionidae	<i>Euryspongia</i> sp.1	<i>Euryspongia</i> sp. 2
<i>Chondropsis</i> sp.	Order Dendroceratida	
Family Tedaniidae	Family Darwinellidae	
<i>Tedania</i> sp.1	<i>Tedania</i> sp. 2	<i>Chelonaplysilla violacea</i> (Lendenfeld, 1883)
Family Myxillidae	<i>Chelonaplysilla</i> sp.	
<i>Myxilla</i> (<i>Burtonanchora</i>) sp.	<i>Darwinella</i> sp.	
Family Clathriidae	<i>Dendrilla</i> sp.	
<i>Clathria</i> (<i>Microcionia</i>) sp.	Family Dictyodendrillidae	
<i>Clathria</i> (<i>Thalysios</i>) cf. <i>reinwardti</i> (Vosmaer, 1880)	<i>Acanthodendrilla</i> sp.	
Order Haplosclerida	Family Halisarcidae	
Family Chalinidae	<i>Halisarca</i> sp.	
<i>Acervochalina</i> cf. <i>confusa</i> (Dendy, 1921)	Order Verongida	
<i>Acervochalina</i> sp.1	<i>Acervochalina</i> sp.3	Family Aplysiniellidae
<i>Acervochalina</i> sp.2	<i>Acervochalina</i> sp.4	<i>Aplysinella rhax</i> (de Laubenfels, 1954)
		<i>Pseudoceratina purpurea</i> (Carter, 1865)
		<i>Pseudoceratina</i> sp.

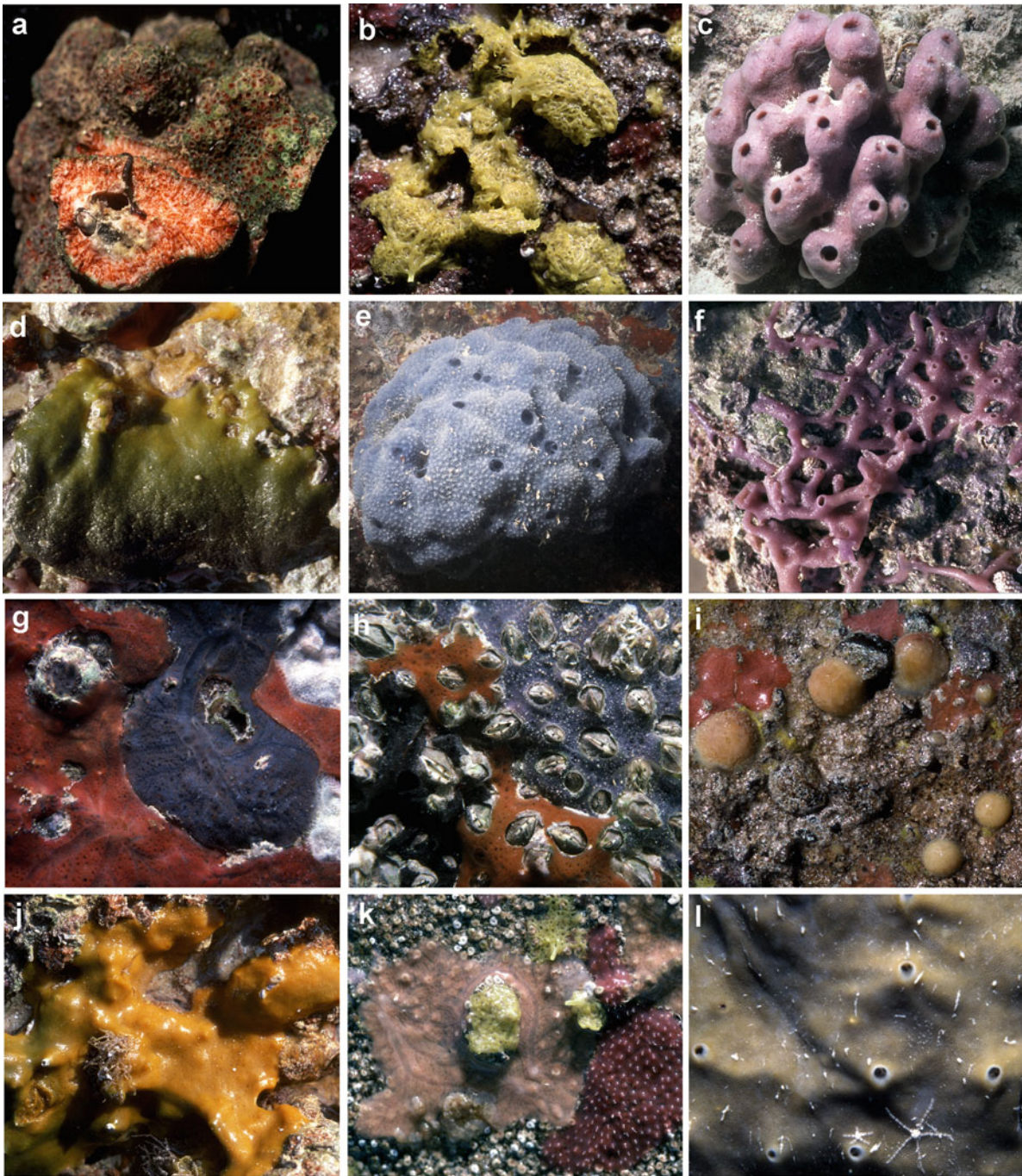


Fig. 13.1 (a) Dead faviid coral bored by the orange/red sponge *Cliona* sp. and the bivalve mollusc *Lithophaga robusta*. (b) The only common calcareous sponge *Clathrina darwinii* under stabilised coral boulders in Abu Dhabi. (c) The sponge *Gellius* sp. with its large oscula readily visible situated on a reef platform. (d) Normally yellow suberitid sponge *Laxosuberites* sp. with endosymbiotic cyanobacteria 'greening' the tissues exposed to strong sunlight. (e) *Dysidea chlorea* is seen often in most available coral reef habitats in Abu Dhabi. (f) Anastomosing network of branches of a *Haliclona* sp. under a piece of coral rock. (g) *Mycale cecilia* and a blue *Chelonaplysilla* sp. on the underside of sheltered coral rock. (h) Red *Clathria (Microciona)* sp. and a blue *Nara* cf. *nematifera* surrounding living barnacles (*Balanus amphitrite*) on the underside of sheltered coral rock. (i) The spherical growth of *Tethya robusta* and polygonal surface patterning is distinctive of the genus. The sponge, which is anchored with a 'skirt' of tissue threads on the underside of stabilised coral boulders and in crevices, occurs more commonly in

Abu Dhabi Emirate in the shallows of reef platforms, often amongst other encrusting sponges such as the red *Clathria (Microciona)* sp. also seen in the photograph. (j) *Pseudoceratina purpurea* can form large masses under sheltered overhangs and also amongst jumbles of coral boulders where it can help to stabilise them. It often has endosymbiotic cyanobacteria in its surface tissues in well-lit areas. (k) *Darwinella* sp., a maroon-coloured flat encrusting sponge with protruding white mineralised fibres, is an easily recognised species and common under overhangs and coral boulders in reef shallows. *Halisarca* sp., the pink sponge, is also common in the same habitat type. The coiled white calcareous tubes are of the serpulid polychaete *Janua (Fauveldora) kayi*. (l) The colour of *Chondrilla* cf. *nucula* varies from pink to khaki, but can be distinguished from other sponge species by the netted appearance of its surface combined with the colourless ring of tissue around its osculae. Small brittlestars on its surface may be feeding on mucus secretions of the sponge (All images © D. George)

a constant source of particulate organic matter in their intricate complex of internal channels for endosymbiotic and 'opportunistic' macroinvertebrates such as polychaete worms, amphipods, shrimps and crabs and sometimes even have a particular modified genus of barnacle (*Acasta*) embedded in their tissues. Brittlestars are also frequently found with their arms spread on the outside of larger sponges (Fig. 13.10l) utilizing the food brought by the inhalent currents generated by the sponge.

Certain species of *Cliona* cause considerable structural damage to dead scleractinian corals on SE Gulf reefs since they are endolithic borers (George and John 1999, 2004, 2005a) (Fig. 13.1a). Another taxon present in the SE Gulf (*Clathria (Microciona)* sp.) is known to overgrow and kill living *Porites lutea* corals in the nearby Arabian Sea (Benzoni et al. 2008), although it has not been observed in the Gulf to do so. By contrast other sponge species present on reefs in the SE Gulf (e.g. *Dysidea* spp. (Fig. 13.1e), *Haliclona* spp. (Fig. 13.1f), *Halichondria* spp.) have, in recent years at least, made an important contribution (along with calcareous algae) to reef stability by binding together loose coral rubble, particularly dead branches of the staghorn coral *Acropora*. Most encrusting sponges occur under sheltered reef overhangs, under stable coral rock boulders on offshore reef shoal tops and on coastal reef platforms as far inshore as the intertidal zone. They include a large range of colourful species including *Mycale cecilia* and *Chelonaplysilla* sp. (Fig. 13.1g), *Nara* cf. *nematifera* and *Clathria (Microciona)* sp. (Fig. 13.1h), *Tethya robusta* (Fig. 13.1i), *Pseudoceratina purpurea* (Fig. 13.1j), *Darwinella* sp. and *Halisarca* sp. (Fig. 13.1k), *Chondrilla* cf. *nucula* (Fig. 13.1l). With few exceptions (e.g. *Adocia atra* (Fig. 13.2a) and some *Haliclona* species) large branching sponges are not common on the reefs of the SE Gulf and only occur in sheltered situations away from the exposed north-facing reef fronts. A *Haliclona* sp. is sometimes found with its branches straggling within seagrass beds at the base of sheltered reef slopes or amongst seagrass on top of extensive reef shoal platforms. *Amphimedon* sp. (Fig. 13.2b) is also located occasionally in seagrass beds adjacent to coral reefs.

Although many sponges manufacture toxins to prevent other organisms settling on them, overgrowing them or eating them, they are nevertheless preyed upon by some other marine species. Notable among these are many sea slugs, some crabs, starfish, fish, and hawksbill turtles all of which have evolved defences against the toxins produced by the sponge they are eating.

Individual sponge species can have a variable body form depending on the environmental conditions under which they live and are difficult to identify to species level in the field. According to Kelly (2002) useful field characters for

identification to genus level at least include, in addition to microhabitat, shape and distribution of oscula, ostia distribution, texture of the surface and compressibility of the sponge body as a whole, colour in life (as well as when preserved in alcohol), colour changes and quantity of mucus exuded on exposure to air as well as a sponge's odour. Once in the laboratory there is a need to examine general skeletal architecture as well as the type, shape and size of the spicules.

Hooper et al. (2000) and Kelly (2002) list pertinent sponge literature from the West Indian Ocean. No detailed taxonomic studies exist on the identity of reef-associated Gulf species apart from those by Kelly (personal communication) from a large collection made in Abu Dhabi Emirate between 1995 and 2001 by NHM scientists (George 2005; George and John 2004; John and George 2004). Additionally, Al-Ansi and Al-Khayat (1999) list sponges that they identified from coral reef grounds off the east coast of Qatar.

13.3.2 Cnidaria

The phylum Cnidaria (previously known as the Coelenterata) contains a large diverse group of macroinvertebrates (Table 13.2) that is often divided into three useful groupings Scyphozoa (jellyfish), Anthozoa (sea anemones and corals), and Hydrozoa (includes hydroids). Although benthic members of the phylum are variable in appearance they are all composed of the same basic structural unit (the polyp) that is radially-symmetrical about a central axis and consists of a sac-like body with food-capturing tentacles surrounding its single opening through which captured food passes inwards and waste products are voided outwards periodically. A species may be a single large polyp or be made up of large groups of these basic units linked together to form a whole. Taxa of the Anthozoa' form the building blocks, along with coralline algae, for the reefs that we see today. Orders within the Zoantharia [=Hexacorallia] (tentacles and internal septa of the polyps often numbering six or larger multiples of this number) apart from corals present on SE Gulf reefs are the Actiniaria (sea anemones) and the Ceriantharia (tube anemones) (Fig. 13.2c, d) that have no calcareous skeleton and play a minor role in the reef ecosystem compared with the hard corals. Generally in the turbid waters of the southern Gulf, reefs do not extend to great enough depths to have representatives of the order Antipatharia (so-called black corals, but yellow in life) (Fig. 13.2e), although they are certainly present on limestone or rock faces in the deeper waters of the offshore islands of the Gulf Emirates (e.g. Dalma) and Iranian coastal islands as are actinarians that are only seen occasionally on inshore reefs (Fig. 13.2f-h).



Fig. 13.2 (a) The dark brown branching sponge *Adocia atra* is flexible enough to 'stream out' in strong currents, but cannot withstand rough seas. (b) This unidentified *Amphimedon* sponge species is usually found in quiet sheltered waters amongst seagrass with its sticky surface covered with sediment particles. (c) Unknown species of *Cerianthus* photographed in low light conditions and showing the main features of the Order: inner and outer rows of tentacles and its tube. (d) *Pachycerianthus maua* embedded in sand amongst seagrass on a reef shoal platform. (e) *Antipathes* sp., the commonest antipatharian in the deeper reefs of Abu Dhabi Emirate. (f) *Aiptasia* sp. is sometimes found attached to reef rock

in the shallows of the Gulf Emirates. (g) A sagartiid anemone on coral rubble off the Gulf Emirates. (h) An unidentified translucent anemone on a wreck off the Gulf Emirates. (i) The easily recognisable bulbous tips of the retracted tentacles of the large anemone *Entacmaea quadricolor*. When fully extended the tentacles resemble those of another anemone *Heteractis crispa*, with which it may be confused. (j) *Heteractis crispa* with an attendant clownfish *Amphiprion clarkii* seen on a coral reef off Abu Dhabi Emirate. (k) *Stichodactyla mertensii* with an attendant *Amphiprion clarkii* photographed off the Iranian Gulf coast (Images a–e, i, j © D. George; f–h © F. Dipper; k © K. Samimi-Namin)

Table 13.2 Non-coral Cnidaria of the reefs of the Gulf Emirates. Identifications by P. Cornelius and D. George

Subphylum Medusozoa	Subphylum Anthozoa
Class Hydrozoa	Class Ceriantipatharia
Subclass Hydroidolina	Order Antipatharia
Order Leptothecata	Family Antipathidae
Family Aglaopheniidae	<i>Antipathes</i> sp.
<i>Macrorhynchia philippina</i> Kirchenpauer, 1872	Order Ceriantharia
Family Campanulariidae	Family Cerianthidae
<i>Obelia</i> sp.	<i>Pachycerianthus</i> cf. <i>maua</i> (Carlgren, 1900)
Family Kirchenpaueriidae	Class Alcyonaria (=Octocorallia)
<i>Ventromma</i> sp.	Order Gorgonacea
Family Pennariidae	Family Plexauridae
<i>Pennaria disticha</i> Goldfuss, 1820	<i>Menella indica</i> (Ridley, 1888)
Family Lafoeidae	Class Zoantharia (=Hexacorallia)
<i>Zygophylax</i> sp.	Order Actiniaria
Family Plumulariidae	Family Actiniidae
<i>Plumularia</i> cf. <i>setacea</i> (Linnaeus, 1758)	<i>Anthopleura</i> cf. <i>carneola</i> (Verrill, 1905)
Family Sertulariidae	<i>Entacmaea quadricolor</i> Rüppell and Leuckart, 1828
<i>Amphisbetia</i> sp.	Family Diadumenidae
<i>Diphasia</i> sp.	<i>Diadumene</i> sp.
<i>Dynamena</i> sp.	Family Edwardsiidae
<i>Idiellana pristis</i> (Lamouroux, 1816)	<i>Edwardsianthus pudica</i> (Klunzinger, 1877)
<i>Sertularella</i> cf. <i>diaphana</i> (Allman, 1886)	Family Hormathiidae
<i>Sertularella</i> sp.	<i>Calliactis polypus</i> (Forsskål, 1775)
<i>Thyroscyphus</i> cf. <i>fruticosa</i> (Esper, 1793)	Family Stichodactylidae
Order Anthoathecata	<i>Heteractis crispa</i> (Ehrenberg, 1834)
Family Solanderiidae	<i>Stichodactyla haddoni</i> (Saville-Kent, 1893)
<i>Solanderia</i> cf. <i>procumbens</i> (Carter, 1873)	

Anemones, like most of the calcareous corals, are capable of catching and incapacitating prey with the aid of their batteries of stinging and/or adhesive cnidae on their tentacles and passing it through their mouths into the gastric cavity. However, many also have symbiotic photosynthetic dinoflagellates in their tissues that considerably aid their nutrition on shallow reefs where strong sunlight occurs. Although anemones are not common on SE Gulf reefs solitary individuals can be seen protruding from narrow gaps between living corals, but with their bases firmly attached deep within the crevices into which they can withdraw if disturbed (e.g. *Entacmaea quadricolor*, *Heteractis crispa* and *Stichodactyla mertensii*) (Fig. 13.2i–k). Larger specimens of these anemones are a common host for the clown

fish *Amphiprion clarkii* (Fig. 13.2j, k). Interestingly certain taxa of anemone (e.g. *Calliactis polypus*) are commensal on the empty shells of gastropod molluscs that have been occupied by hermit crabs (e.g. by *Dardanus pedunculatus*, *D. tinctor*) (Fig. 13.3a). This hermit crab commensal is sometimes seen along with its host on the calcareous sand deposits between coral mounds, and the sediment-dwelling anemone *Edwardsianthus pudica* is also found in this habitat.

The Alcyonaria [=Octocorallia] (soft and flexible corals whose polyps have eight tentacles and internal septa) is well represented along the Iranian Gulf coast (Samimi-Namin and van Ofwegen 2009 and see chapter by Samimi-Namin and van Ofwegen).

The bottom-dwelling members of the Hydrozoa (commonly called the hydroids) are among the least well-known of the colonial cnidarians and their taxonomy is confused. The latest classification (Schuchert 2009) uses a subclass Hydroidolina that is divided into two orders, the Leptothecata (= thecate hydroids) whose members have protective cups (hydrothecae) around their small feeding polyps and the Anthoathecata (= athecate hydroids) that do not. The Leptothecata are important members of the present day ‘fouling’ community of the SE Gulf, where they overgrow dead corals (Fig. 13.3b–f). Once established they can expand the size of their colonies rapidly by asexual budding and their many feeding polyps provide a major hazard for coral planulae attempting to settle as do suspension feeding members of the fouling community such as sponges and ascidians.

13.3.3 Platyhelminthes

The phylum Platyhelminthes is best known for its parasitic organisms. However, the polyclad Turbellaria contain free-living species (flatworms) that inhabit Gulf coral reefs. They have bilaterally symmetrical much flattened unsegmented acoelomate soft bodies with a mouth on the underside leading to a pharynx that can be everted in some species to engulf prey. They usually have a multi-branched intestine, but no anus. The head can have a pair of permanent tentacles in some families whilst in others there are pseudotentacles that are formed from folds in the anterior margin of the body (e.g. *Pseudoceros*, *Pseudobiceros*) (Fig. 13.3g, h). Various sensory organs such as primitive light sensors are present on the upper surface of the body usually towards the anterior end. Dense masses of epidermal cilia beating in unison on the ventral side combined with secretions of mucus from glands allow the worms to glide forward. Many are also capable of swimming using waves of movement along the body from front to back. Reef-dwelling forms often have distinctive colour patterns on their dorsal surface and as a result are



Fig. 13.3 (a) Commensal anemone *Calliactis polypus* attached to a gastropod shell occupied by the hermit crab *Dardanus tinctor*. (b) A mixture of hydroids on dead coral that includes species of *Dynamena*, *Obelia* and *Plumularia*. (c) *Pennaria disticha* is one of the most frequently seen hydroid species in reefal situations in the SE Gulf as it can grow up to 30 cm or more in height and has white polyps and black stems. (d) This unidentified species of *Sertularella* that has red stems and hydrothecae that are often covered with fine sediment seems to flourish in turbid water conditions, particularly where there is a moderate current. (e) Another sertulariid, thought to be a species of *Dynamena*, living in the turbid water conditions of reefs in the SE Gulf. This colony has its polyps fully extended despite a covering of sediment. (f) *Macrorhynchia philippina* has a painful sting and although common on reefs outside the Strait of Hormuz is rarely seen within the Gulf. (g) *Pseudoceros* cf. *rubronanus* in the shallows of a

reef platform in Abu Dhabi Emirate. (h) *Pseudobiceros* sp. on the didemnid ascidian *Didemnum perlucidum* on a coral reef in the SE Gulf. (i) Lateral view of the solitary 'mobile' coral *Heteropsammia cochlea* with the sipunculan *Aspidosiphon* (*Aspidosiphon*) *muelleri muelleri* protruding from its base; (i inset) ventral view of the coral's base showing the large orifice from which the sipunculan protrudes. (j) *Eurythoe complanata* is known as a 'fireworm' as its long brittle chaetae break off easily and lodge in the skin if handled. Apart from causing minor mechanical irritation there are glands at the base of the chaetal bundles that produce a secretion that can cause intense pain. (k) The anterior end of a cirratulid *Tharyx* sp. clearly showing its pair of muscular grooved feeding tentacles that are readily distinguishable from the segmentally arranged more delicate respiratory branchiae (Images © D. George except a, j © C. Harris and i © Nautica Environmental Associates)

sometimes mistaken for nudibranch molluscs even though they have no gills (see later). Prudhoe (personal communication and 1985, 1989) and Newman and Cannon (1995a) believe that these colour patterns help to distinguish species much as they do in the nudibranchs, thus photography of living material before it is preserved is of considerable importance to specialists in the group, especially as the animals are fragile and may fragment as well as lose their colour and pigmentation if not preserved carefully (Newman and Cannon 1995b, 2003, 2005).

All reef-dwelling platyhelminths appear to be carnivorous, feeding on a range of sessile colonial macroinvertebrates such as corals, bryozoans, ascidians, or on small gastropods, bivalve molluscs and barnacles that are plentiful in the SE region of the Gulf. Predatory fish are said to be wary of flatworms because some exude distasteful mucus whilst others may avoid capture by mimicking nudibranch molluscs containing toxic substances. They are generally cryptic in nature and always seem to move away from the strong light but can be found often with their prey under coral boulders on reef platforms as well as amongst coral rubble, under overhangs, and in cracks and crevices on the reef front.

The only taxa to be identified to date from coral reefs of the Gulf Emirates are *Pseudoceros* cf. *rubronanus* and *Pseudobiceros* sp.

13.3.4 Nemertea

The Nemertea (ribbon-worms) are mainly marine free-living unsegmented bilaterally symmetrical flattened worms that are acoelomate with a separate mouth (usually vertically placed behind the head) and anus. Their long eversible muscular proboscis may be armed with one or more piercing spikes or unarmed but with sticky mucus. This distinction is currently used to divide the phylum into two classes. They are rarely seen in the open on coral reefs in the SE Gulf, but can be located occasionally under coral boulders, amongst coral rubble and in crevices in the limestone surfaces of reef platforms. Individuals in the Arabian region are thought to prey primarily on polychaetes (Vine 1986), but opisthobranchs and small crustaceans have also been targeted elsewhere in the world. Species are difficult to identify and histological studies on the proboscis and other parts of the body are essential for identifications (Gibson 1983, 1995, 1997). No detailed studies of the phylum have apparently been carried out on Gulf reefs and Jones (1986) only recorded two species from Kuwait. To date the only species to be provisionally identified from reefs of the Gulf Emirates are *Basiodiscus unistriatus* (Isler, 1900), *B. hemprichii* (Ehrenberg, 1831), *Notospermus* sp. and *Lineus* sp.

13.3.5 Sipuncula

The phylum Sipuncula (peanut worms) is another small but less obscure phylum than the Nemertea in the SE Gulf. Members of the phylum are unsegmented, soft-bodied, coelomate invertebrates with an extensible 'introvert' bearing a mouth, sometimes surrounded by tentacles, at its anterior end. The introvert in some species can be completely retracted back into the body. The gut is long and coiled and terminates in an anus situated at the front end on the dorsal side near its junction with the introvert. With their introvert extended they feed on surface deposits from which they extract plant and animal organic matter. Specimens can sometimes be found embedded in dead coral and in coral rock boulders if broken open with a sharp blow from a hard object, and also in clefts in the rock on back reef and shoal platforms. The developing juveniles of some species are said to be able to bore by chemical means into the soft calcareous materials such as coral rock and shells. There is a well-researched symbiotic relationship between the sipunculan species *Aspidosiphon* (*Aspidosiphon*) *muelleri* *muelleri* Diesing, 1851 and the solitary corals *Heterocyathus aequicostatus* and *Heteropsammia cochlea* in the Western Indian Ocean. According to Feustal (1965) and Yonge (1975) a coral larva settles on a shell of a dead gastropod already bored by a previously settled sipunculan larva and as the coral grows it gradually envelopes the shell until the sipunculan worm protrudes from the base of the coral (Fig. 13.3i). The relationship is mutually beneficial since the sipunculan has a safe haven into which to retire if attacked by a predator whilst feeding on organically rich surface sediment deposits. The coral is prevented from being buried by sediment during rough seas by the activities of the sipunculan as it pulls its 'shell home' along and is able to brush its tentacles along the surface of the sediment to pick up suitable organic matter as well as to feed on plankton in the normal way. Both the sipunculan and its coral hosts occur on sediments amongst coral reefs in the Gulf Emirates although not strictly coral reef inhabitants. Apart from the species above the only species identified so far from the SE Gulf was a *Phascolosoma meteori* (Hérubel, 1904) located by splitting open coral rock. Jones (1986) also reported finding this papillated species in crevices low on the shore in Kuwait and Al-Khayat and Al-Ansi (2008) on subtidal reefs of Qatar amongst pearl oysters. For monographs and reviews see Stephen and Edmonds (1972), Cutler (1994) and Edmonds (2000). No detailed investigations of reef-dwelling sipunculans have been carried out in the Gulf.

13.3.6 Echiura

Members of the small phylum known as the Echiura (spoon worms) have a similar coelomate bilaterally symmetrical body form to the Sipuncula with a bulky muscular trunk

and a variously-shaped proboscis, depending on the taxon to which it belongs, that is very extensible but which cannot be retracted into the trunk. The proboscis does not bear the mouth that is instead situated at the anterior end of the trunk beneath the proboscis. In some genera a ring or rings of chaetae surround the body near the posterior end. In addition a pair of chaetae is often present on the ventral surface of the trunk quite close to the mouth. They have a long winding gut suspended within the coelom that ends in an anus at the rear end of the trunk. The species that occur on reefs live in burrows once occupied by other organisms or in clefts in reef platform surfaces. The presence of an echiuran individual can only be detected when its proboscis is extended over the surface of the surrounding substratum whilst feeding on surface detritus. I have twice seen an echiuran proboscis extending over limestone reef rock off the coastline of Abu Dhabi Emirate, but in each case was unable to identify the individual of which it was part as I was unable to extract it from the crevice in which it was situated.

Stephen and Edmonds (1972) gave an account of the Echiura in addition to the Sipuncula. According to George and Southward (1973) the development and complex structure of echiuran chaetae is identical to that of the pogonophorans and of other polychaetous Annelida suggesting a close evolutionary relationship between them, and more recent papers by Thoai (1976) and Winnepenninckx et al. (1995) have confirmed the view that echiurans have fewer affinities with the sipunculans than was at first thought.

13.3.7 Polychaeta

The Polychaeta (bristleworms) consist of a large group of, mainly marine, typically soft-bodied worms with generally elongated bilaterally symmetrical coelomate and segmented bodies with a separate mouth and anus at either end of the body. They are often grouped together with the Oligochaeta (earthworms) and Hirudinea (leeches) into an overarching group referred to as the phylum Annelida, although there is very little scientific evidence that they form a monophyletic grouping. The basic body plan of a polychaete starting from its anterior end consists of a number of subdivisions, the presegmental prostomium and peristomium (bearing the mouth), a segmented trunk and a postsegmental pygidium (bearing the anus). Proliferation of trunk segments as a worm grows occurs from a region immediately in front of the pygidium. The sides of the body in the segmented region frequently bear a bundle of bristles (chaetae) on each side of a segment that aid in locomotion or for anchoring a worm in its tube if a tube-dweller. In mobile species that crawl actively over the substratum in search of food, the chaetal

bundles are born on side-body protruberances known as parapodia and several different types of sensory organs are concentrated on the head (prostomium plus peristomium) of the worm as well as the food-gathering appendages. Wehe and Fiege (2002) produced an annotated checklist based on the literature of species from the Arabian Peninsula. Of the 807 valid taxa only 234 were said by them to occur in the Gulf.

Many polychaete families, dominated in numbers by mobile species, exist on the shallow coral/algal reefs of the SE Gulf where they play an important role in the reef food webs, yet are rarely seen except for certain species of sessile worm that live in tubes embedded in live coral heads (or sometimes in narrow crevices in the coral heads) that inadvertently advertise their presence by beautiful fans of often brightly coloured, relatively rigid, feeding appendages extending from their tube entrances. Other sessile worm species with extensible food-collecting tentacles live under rocks or coral boulders.

Worms within the family Amphinomidae are stout-bodied, mostly voracious carnivores that browse on sponges, hydroids, coral polyps and ascidians by everting their rasping lower lip. Some species within this family protect themselves from predators with long spine-like chaetae that are easily shed and embedded in the attacker causing severe irritation as some have poison secreting glands at the base of the spines. These particular species are commonly known as 'fireworms' (Fig. 13.3j).

The Chrysopetalidae is a small enigmatic family of stout-bodied mobile worms with few species representatives in the Gulf. Little is known about their feeding preferences, but it is likely that they are opportunistic carnivores. They occur amongst corals and under coral boulders on back reefs along the coastline of Abu Dhabi Emirate.

The Cirratulidae is a cryptic family in the Gulf whose coral reef-dwelling species inhabit cracks and crevices and coral rubble where muddy sand has accumulated and also amongst the sediment accumulations around byssal threads of mussel and oyster beds on shallow reef platforms. The majority are essentially surface deposit feeders who use their extensible grooved ciliated tentacles (palps) to feed on particulate organic matter regularly dropping out of suspension in the water column on to reef platforms behind reef fronts after rough sea conditions have subsided or when tidal currents slacken (Fig. 13.3k). One genus within the family (*Dodecaceria*) has the ability to bore into dead coral, coral-line algae and other limestone surfaces and use the boring as a permanent base from which to extend its feeding tentacles into the water column as well as over nearby surrounding surfaces. Many cirratulid identifications from the Gulf are suspect since they have been assigned to species that have an essentially northern temperate distribution and not a Western Indian Ocean one.

There is some confusion as to the diet of the Dorvilleidae in the Gulf and elsewhere in the world's oceans (Fauchald and Jumars 1979). Some researchers believe they are mainly carnivorous, feeding on a diet of small invertebrates. Small genera such as *Schistomeringos* and *Ophryotrocha* survive well on a completely herbivorous diet under laboratory conditions. They were observed scraping diatoms and other algae off the glass walls of aquaria using their multi-toothed jaw apparatus rather like a radula is used by grazing gastropod molluscs. There is certainly no shortage of filamentous green algae in the SE Gulf for them to feed on.

The Eunicidae is a large family well represented on coral reefs in the Gulf (Fig. 13.4a). Most of them are free-living, but some species become tubicolous as they increase in size, some boring into dead coral excavating burrows by mechanical and chemical means, although some are claimed to occupy burrows already excavated by other invertebrates such as sipunculans (Hauenschield et al. 1968). All eunicids have well-developed sets of jaws (Hutchings 2009) and depending on species are regarded as carnivores, herbivores, omnivores and/or scavengers feeding on both invertebrate and algal material. Fauchald (1992a, b) revised species of the genera *Eunice* and *Palola* based on available type material.

The Euprosinidae is a relatively small family with few species in the Gulf. They are all errant worms with a similar body shape to the closely related Amphinomidae and are all considered to be carnivores. They are known to feed primarily on encrusting sponges, but may also feed on other sessile macroinvertebrates that they locate along with their sponge prey under sheltered overhangs on the reef slope, amongst consolidated coral rubble and in fissures and crevices on reefs in the SE Gulf.

The Hesionidae is a poorly known family of mainly small worms with only a very few larger species recorded in the Gulf in reefal environments (Fig. 13.4b). Most of the larger non-interstitial forms appear to be active carnivores that range over the surface of sediments as well as venturing on to coral rubble and other reef substrata (personal observation and Hutchings 2009) in search of prey that may include a variety of invertebrates (Fauchald and Jumars 1979). Phylogeny and classification of the Hesionidae are outlined in Pleijel (1998).

The Nereididae is a large family represented by many species in the Gulf and Wehe and Fiege (2002) report many unrecorded species. In the Gulf Emirates many nereidid species live associated with small amounts of sediment trapped in cracks and crevices on reefs, under coral boulders and under sheltered overhangs as well as in borings in coral rock that have been vacated as a result of the death of the original occupants. Others are found amongst consolidated coral rubble. Few *in situ* observations exist on the feeding

habits although some have been seen to extend out of their burrows and drawing pieces of algae from the surrounding substratum using their jaws (Fig. 13.4c, d). Some species have been detected within the inhalent channels of larger sponges and are possibly feeding on the organic matter drawn into the interior of the sponge by the strong inhalent water currents generated by the sponge or on some of the other invertebrate inhabitants of sponges such as amphipods and shrimps. Nereidids also feed on remains of soft-bodied victims of crabs and on small colonies of ascidians (personal observation). In aquaria many species take both invertebrate and green algal pieces if offered and appear to be truly omnivorous.

No members of the Phyllodocidae present on the reefs of the SE Gulf appears to be tubicolous, but instead have been found nestling in cracks and crevices and under boulders on the reef platform or amongst coral rubble or mussel aggregations. Most species are thought to prey on other polychaetes which they attack with their long eversible pharynges (Fauchald and Jumars 1979), but probably also feed on other benthic invertebrates such as small crustaceans (Fig. 13.4e, f). It is likely, as with so many other predators, that they will feed on any carrion that they find.

The Polynoidae family is well represented on reefs in the Gulf. The taxonomy of species living around the Arabian Peninsula as well as in the Gulf has been studied recently by Wehe (2006) who also gave a detailed account of the history of collections made in the Gulf. However, surprisingly little has been published on their biology and ecology in the region. They are easily recognised by the presence of pairs of overlapping scales (elytra) covering the major part of their short broad flattened bodies (Fig. 13.4g). If not seen in the open underwater on reefs they can usually be located under coral boulders, in crevices and cracks on the reef platform but are also amongst coral rubble and on the reef slope. The scales of the worm when alive can be quite colourfully patterned and this can assist with its identification if notes are made before it is preserved (Hutchings 2000). Free-living polynoids are said to be mainly carnivorous, feeding on a variety of invertebrates including sponges, hydroids, other polychaetes, small crustaceans such as amphipods, gastropods and even on echinoderms (Fauchald and Jumars 1979).

The Sabellidae is not a particularly species-rich family on the coral reefs of the SE Gulf, although many of the smaller species are found living in the surface layers of nearby calcareous sand deposits where they feed using their flexible crowns of tentacles either to extract particulate matter directly from the water column or on surface bottom deposits by flexing their bodies to allow their tentacle crowns to sweep over the deposits thereby picking up organic debris that adheres to the copious amounts of mucus secreted by the



Fig. 13.4 (a) The eunicid genus *Marphysa* has an obvious group of large gills towards the front end of the body and can be found in sediment-filled crevices as well in open sediments adjacent to reefs. (b) A hesionid with its pharynx everted showing a ring of terminal papillae. (c) Unidentified nereidid with retracted jaws and pharynx visible through the body wall. (d) Nereidid with a partly everted pharynx showing teeth (paragnaths) whose arrangement is an important character in nereidid identification. (e) *Eulalia viridis* is an agile phyllodocid worm sometimes found in cracks and crevices in the coral rock. (f) The impressive eversible pharynx of the carnivorous *E. viridis* is clearly visible in the photograph. (g) In *Lepidonotus* species the scales on the

dorsal surface do not cover the upper body of the worm completely. (h) Three different colour variants of tentacle crowns of the sabellid worm *Sabellastarte spectabilis* that occurs on Gulf reefs. (i) A blue colour morph of a member of the *Spirobranchus corniculatus* complex photographed on a reef in Abu Dhabi Emirate prior to 1998 when much of the *Porites* died. (j) The ornamented operculum used to plug the entrance to the calcareous tube of the serpulid *Hydroides elegans* when it withdraws. (k) Anterior end of the carnivorous syllid *Trypanosyllis zebra*. The eversible muscular pharynx can be seen through the body wall (Images © D. George except **h** (yellow and red crowns) © K. Samimi-Namin; **h** (white crown) © C. Harris)

tentacle crowns. Larger species that live in permanent membranous tubes, often coated with sediment and tightly wedged between coral heads or in sand pockets between corals feed only by filtering small planktonic organisms and organic fragments from the water column using their upright branchial crowns (Fig. 13.4h). They have sensory organs on their crowns that enable them to withdraw their crowns rapidly into their tubes in response to shadows passing across them and to pressure waves in the water column that might herald the approach of predators such as fish.

Members of the Serpulidae are a common sight on coral reefs in the SE Gulf with their calcareous tubes attached to the surface of dead corals, under coral boulders or protruding from cracks and crevices on the reef platform. One species belonging to the *Spirobranchus corniculatus*-complex (Fig. 13.4i) seen occasionally protruding from boulder corals such as *Porites* before the mass mortalities of this coral in 1998 (personal observation), is unusual in that it appears only to be able to live successfully in association with living coral with its tube deeply buried within the coral head (Hutchings 2009). Serpulids, like the sabellid fanworms, use a crown of tentacles to filter feed on the minute plankton and organic matter suspended in the water column. Many serpulid species have tubes whose entrance can be closed by a hard plug (operculum) formed from a modified crown tentacle, when the worm withdraws into the tube (Fig. 13.4j). A distinct group of species within the family (the spirorbiniids) are generally much smaller in size and have calcareous tubes that are helical or are coiled in either a clockwise or anticlockwise direction. Some spirorbiniids, notably *Janua (Fauvelidora) kayi* (Fig. 13.1k) can settle in large numbers on undersides of coral limestone slabs and in cracks and crevices in sheltered areas of shallow back reef platforms in Abu Dhabi Emirate as well as on algal fronds and seagrass blades.

Very few members of the family Spionidae were detected on the hard substrata of coral reefs in the SE Gulf since the majority live in burrows in sediments where they feed using their two large ciliated tentacles (palps) to capture organic particles from the water column or to deposit-feed by wiping them across the surface of the sediment. However, there are some species of the *Polydora* complex and of related genera that can bore into dead coral and into other calcareous substrata using modified chaetae on the 5th chaetiger and/or by chemical dissolution in order to provide themselves with a burrow in which to live (Sato-Okoshi 1999). *Polydora* species are often seen as a pest on commercial shellfish farms as they bore into the structure of the shells.

The Syllidae has a large number of species that are common on reefs of the SE Gulf. These mostly free-living elongated worms are active predators that can be found in sponges (Lattig and Martin 2011) amongst 'fouling organisms'

on dead coral as well as under boulders, amongst coral rubble, and in cracks and crevices on reef top platforms (Fig. 13.4k). Some feed on sponges whilst others are hydroid specialist feeders and often appear to live permanently amongst dense hydroid colonies. Most other sessile macroinvertebrate colonies including bryozoans and ascidians are also vulnerable to attack. Syllids have an eversible pharynx that is often armed with a single sharply pointed tooth or an array of teeth circling the opening.

Although members of the Terebellidae live in soft sediments, they can sometimes be found on coral reefs of the SE Gulf living in mucus-lined burrows in sediments deposited under stabilised boulders on reef slopes or on reef flats and in large sediment filled cracks and crevices, as well as around the base of coral heads protruding from the sand at reef-sediment interfaces. Their deeply grooved highly contractile feeding tentacles can often be seen protruding from beneath a rock or between coral heads and extending out for surprisingly long distances over the surrounding substratum, gathering particulate organic matter (see Hutchings 2009 for a description of how this is accomplished) (Fig. 13.5a).

A summary of habitats and feeding behaviour of polychaete families found subtidally on reefs in the SE Gulf is given in Table 13.3. Excellent summaries of the history of polychaete research in the Gulf have been given in Wehe (2006) and Wehe and Fiege (2002). Very little of eco-taxonomic value has been published on Gulf polychaetes since the 1970s papers on the polychaetes of Kuwait by Mohammad (1970a, b, c, 1971, 1972, 1973, 1975, 1980). Numerous unpublished reports (many confidential) with an extremely limited circulation were produced with a considerable amount of possibly useful information relating to polychaetes in various localities and habitats within the Gulf (e.g. O'Donnell's unpublished reports providing keys to the identification of species from the polychaete families Nereididae, Spionidae, Syllidae and Dorvilleidae from the Gulf coast of Saudi Arabia that are held in the collections of the Arabian American Oil Company).

13.3.8 Mollusca

The Mollusca is a phylum of species with highly variable body forms, most with unsegmented (one known primitive exception) soft, approximately bilaterally symmetrical, coelomate bodies with a mouth and anus and a visceral mass containing the major body organs, surrounded by a mantle that secretes the external shell if present. The phylum is generally considered to be divisible into seven classes, but only four of these (Polyplacophora, Gastropoda, Bivalvia, Cephalopoda) occur on the shallow reefs of the Gulf.

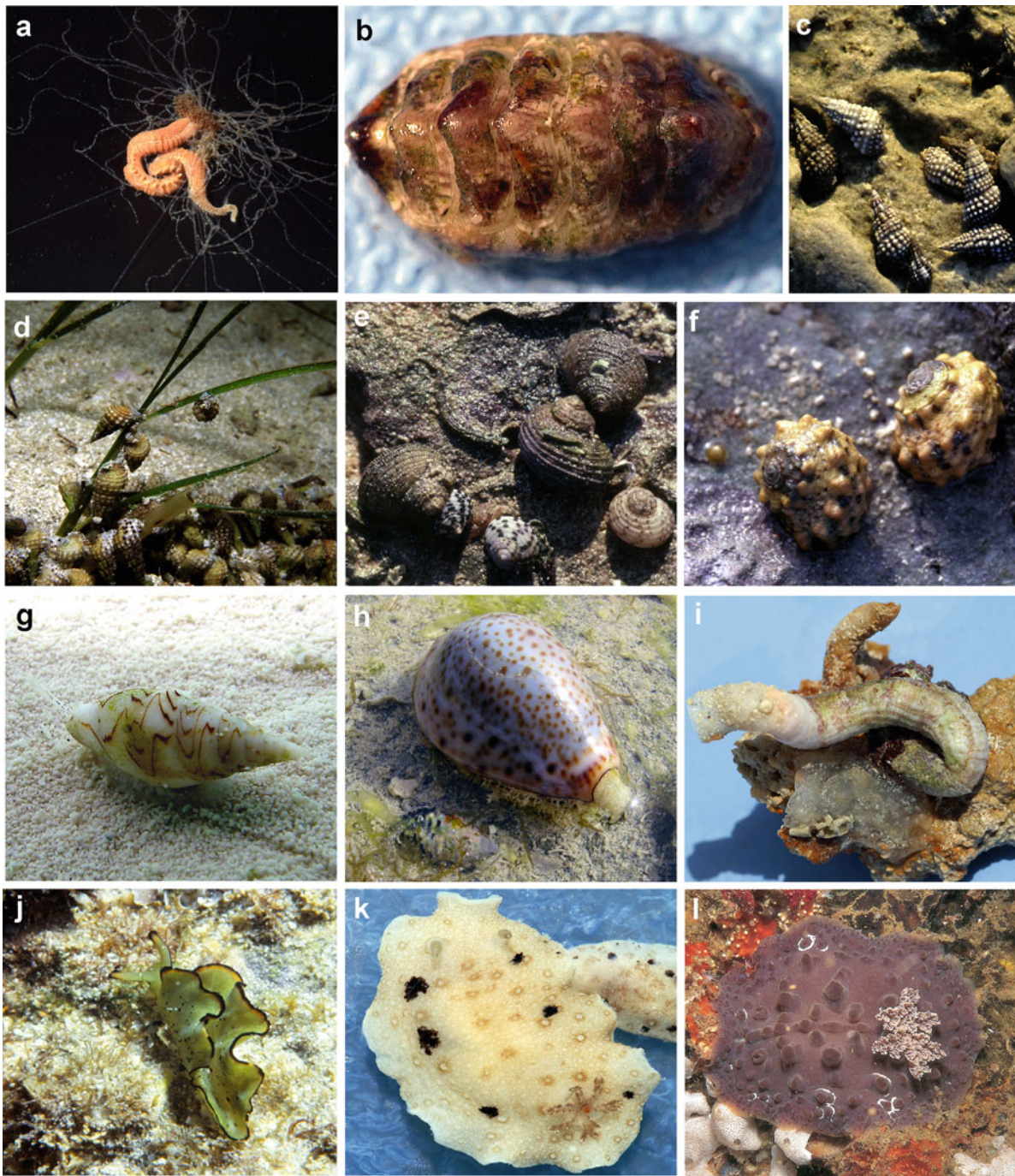


Fig. 13.5 (a) A specimen of the terebellid *Eupolyornia nebulosa* removed from the sediment to show its array of extensible feeding tentacles as well as bushy respiratory branchiae at the anterior end. (b) Dorsal view of a chitonid *Ischnochiton yerburyi* clearly showing the eight dorsal valves. (c) The cerithid *Clypeomorus bifasciatus persicus* although found under loose slabs of coral rock intertidally also occurs subtidally on shallow reef platforms where it grazes on algal films. (d) Cerithids such as *Cerithium caeruleum* and *C. scabridum* seem equally at home grazing subtidally as well as intertidally on algal films on shallow reef rock platforms as well as on biofilms on seagrass blades. (e) The trochid *Euchelus asper* is another species that is found both under intertidal coral boulders and on shallow subtidal reef platforms where algal films occur. (f) *Lunella coronata* is a turbinid that does not discriminate between the shallow subtidal of back reef platforms and the intertidal zone as long as it can obtain sufficient moist shelter

intertidally under stable coral boulders when exposed periodically to the air. (g) A columbellid *Mitrella blanda* gliding on its foot over a sand-covered reef platform in Abu Dhabi Emirate whilst searching for food. (h) The cowry *Cypraea turdus winckworthi* performing the same type of manoeuvre off Hengam Island, Iran. (i) The calcareous tube of this vermetid gastropod *Serpuloorbis variabilis* can easily be mistaken for that of a serpulid polychaete. (j) The flap-like parapodia and sensory tentacles of *Elysia ornata* are obvious features of this delicate algal-feeding species of opisthobranch. (k) The dorso-ventrally flattened body of the shallow-water-dwelling dorid nudibranch *Paradoris erythraeensis* found on top of a reef shoal in Abu Dhabi Emirate. (l) *Asteronotus cespitosus* feeds on sponges and cannot easily be visually confused with other species occurring within the Gulf (Images © D. George except g © C. Teasdale; h © K. Samimi-Namin; j © F. Dipper; l © C. Harris)

Table 13.3 Habitats and feeding behaviour of the Polychaeta of the Gulf Emirates. Identifications by A. Muir, G. Pillai, T. Wehe, D. George

Taxa	Habitat	Feeding
Family Amphinomidae <i>Euphrosyne foliosa</i> Audouin and Milne Edwards, 1883 <i>Euphrosyne myrtosa</i> Savigny in Lamarck, 1818 <i>Eurythoe complanata</i> (Pallas, 1776) <i>Linophenus</i> sp. <i>Palaeonotus debilis</i> (Grube, 1855)	In coral sand under boulders or with corals	Voracious carnivores feeding on sponges, hydroids, coral polyps and ascidians
Family Chrysopetalidae <i>Bhawania cryptocephala</i> Gravier, 1901 <i>Bhawania goodei</i> Webster, 1884 <i>Chrysopetalum debili</i> (Grube, 1855) <i>Chrysopetalum</i> sp.	Amongst coral assemblages and under coral boulders on back reefs	Opportunistic carnivores
Family Cirratulidae <i>Caulleriella</i> sp. <i>Dodecaceria jubini</i> Gravier, 1905 <i>Timarete anchylochaeta</i> (Schmarda, 1861) <i>Timarete</i> cf. <i>filigera</i> (Delle Chiaje, 1828) <i>Tharyx multifilis</i> Moore, 1909	Inhabits, crevices, cracks and coral rubble where muddy sand accumulates. Also in sediment in mussel and oyster beds on shallow reef platforms	Surface deposit feeders, using tentacles (palps) to feed on particulate organic matter
Family Dorvilleidae <i>Dorvillea</i> cf. <i>angolara</i> (Augener, 1918) <i>Dorvillia gardineri</i> (Crossland, 1924) <i>Dorvillea</i> sp. <i>Ophryotrocha</i> sp. <i>Schistomeringos incerta</i> (Schmarda, 1861)	Free-living worms on reef platforms	Mainly carnivorous feeding on small invertebrates, but smaller worms may feed on green algae
Family Eunicidae <i>Eunice antennata</i> Savigny in Lamarck, 1818 <i>Eunice indica</i> Kinberg, 1865 <i>Eunice australis</i> Quadrefages, 1866 <i>Lysidice collaris</i> Grube, 1870 <i>Lysidice ninetta</i> (Audouin and Milne Edwards, 1833) <i>Marphysa</i> sp. <i>Nematonereis unicornis</i> (Grube, 1840) <i>Palola siciliensis</i> (Grube, 1840)	Majority are free living but some larger forms may become tubicolous. Some species bore into dead coral excavating burrows	Species may be carnivores, herbivores, omnivores and/or scavengers feeding on both invertebrate and algal material
Euphrosinidae <i>Euphrosine foliosa</i> Audouin and Milne Edwards, 1833	Occur under sheltered overhangs on the reef front and amongst coral rubble and in cracks and crevices on reef platforms	Carnivores, feeding mainly on encrusting sponges and also on other sessile macroinvertebrates
Family Hesionidae <i>Hesione pantherina</i> Risso, 1826 <i>Leocrates claparedii</i> (Costa in Claparède, 1868) <i>Ophiodromus angustifrons</i> (Grube, 1878) hesionid	Larger forms can be found on coral rubble and other reef substrata	Active carnivores feeding on a variety of invertebrates
Family Nereididae <i>Ceratonereis</i> cf. <i>burmensis</i> (Monro, 1937) <i>Ceratonereis erythraeensis</i> Fauvel, 1918 <i>Ceratonereis mirabilis</i> Kinberg, 1865 <i>Ceratonereis</i> sp. <i>Leonnates decipiens</i> Fauvel, 1929 <i>Leonnates indicus</i> Kinberg, 1866 <i>Nereis coutieri</i> Gravier, 1900 <i>Nereis (Neanthes) deplanata</i> Mohammed, 1971 <i>Nereis</i> cf. <i>gisserana</i> (Horst, 1924) <i>Perinereis cultrifera</i> (Grube, 1840) <i>Perinereis nigropunctata</i> (Horst, 1889) <i>Perinereis nuntia</i> var. <i>heterodonta</i> (Gravier, 1901)	Some species are associated with sediment in cracks and crevices on reef platforms, whilst others occur under coral boulders and sheltered overhangs or in coral rubble	Probably omnivores and scavengers as some species have been observed feeding on algae, others on invertebrates such as ascidians and others on carrion

(continued)

Table 13.3 (continued)

Taxa	Habitat	Feeding
<i>Perinereis nuntia</i> var. <i>typica</i> (Grube, 1857)		
<i>Perinereis nuntia</i> var. <i>vallata</i> (Grube, 1857)		
<i>Perinereis obfuscata</i> ? (Grube, 1878)		
<i>Perinereis vancaurica</i> (Ehlers, 1868)		
<i>Platynereis</i> sp.		
<i>Pseudonereis anomala</i> Gravier, 1899		
<i>Websterinereis punctata</i> (Wesenberg-Lund, 1949)		
Family Phyllodoceidae	Occur in cracks and crevices and under boulders on the reef platform or amongst coral rubble or in mussel beds	Carnivores with many species probably preying on other polychaetes and others on small invertebrates such as crustaceans
<i>Steggoa magalaensis</i> (Kinberg, 1866)		
<i>Eulalia viridis</i> (Johnston, 1829)		
<i>Genetyllis castanea</i> (Maranzeller, 1879)		
<i>Nereiphylla castanea</i> (Maranzeller, 1879)		
<i>Phyllodoce</i> spp. (3)		
Family Polynoidae	Occur in the open on reefs, but often located under coral boulders, or in cracks and crevices on the reef platform or in coral rubble and on the reef slope	Mainly carnivores feeding on a variety of invertebrates such as sponges, hydroids, other polychaetes, small crustaceans (amphipods), gastropods and echinoderms
<i>Harmothoe</i> sp.		
<i>Lepidonotus tenuisetosus</i> (Gravier, 1902)		
<i>Lepidonotus</i> sp.		
<i>Paralepidonotus ampulliferus</i> (Grube, 1878)		
<i>Paralepidonotus indicus</i> (Kinberg, 1856)		
Family Sabellidae	Larger species occur in permanent tubes between coral heads or in sand pockets between corals. Smaller species are found living in the surface layers of nearby calcareous sand deposits	Larger species feed by filtering plankton and organic particles from the water column using their upright branched crown of tentacles. Smaller species can pick up organic matter from the sediments using their flexible tentacular crown as well as filtering organic matter from the water column
<i>Amphiglena mediterranea</i> (Leydig, 1851)		
<i>Branchiomma cingulata</i> (Grube, 1870)		
<i>Chone filicauda</i> Southern, 1914		
<i>Hypsicomus phaeotaenia</i> (Scharmda, 1861)		
<i>Jasmineira caducibranchiata</i> Willey, 1905		
<i>Potamilla ceylonica</i> Augener, 1926		
<i>Potamilla ehlersi</i> Gravier, 1906		
<i>Pseudobranchiomma</i> sp.		
<i>Notaulax phaeotaenia</i> (Schmarda, 1861)		
<i>Sabellastarte spectabilis</i> (Grube, 1878)		
Family Serpulidae	Live in calcareous tubes attached to dead corals, or under coral boulders or in cracks and crevices on the reef platform	Filter feed using a crown of tentacles to extract minute plankton and organic matter from the water column
<i>Hydroides bulbosus</i> ten Hove, 1990		
<i>Hydroides elegans</i> (Haswell, 1883)		
<i>Hydroides perezii</i> Fauvel, 1918		
<i>Hydroides</i> sp.		
<i>Janua (Fauveldora) kayi</i> Knight-Jones, 1972		
<i>Serpula</i> cf. <i>jukesii</i> Baird, 1865		
<i>Spirobranchus corniculatus</i> (Grube, 1862)		
<i>Vermiliopsis</i> sp.		
Family Spionidae	Some species e.g. the <i>Polydora</i> complex burrow into dead coral and other calcareous substances	Feed using their two large ciliated tentacles (palps) to capture organic matter from the water column or from the surface of the coral
<i>Dipolydora armata</i> (Langerhans, 1880)		
<i>Polydora</i> sp.		
<i>Pseudopolydora antennata</i> (Claparède, 1869)		
Family Syllidae	Occur under boulders, amongst coral rubble or in cracks and crevices on reef top platforms Can also be found in 'fouling organisms' on dead coral	Active predators with several species feeding on hydroids and often living permanently amongst hydroid colonies. Others feed on sessile invertebrates such as sponges, bryozoans and ascidians
<i>Branchiosyllis exilis</i> (Gravier, 1900)		
<i>Haplosyllis djiboutiensis</i> (Gravier, 1900)		
<i>Syllis gracilis</i> Grube, 1840		
<i>Trypanosyllis zebra</i> (Grube, 1860)		
<i>Typosyllis cornuta</i> (Rathke, 1843)		
<i>Typosyllis</i> cf. <i>prolifera</i> (Krohn, 1852)		
<i>Typosyllis variegata</i> (Grube, 1860)		
autolynid		

(continued)

Table 13.3 (continued)

Taxa	Habitat	Feeding
Family Terebellidae	Occur in mucus-lined burrows in sediment under boulders on the reef slope or reef flat.	Feed on particulate organic matter using deeply grooved contractile tentacles (palps) that can extend long distances over the substratum
<i>Eupolymnia nebulosa</i> (Montagu, 1818)	Also in sediment-filled cracks and crevices and in the sediment around the base of coral heads	
<i>Eupolymnia trigonostoma</i> (Schmarda, 1861)		
<i>Loimia medusa</i> (Savigny, 1822)		
<i>Neolepraea? clavata</i> (Mohammed, 1973)		
<i>Nicolea gracilibranchia</i> (Grube, 1878)		
<i>Nicolea</i> sp.		
<i>Polycirrus</i> cf. <i>plumosus</i> (Wolleback, 1912)		
<i>Streblosoma persica</i> (Fauvel, 1908)		

The class Polyplacophora (coat-of-mail shells or chitons) has a relatively few species all with a simple (primitive?) body plan. They are distinctive, having a dorso-ventrally flattened body with a strongly adhesive broad foot ventrally and a series of eight calcareous plates protecting the upper surface of the body below which a tough leathery girdle surrounding the body (Fig. 13.5b). The majority are microalgal grazers that scrape food off the substratum surface using a toothed organ known as the radula that is unique to some mollusc groups. In the SE Gulf they can be found in the open on back reef platforms as well as on dead coral and other limestone surfaces (including calcareous algae) on fringing reef slopes and on patch reefs (see Table 13.4 on the habitats and feeding types of molluscan families represented in the Gulf). Kass and van Belle (1988) wrote a paper on chitons from the coast of Oman and the Gulf.

The Gastropoda is the largest class of the molluscs and contains the snails and sea slugs (see Table 13.5). They usually have a distinctive head with a pair of sensory tentacles and eyes, and a foot with a flat ventral surface for creeping over the substratum or attaching them securely to it when necessary. Most have a variably toothed radula that is used for rasping algal food off rocks or for rasping tissue from carrion or live macroinvertebrate prey (Table 13.4). The class is subdivided into three subclasses, the Prosobranchia (snails), the Opisthobranchia (sea-slugs), and the Pulmonata that are air-breathing and adapted for life on land and therefore will not concern us further as they are not found on subtidal reefs.

Most species within the subclass Prosobranchia have either a simple domed shell or a spirally arranged shell that contains the gills and the digestive and reproductive organs (Fig. 13.5c–h). The gills are situated in the mantle cavity above the head where they are flushed with water drawn in through a siphon. Most can withdraw the head and foot into the shell if dislodged by rough seas or attacked by a predator and many species have additional protection afforded by a hard plate (the operculum) attached to the foot that can seal the entrance to the shell. The Vermetidae

(e.g. *Serpulorbis variabilis*) (Fig. 13.5i) are an exception to the general prosobranch pattern and produce long calcareous shell tubes, much like the tubes of serpulid polychaetes, that are firmly cemented to dead coral and coral rock and tightly closed by a chitinous operculum when they are not feeding on plankton and organic detritus in the water column. They feed by streaming out strings of sticky mucus, produced by a gland on the foot, into the current passing the entrance to their tube and then at intervals pulling the strings of mucus plus what particulate organic matter they have captured back into the mouth with the aid of the radula.

With few exceptions the subclass Opisthobranchia do not have shells externally or internally, and those small orders of the subclass that retain them (Cephalaspidea, Sacoglossa, Anaspidea, Pleurobranchomorpha) may have species with or without shells. The Cephalaspidea are generally considered to be the most primitive in evolutionary terms of these four orders. With few exceptions they are carnivores feeding on macroinvertebrates, but are not usually found on reefs. Sacoglossans are mainly specialized herbivores with many such as the genus *Elysia* feeding on green algae on coral reef platforms and coral rubble. They have a pair of 'rolled' sensory tentacles (rhinophores) and in the case of the green-coloured *Elysia ornata* (Fig. 13.5j) obvious flaps (parapodia) on either side of the body. Members of the Anaspidea (sea hares) are easily distinguished from other opisthobranchs since they have two pairs of sensory tentacles on their elongated head region. Members of this order are all herbivorous with the best-known genus *Aplysia*, also with prominent parapodia, occasionally seen feeding on algae on sheltered reef platforms in the SE Gulf. Species in the Pleurobranchomorpha have two pairs of rolled tentacles on the head, strong jaws, and a broad radula that allows them to graze on sponges, tunicates and other sessile macroinvertebrates. Most are capable of defending themselves against predators by excreting sulphuric acid.

The largest order in the opisthobranchs is the highly successful group known as the Nudibranchia. Species in this

Table 13.4 Molluscan taxa and feeding habits in the Gulf

Taxa	Feeding With relevant notes for some species where known
Class Polyplacophora (Chitons)	
Family Ischnochitonidae	Algal-grazers
Family Chitonidae	Algal-grazers
Class Gastropoda	
Prosobranchia	
Family Scissurellidae	Algal-grazers
Family Fissurellidae	Algal-grazers, also graze on encrusting sponges
Family Patellidae	Algal-grazers
Family Cerithiidae	Algal-grazers and detritus feeders
Family Dialidae	Algal-grazers
Family Diastomatidae	Live among weeds in shallow water. Feed on minute algae
Family Planaxidae	Algal-grazers
Family Trochidae	Algal-grazers, also graze on encrusting sponges
Family Turbinidae	Algal-grazers
Family Phasianellidae	Algal-grazers
Family Potamididae	Graze on diatoms, bacteria and detritus
Family Cypraeidae	Algal-grazers. Also graze on encrusting sponges. Cypraeids favour a thin layer of sand over the hard substratum
Family Triphoridae	Algal-grazers, also graze on encrusting sponges
Family Muricidae	Live exclusively on hard substrata. Drill holes into their shelled prey such as barnacles, other molluscs (mussels, oysters, vermetids). Also feed on polychaetes
Family Columbelloidea	Varied diet. Feed on polychaetes and crustaceans as well as algae
Family Nassaridae	Scavengers on dead, moribund animals, but some live prey taken.
Family Olividae	Feed on small bivalves and gastropods
Family Costellariidae	Probably carnivorous
Family Conidae	Live exclusively on hard substrata. Majority feed on polychaetes, but some feed on other molluscs and small fish.
Family Vermetidae	Suspension-feeders
Family Rissoidae	Feed on algae and diatoms
Family Rissoellidae	Feed on seaweeds and diatoms
Opisthobranchia	
Family Pyramidellidae	Feed on worms and bivalves. Have long proboscis with stylet to pierce prey from which they suck body fluids
Family Hydatinidae	
<i>Micromelo undata</i> (Brugiere, 1792)	Feeds on cirratulid worms
Family Philinidae	Feed on small bivalves
Family Aglajidae	Active predators on other invertebrates. Swallow prey whole. On sand deposits on coral reef shoals (DG, personal observation)
<i>Chelidonura livida</i> Yonow, 1994	
Family Haminoeidae	Grazers on green algae
Family Bullidae	Herbivores. Live in sea grass beds and algal mats. Found in sand deposits on coral reef shoals (DG, personal observation)
<i>Bulla arabica</i> Malaquias and Reid, 2008	
Family Notarchidae	Herbivorous
Family Aplysiidae	Feed on algae and seaweeds
Family Pleurobranchidae	Probably feed on ascidians
Family Plakobranchidae = Elysiidae	Herbivorous. Many collect and harvest algal chloroplasts
<i>Elysia ornata</i> (Swainson, 1840)	Feeds on green algae
Family Gymnodoriidae	Many feed on bryozoans. Some eat other opisthobranchs.
Family Triophidae	Feed on encrusting and arborescent bryozoans and sponges
Family Aegiridae	Feed on sponges
Family Discodorididae	Feed on sponges
Family Halgerdidae	Feed on sponges
<i>Asteronotus cespitosus</i> Van Hasselt, 1824	Shallow sublittoral under stones and boulders feeding on sponges.

(continued)

Table 13.4 (continued)

Taxa	Feeding
Family Kentroborididae	With relevant notes for some species where known
Family Chromodorididae	Feed on sponges
	Feed on sponges from which they acquire their toxins which are stored in mantle glands or special projections
<i>Chromodoris annulata</i> Eliot, 1904	Feeds on sponge <i>Chelonaplysilla violacea</i> (DG, personal observation)
<i>Chromodoris cazae</i> Gosliner and Behrens, 2004	Feeds on sponges
<i>Chromodoris obsoleta</i> (Ruppell and Leuckart, 1830)	Feeds on sponge <i>Chelonaplysilla</i> sp. (DG, personal observation)
<i>Hypselodoris infucata</i> (Ruppell and Leuckart, 1830)	Feeds on the sponge <i>Dysidea</i> (DG, personal observation)
<i>Hypselodoris nigrostriata</i> (Eliot, 1904)	Feeds on the sponge <i>Dysidea</i>
<i>Glossodoris cincta</i> (Bergh, 1888)	Feeds on sponge <i>Hyatella intestinalis</i>
Family Dendrodorididae	Feed on sponges. No radula or jaws They have a long oral tube that is inserted into the sponge. Secretions digest externally, then digested material is sucked up
Family Phyllidiidae	Feed on sponges. No radula or jaws. Digest sponge externally and suck up juices. Concentrate terpenoids from sponge in dorsal glands. Exude secretions when disturbed which repel fish and crab predators
Family Tritoniidae	Feed on soft corals and gorgonians
Family Flabellinidae	Feed on hydroids
Family Aeolidiidae	Feed on sea anemones and other cnidarians such as hydroids
Family Glaucidae	Some feed on alcyonarians, others on hydroids and egg masses
<i>Phyllodesmium magnum</i> Rudman, 1991	Said to feed on soft corals exclusively but are found on the Gulf coast of the UAE where few octocorals have yet to be reported as occurring (DG, personal observation)
Family Tergapedidae	Majority feed on hydroids, but also on hard corals
<i>Phestilla lugubris</i> (Bergh, 1870)	<i>Phestilla</i> feeds on corals
Class Bivalvia	
Family Arcidae	Suspension feeders
Family Malleidae	Suspension feeders
<i>Vulsella vulsella</i> Linnaeus, 1758	Embedded in sponges, sublittoral
Family Isognomonidae	Suspension feeders
Family Mytilidae	Suspension feeders
Family Pinnidae	Suspension feeders
Family Pteriidae	Suspension feeders
Superfamily Limoidea	Suspension feeders
Family Ostreidae	Suspension feeders
Family Pectinidae	Suspension feeders
Family Spondylidae	Suspension feeders
Superfamily Plicatuloidea	Suspension feeders
Family Lucinidae	Suspension feeders
Family Ungulinidae	Closely related to lucinids, probably suspension feeders
Family Chamidae	Suspension feeders
Superfamily Carditoidea	Suspension feeders
Family Cardiidae	Suspension feeders
Family Psammobiidae	Suspension feeders
Family Tellinidae	Suspension feeders
Family Semelidae	Suspension feeders
Superfamily Articoidea	Suspension feeders
Family Veneridae	Suspension feeders
Superfamily Gastrochaenoidea	Burrow into soft rock or coral. Suspension feeders
Class Cephalopoda	
Family Sepiidae	
<i>Sepia pharaonis</i> Ehrenberg, 1839	Predator on prawns, shrimps, and small fish
Family Loliginidae	.
<i>Loligo duvauceli</i> Orbigny, 1839	Predator on fish, crustaceans and other molluscs
Family Octopodidae	
<i>Octopus cyaneus</i> Gray, 1849	Predator on crabs, other molluscs and fish

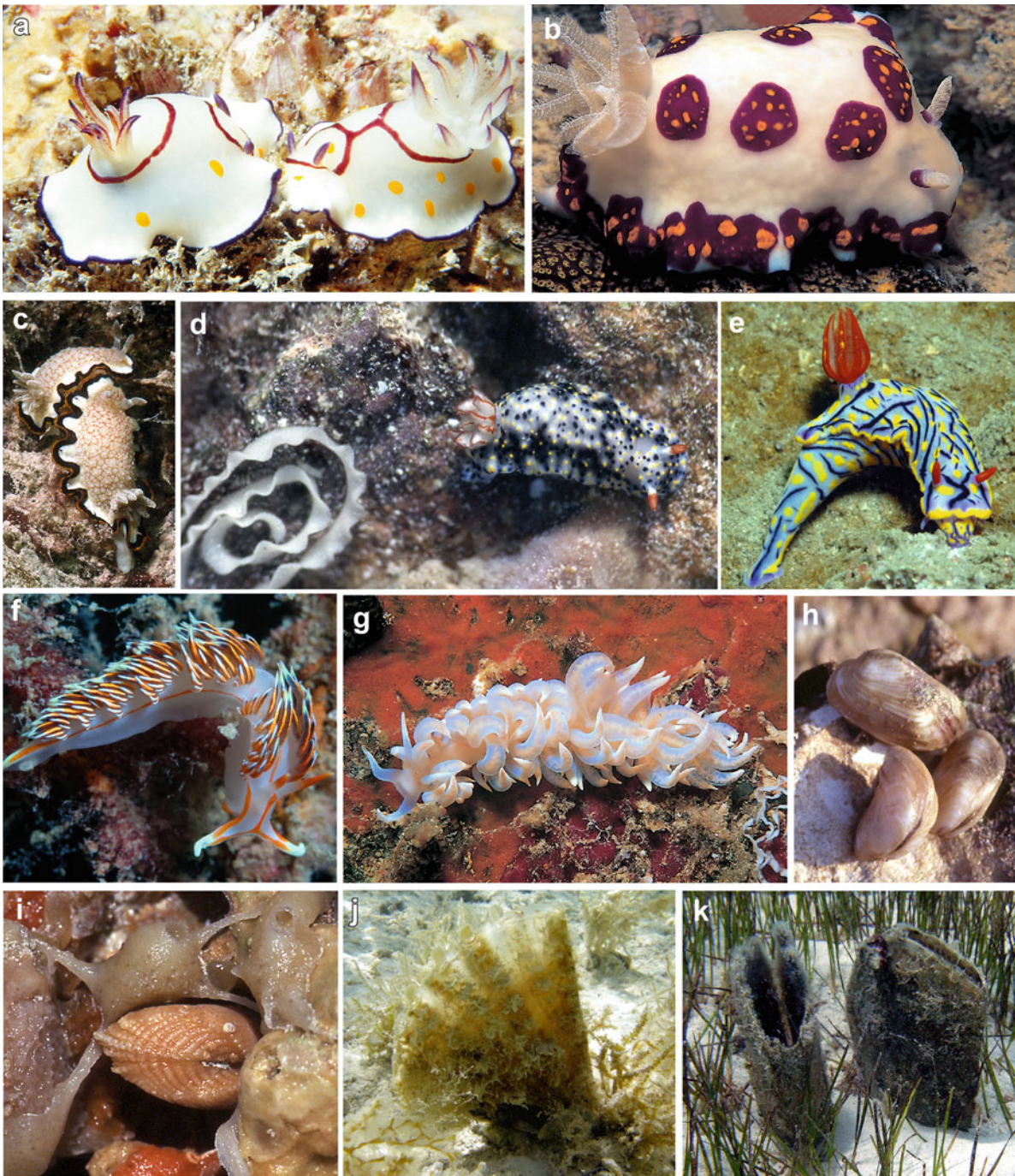


Fig. 13.6 (a) *Chromodoris annulata* is a distinctive species that in the Gulf may have the two purple rings around the rhinophores and gills joined mid-dorsally by a purple line. This sponge-feeder (see Table 13.4) seems unaffected by relatively strong water currents on reef fronts and over coral rubble as well as around wrecks. (b) *Chromodoris cazae* is a recently described species known to occur in the Gulf Emirates and Qatar. (c) *Chromodoris obsoleta* is a sponge-feeder (see Table 13.4) that is relatively common on the reefs of the SE Gulf. (d) *Hypselodoris infucata* alongside the egg mass it has laid and feeding on what seems to be a common *Dysidea* species on the coral reefs of Abu Dhabi, Emirate. (e) *Hypselodoris nigrostriata* although relatively common outside the Strait of Hormuz has been recorded only to a limited extent within the Gulf. (h) *Phidiana militaris* feeds on hydroids and is said to be able to transfer

the undischarged stinging nematocysts of the hydroids into its cerata tips to aid its own defence against predators. (g) The ducts of the digestive gland can be seen through the walls of the large cerata of this specimen of *Phylloidesmium magnum* photographed in Dubai Emirate. (h) *Trapezium sublaevigatum*, that shows the typical bilateral symmetry of bivalves, is found under coral boulders and slabs on shallow reef platforms as well as in the intertidal zone in a similar habitat. (i) *Acar plicata* is a characteristic species of the underboulder invertebrate fauna on shallow reef shoals in Abu Dhabi Emirate. (j) A young specimen of the pen shell *Pinna muricata* developing on a sand-covered offshore reef shoal in Abu Dhabi Emirate. (k) Two long-dead specimens of *Pinna* with shell valves still intact and the majority of their length proud of the sand (Images c, d, i–k © D. George; b, e–h © C. Harris; a © F. Dipper; l © C. Teasdale)

order are famed amongst SCUBA-divers throughout the world because of the delicate beauty of many of them and the range of colours and patterns on their upper surfaces (Figs. 13.5k, l and 13.6a–e). Their appearance, however, is deceptive as they are voracious carnivores (Table 13.4) with a range of defensive devices to prevent themselves being eaten by would-be predators. One of these devices is camouflage to resemble prey, often sessile colonial macroinvertebrates. Some of those that feed on sponges are able to transfer the hard spicules from their sponge meal up into their own dorsal surfaces providing themselves with a physical defence (e.g. *Paradoris*) against predators (Dayrat 2006). Many species of the family Chromodoridae have bright colour patterns on their dorsal surfaces to warn would be predators (mainly fish with good colour vision) that they may have distasteful chemicals stored in glands within their bodies, exude toxins and/or have other defensive devices stored within them that they have acquired from their prey. Another nudibranch group, the aeolidinids (Fig. 13.6g, h), contains species that feed on hydroids and anemones and are able to transfer the stinging nematocysts of their prey without them discharging into the tips of their own dorsal extensions of the body (cerata) to discharge in their defence if attacked. Nudibranchs unlike most other invertebrates are able to use the toxins and nematocysts of their prey for their own defence rather than having to manufacture them themselves.

The class Bivalvia is a large group (see Table 13.5) of laterally compressed suspension-feeding bilaterally symmetrical molluscs and as the name implies species within the group have a pair of shell valves. These valves are joined at a dorsal hinge (usually of interlocking teeth held together by a ligament) and opened and closed by means of two adductor muscles (Fig. 13.6i, j). A large proportion of them live only within soft sediments that they burrow into with a muscular foot, maintaining their connection to the surface of the sediment with a pair of siphons through which seawater is drawn in to satisfy their respiratory and filter-feeding requirements and excretory products are ejected. Others, however, such as the pen shell *Pinna muricata* (Fig. 13.6k, l) that is found in seagrass adjacent to corals and commonly in stabilised sand on top of shallow offshore reef shoals in the SE Gulf normally has only about two thirds of its fan-shaped shell buried vertically in the sand with the largest width exposed in the water column. Those that are only associated with hard substrata such as coral reefs have various methods of keeping themselves in position, some using strong chitinous byssal threads to attach themselves to the coral rock (e.g. *Brachidontes variabilis* and *Chlamys livida*) (Fig. 13.7a, b), others cement one of their shell valves to the hard surface (e.g. *Chama reflexa* and *Spondylus marisrubri*) (Fig. 13.7c, d) and some actually bore into dead coral skeletons or coral rock to maintain their position (e.g. *Gastrochaena gigantea*).

The best-known bivalves in the SE Gulf are the pearl oysters (*Pinctada radiata*, *P. margaritifera*) (Fig. 13.7e) – a brief but good summary of their life history is given in Vine (1986).

The Cephalopoda (Octopuses, Cuttlefishes, and Squids) is a small class of carnivorous molluscs that represent the pinnacle of molluscan development (see Table 13.5). All, other than individuals of the well-known ‘living-fossil’ *Nautilus* have lost their external shells, but some such as the squid and cuttlefish have an internal supporting structure that in the case of cuttlefish also acts as a sophisticated buoyancy aid. The molluscan foot in cephalopods has been modified into eight (octopuses) or ten (cuttlefishes and squids) grasping appendages (known as arms and/or tentacles) that are mostly suckered and used for catching prey. The mouth situated in the centre of the arms has a parrot-like chitinous beak for biting into and tearing the flesh of its prey. A muscular mantle with a free edge around the head end of the body surrounds the visceral mass and the ventrally positioned mantle cavity containing the gills and anus. Normally water enters the mantle cavity around its free edge and exits via a funnel under the head. When rapid movement is required the mantle contracts and seals around the body and water is propelled out of the mantle cavity through the narrow neck of the funnel with sufficient force to propel the animal through the water at great speed in the opposite direction. Cephalopods have a well-developed nervous system with a concentration of nerve ganglia in the head that form a brain. Eyes are large and structurally akin to those of vertebrates and are said to be able to form an image. Within the southeastern region of the Gulf it is not uncommon to see whilst SCUBA-diving cuttlefish (e.g. *Sepia pharaonis*) (Fig. 13.7f–h) and small shoals of squid (e.g. *Loligo duvauceli*) hunting over offshore reef platforms. Bottom-dwelling octopuses (e.g. *Octopus cyaneus*) are more secretive but have sometimes been seen by me patrolling in the open hunting for prey or hiding in large crevices waiting to pounce on passing prey (see Table 13.4) for prey of cephalopods in the region.

There is a fisheries interest in molluscs in the SE Gulf with commercial beds of pearl oysters existing on reefs off the UAE, Qatar and Bahrain. A few gastropod species from hard substrata appear in fish markets in the SE Gulf, but these are usually bought and consumed by the expatriate population according to Carpenter et al. (1997). Several cuttlefish and squid species also occur in fish markets but it is rare to see an octopus.

The shelled gastropods and to a lesser extent bivalve molluscs are some of the better-known macroinvertebrate groups on Gulf reefs due to the interest shown by a large number of amateur and shell-trade collectors in the beauty and variety of their protective, sometimes ornamented, shells. As a consequence there are many well-illustrated books available to aid in the identification of seashells of the Eastern Arabian region,

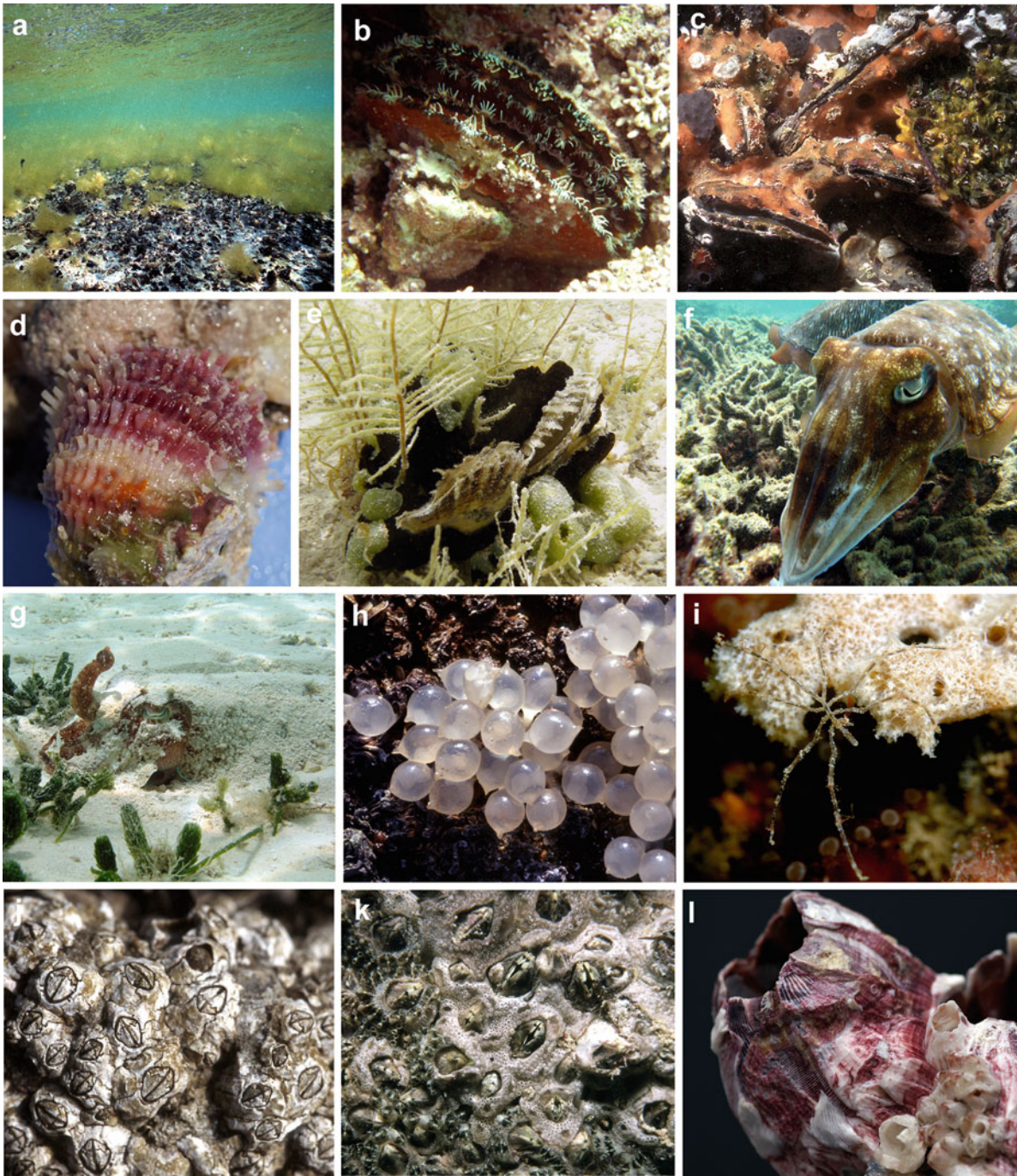


Fig. 13.7 (a) A mounded bed of the mussel *Brachidontes variabilis* on top of a current-swept shallow reef offshore shoal in Abu Dhabi Emirate. The macroalgae *Cladophora koeiei* on the mussel bed only occurs in the cooler winter/spring months. (b) *Chlamys livida* the larger fan-shaped species is using byssal threads to attach itself to dead coral substrata whilst the dead ‘jewel-box’ clam *Chama* sp. beneath it had cemented one of its valves to the substratum when alive to secure it in position. (c) A group of four living *Chama reflexa* that is barely discernible beneath a coating of sponges. (d) This old and well-worn specimen of *Spondylus marisrubri* has cemented its lower valve to the rock to maintain its position. (e) Two specimens of *Pinctada radiata* attached to a stable coral rock on top of a shallow reef shoal. (f) The cuttlefish *Sepia pharaonis* patrolling over a patch of long-dead *Acropora* coral. (g) *Sepia pharaonis* in a less familiar posture and with a portion of its

body hidden beneath a thin layer of sand. The cuttlefish may have been feeding on recently caught prey when photographed. (h) Developing eggs of *Sepia pharaonis* attached under a coral boulder in the shallows of a sheltered reef platform in Abu Dhabi Emirate. (i) This specimen of *Nymphon andamanense* has its left front walking leg missing and its pharynx clearly delineated. It also has red algal epibionts on some of its walking legs. (j) The four protective opercula valves of these individuals of a chthamalid are clearly delineated. (k) These living specimens of *Amphibalanus amphitrite* in a sheltered situation under an overhang have their wall plates almost completely covered by a colonial ascidian. (l) *Megabalanus tintinnabulum* is reasonably common on the reefs of the SE Gulf. The specimens in this photograph are long dead, but their wall plates are still in place (Images © D. George except b, e, g © C. Teasdale; f © K. Samimi-Namin; i © C. Harris)

Table 13.5 Known distribution of Mollusca in the Gulf. UAE Gulf identifications by J. Taylor and E. Glover

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
Class Polyplacophora (Chitons)						
Family Ischnochitonidae						
<i>Ischnochiton yerburyi</i> (Smith, 1891)	+	+			+	
<i>Callistochiton</i> sp.	+	+			+	
<i>Callochiton</i> sp.	+					
Family Chitonidae						
<i>Acanthochiton woodwardi</i> Kaas and Van Belle, 1988	+					
<i>Chiton (Rhyssoplax) affinis</i> Issel, 1869	+					
<i>Chiton</i> sp. a	+					
<i>Chiton</i> sp. b	+					
<i>Tonicia sueziensis</i> (Reeve, 1847)	+					
Class Gastropoda						
Prosobranchia						
Family Scissurellidae						
<i>Anatoma cf. jacksoni</i> (Melvill, 1904)	+					
<i>Scissurella rota</i> Yaron, 1903	+					
Family Fissurellidae						
<i>Diodora funiculata</i> (Reeve, 1850)	+	+	+		+	+
<i>Diodora rueppellii</i> Sowerby, 1834	+	+			+	
Family Patellidae						
<i>Cellana rota</i> (Gmelin, 1791)	+					
Family Cerithiidae						
<i>Bittium</i> sp.	+				+	
<i>Cerithium caeruleum</i> Sowerby, 1855	+		+		+	
<i>Cerithium rueppelli</i> Philippi, 1848	+					
<i>Cerithium scabridum</i> Philippi, 1848	+	+		+	+	
<i>Clypeomorus bifasciatus</i> (Sowerby, 1855)	+	+	+		+	
Family Dialidae						
<i>Diala semistriata</i> (Philippi, 1849)	+			+	+	
<i>Diala</i> sp.	+					
Family Diastomatidae						
<i>Cerithidium cerithinum</i> (Philippi, 1849)	+	+				
<i>Obtortia</i> sp.	+					
Family Planaxidae						
<i>Planaxis sulcatus</i> (Born, 1780)	+	+		+	+	+
Family Trochidae						
<i>Euchelus asper</i> (Gmelin, 1791)	+	+	+		+	+
<i>Vaceuchelus angulatus</i> (Pease, 1868)	+					
<i>Monodonta nebulosa</i> (Forsskål, 1775)	+	+	+		+	
<i>Clanculus pharaonius</i> (Linnaeus, 1758)	+		+		+	
<i>Clanculus gennisi</i> Fischer, 1901	+					
<i>Trochus erithraeus</i> Brocchi, 1823	+	+	+	+	+	+
<i>Ethalia carneolata</i> Melvill, 1897	+				+	
<i>Ethminolia</i> sp.	+					
<i>Priotrochus obscurus</i> (Wood, 1828)	+	+				
<i>Osilinus kotschy</i> (Philippi, 1849)	+		+			
<i>Umbonium vestiarii</i> (Linnaeus, 1758)	+	+			+	+
<i>Pseudominolia climacota</i> (Melvill, 1897)	+					
"Stomatia" sp.	+					
Family Turbinidae						
<i>Cyclostrema cf. ocrinium</i> Melvill and Standen, 1901	+				+	
<i>Bothropoma bellata</i> (A. Adams, 1873)	+					

(continued)

Table 13.5 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
<i>Bothropoma cf. munda</i> A. Adams, 1873	+					
<i>Lunella coronata</i> (Gmelin, 1791)	+	+		+	+	+
<i>Turbo radiatus</i> Gmelin, 1791	+	+	+	+	+	+
Family Phasianellidae						
<i>Tricolia fordiana</i> (Pilsbury, 1888)	+			+	+	
<i>Tricolia variabilis</i> (Pease, 1861)	+					
<i>Phasianella solida</i> (Born, 1778)	+		+		+	+
<i>Phasianella</i> sp.	+					
Family Potamididae						
<i>Cerithidea cingulata</i> (Gmelin, 1791)	+	+			+	
<i>Potamidea conicus</i> (Blainville, 1826)	+					
Family Cypraeidae						
<i>Cypraea carneola</i> Linnaeus, 1758		+		+	+	+
<i>Cypraea caurica</i> Linnaeus, 1758		+		+		
<i>Cypraea gracilis</i> (Gaskoin, 1849)	+	+		+	+	+
<i>Cypraea pulchra</i> Gray, 1824					+	+
<i>Cypraea teres</i> Gmelin, 1791	+					
<i>Cypraea turdus winckworthi</i> Schilder and Schilder, 1938	+		+	+	+	+
Family Triphoridae						
<i>Triphora cingulata</i> (A. Adams, 1854)	+				+	
<i>Triphora</i> sp.	+					
Family Muricidae						
<i>Hexaplex kuesterianus</i> (Tapperone Canefri, 1875)	+	+	+	+	+	+
<i>Murex scoloplax</i> Dillwyn, 1817	+	+	+		+	+
<i>Cronia konkanensis</i> (Melvill, 1893)	+	+	+			+
<i>Cronia martensi</i> Dell, 1923	+					
<i>Morula granulata</i> (Duclos, 1832)	+					
<i>Morula martensi</i> (Schepman, 1892)	+					
<i>Thais lacera</i> (Born, 1778)	+					
<i>Thais savignyi</i> (Deshayes, 1844)	+	+	+	+	+	+
<i>Thais squamosa</i> (Pease, 1868)	+					
Family Columbidae						
<i>Anachis fauroti</i> (Jousseume, 1888)	+					
<i>Mitrella blanda</i> (Sowerby, 1844)	+	+	+		+	+
<i>Zafra selasphora</i> (Melvill and Standen, 1901)	+					
<i>Zafra phaula</i> (Melvill and Standen, 1901)	+			+	+	
Family Nassariidae						
<i>Nassarius arcularia plicatus</i> (Röding, 1798)	+	+			+	+
<i>Nassarius gemmuliferus</i> (A. Adams, 1852)	+				+	
<i>Nassarius</i> sp.	+					
Family Olividae						
<i>Ancilla cf. ovalis</i> (Sowerby, 1859)	+	+			+	
<i>Oliva bulbosa</i> (Röding, 1798)	+					
Family Costellariidae						
<i>Costellaria</i> sp.	+					
Family Conidae						
<i>Conus flavidus</i> Lamarck, 1810	+	+				+
<i>Conus striatus</i> Linnaeus, 1758						+
Family Vermetidae						
<i>Serpulorbis variabilis</i> Hadfield and Kay, 1972	+					
Family Rissoidae						
<i>Scaliola</i> sp.	+					

(continued)

Table 13.5 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
Family Rissoellidae						
<i>Rissoella</i> sp.	+					
Opisthobranchia						
Family Pyramidellidae						
<i>Pyramidella</i> cf. <i>terebelloides</i> (A. Adams, 1854)	+					
<i>Otopleura mitralis</i> (A. Adams, 1854)	+					
<i>Turbonilla</i> sp.	+					
Family Hydatinidae						
<i>Micromelo undata</i> (Brugiere, 1792)	+					
Family Philinidae						
<i>Philine</i> sp.				+		
Family Aglajidae						
<i>Chelidonura livida</i> Yonow, 1994	+	+	+			
<i>Philinopsis</i> sp.				+		
Family Haminoeidae						
<i>Haminoea</i> sp.	+					
Family Bullidae						
<i>Bulla ampulla</i> Linnaeus, 1758 (= <i>B. arabica</i> ?)		+			+	+
<i>Bulla arabica</i> Malaquias and Reid, 2008	+					
Family Aplysiidae						
<i>Aplysia</i> sp.					+	+
Family Notarchidae						
<i>Bursatella leachii</i> Audouin, 1826						+
<i>Stylocheilus striatus</i> Quoy and Gaimard, 1832						+
Family Pleurobranchidae						
<i>Pleurobranchus</i> sp.				+		
Family Plakobranchidae = Elysiidae						
<i>Elysia ornata</i> (Swainson, 1840)	+					+
Family Gymnodoriidae						
<i>Gymnodoris impudica</i> (Ruppell and Leuckart, 1828)						+
Family Triophidae						
<i>Plocamopherus ocellatus</i> Ruppell and Leuckart, 1828					+	
Family Aegiridae						
<i>Aegires</i> sp.	+					
Family Discodorididae						
<i>Paradoris erythraeensis</i> (Vayssiere, 1912)	+					
Family Halgerdidae						
<i>Asteronotus cespitosus</i> Van Hasselt, 1824	+					+
Family Kentrodorididae						
<i>Jorunna funebris</i> (Kelaart, 1858)	+					+
Family Chromodorididae						
<i>Ardeadoris egretta</i> Rudman, 1984	+					+
<i>Chromodoris annulata</i> Eliot, 1904	+	+	+	+		+
<i>Chromodoris cazae</i> Gosliner and Behrens, 2004	+	+				
<i>Chromodoris obsoleta</i> (Ruppell and Leuckart, 1830)	+	+	+	+	+	
<i>Chromodoris</i> sp.				+		
<i>Hypselodoris infucata</i> (Ruppell and Leuckart, 1830)	+	+				
<i>Hypselodoris dollfusi</i> (Pruvot-Fol, 1933)	+					
<i>Hypselodoris whitei</i> (Adams and Reeve, 1850)	+					+
<i>Hypselodoris nigrostriata</i> (Eliot, 1904)						+
<i>Glossodoris cincta</i> (Bergh, 1888)	+	+		+		
<i>Glossodoris pallida</i> (Ruppell and Leuckart, 1830)	+			+		

(continued)

Table 13.5 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
<i>Glossodoris</i> sp.	+					
<i>Risbecia pulchella</i> (Ruppell and Leuckart, 1830)	+					
<i>Ceratosoma trilobatum</i> (Gray, 1827)	+					
Family Dendrodorididae						
<i>Dendrodoris fumata</i> (Ruppell and Leuckart, 1830)				+	+	+
<i>Dendrodoris nigra</i> (Stimpson, 1855)					+	+
<i>Dendrodoris</i> sp.		+		+		
<i>Doriopsilla</i> sp.				+		
Family Phyllidiidae						
<i>Phyllidiopsis monacha</i> (Yonow, 1986)	+					
<i>Phyllidiopsis sinaiensis</i> (Yonow, 1958)	+					
<i>Fryeria rueppellii</i> (Bergh, 1869)						+
Family Tritoniidae						
<i>Marioniopsis viridescens</i> (Eliot, 1904)						+
Family Flabellinidae						
<i>Flabellina rubrolineata</i> (O'Donoghue, 1929)	+	+				
Family Aeolidiidae						
<i>Cerberilla incola</i> Burn, 1974						+
Family Glaucidae						
<i>Phidiana militaris</i> (Alder and Hancock, 1864)				+		+
<i>Phyllodesmium magnum</i> Rudman, 1991	+					
Family Tergepedidae						
<i>Phestilla lugubris</i> (Bergh, 1870)						+
<i>Trinchesia (Cuthona) yamasui</i> Hamatani, 1993						+
Class Bivalvia						
Family Arcidae						
<i>Acar plicata</i> (Dillwyn, 1817)	+	+	+	+	+	
<i>Arca avellana</i> Lamarck, 1819	+	+				
<i>Barbatia parva</i> (Sowerby, 1833)	+	+				
<i>Barbatia setigera</i> (Reeve, 1844)	+	+	+			
Family Malleidae						
<i>Malvufundus normalis</i> Lamarck, 1819	+					
<i>Malvufundus regula</i> (Forsskål, 1775)	+	+	+		+	
<i>Vulsella vulsella</i> Linnaeus, 1758	+		+			+
Family Isognomonidae						
<i>Isognomon legumen</i> (Gmelin, 1791)	+				+	+
<i>Isognomon</i> sp.	+	+		+		
<i>Parviperna nucleus</i> (Lamarck, 1819)	+					
Family Mytilidae						
<i>Brachidontes variabilis</i> (Krauss, 1848)	+	+		+	+	
<i>Botula cinnamomea</i> (Gmelin, 1791)	+				+	
<i>Gregariella</i> sp.	+					
<i>Leiosolenus</i> cf. <i>tripartitus</i> (Jousseaume, 1888)	+					
<i>Lithophaga robusta</i> (Lamy, 1919)	+		+	+		
<i>Musculista senhousia</i> (Benson, 1842)	+					
<i>Musculus cumingianus</i> (Reeve, 1857)	+					
<i>Musculus</i> sp.	+			+		
<i>Septifer bilocularis</i> (Dunker, 1855)	+		+	+	+	
Family Pinnidae						
<i>Pinna muricata</i> Linnaeus, 1758	+	+			+	+
<i>Atrina vexillum</i> (Born, 1778)	+					+

(continued)

Table 13.5 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
Family Pteriidae						
<i>Pinctada margaritifera</i> (Linnaeus, 1758)	+	+	+	+	+	+
<i>Pinctada radiata</i> (Leach, 1814)	+	+	+	+	+	+
<i>Pterelectroma</i> cf. <i>vexillum</i> (Reeve, 1857)	+					
<i>Pterelectroma zebra</i> (Reeve, 1857)	+					
<i>Pteria</i> sp.	+				+	+
Superfamily Limoidea						
<i>Lima sowerbyi</i> Deshayes, 1863	+					
<i>Limatulella viali</i> Jousseau in Lamy, 1920	+					
<i>Limaria fragilis</i> (Gmelin, 1791)	+		+			
Family Ostreidae						
<i>Alectryonella plicatula</i> (Gmelin, 1791)	+				+	+
<i>Alectryonella</i> sp.	+					
<i>Lopha cristagalli</i> (Linnaeus, 1758)	+			+	+	+
<i>Ostrea</i> sp.	+			+		
Family Pectinidae						
<i>Chlamys livida</i> (Reeve, 1853)	+			+	+	+
Family Spondylidae						
<i>Spondylus marisrubri</i> Röding, 1798	+				+	
Superfamily Plicatuloidea						
<i>Plicatula australis</i> Lamarck, 1815	+					
Family Lucinidae						
<i>Anodontia edentula</i> (Linnaeus, 1758)	+				+	
<i>Cardiolucina semperianum</i> (Issel, 1869)	+					
<i>Ctena divergens</i> (Philippi, 1850)	+		+		+	
<i>Pillucina vietnamica</i> Zorina, 1978	+					
Family Ungulinidae						
<i>Diplodonta subrotundata</i> Issel, 1869	+					
<i>Diplodonta</i> sp.	+					+
Family Chamidae						
<i>Chama aspersa</i> , Reeve, 1846	+				+	
<i>Chama asperella</i> Lamarck, 1819	+	+	+			
<i>Chama reflexa</i> Reeve, 1846	+	+	+			
<i>Chama</i> sp, juvenile	+					
Superfamily Carditoidea						
<i>Carditopsis majeeda</i> (Biggs, 1973)	+					
Family Cardiidae						
<i>Acrosterigma lacunosa</i> (Reeve, 1845)	+	+				
<i>Parvicardium sueziense</i> (Issel, 1869)	+				+	
Family Psammobiidae						
<i>Asaphis violascens</i> (Forsskål, 1775)	+					
Family Tellinidae						
<i>Cadella semen</i> (Hanley, 1845)	+					
<i>Tellidora lamellosa</i> (Issel, 1869)	+					
<i>Tellina arsinoensis</i> Issel, 1869	+					
Family Semelidae						
<i>Ervilia scaliola</i> (Issel, 1869)	+					
<i>Ervilia</i> sp.	+					
Superfamily Articoidea						
<i>Trapezium sublaevigatum</i> (Lamarck, 1819)	+				+	

(continued)

Table 13.5 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
Family Veneridae						
<i>Amiantis umbonella</i> (Lamarck, 1818)	+		+			
<i>Circe rugifera</i> (Lamarck, 1818)	+					
<i>Circe scripta</i> (Linnaeus, 1758)	+	+	+		+	
<i>Circenita callypyga</i> (Born, 1780)	+	+	+		+	+
<i>Dosinia alta</i> (Dunker, 1848)	+	+			+	+
<i>Dosinia ceylonica</i> Dunker, 1865	+		+			
<i>Dosinia contracta</i> (Philippi, 1844)	+					
<i>Gafrarium pectinatum</i> (Linnaeus, 1758)	+	+	+		+	+
<i>Irus macrophylla</i> (Deshayes, 1853)	+		+			
<i>Microcirce</i> sp.	+					
Superfamily Gastrochaenoidea						
<i>Gastrochaena gigantea</i> Deshayes, 1830	+					
<i>Gastrochaena</i> sp.	+			+		
Class Cephalopoda						
Family Sepiidae						
<i>Sepia pharaonis</i> Ehrenberg, 1839	+	+	+	+	+	+
Family Loliginidae						
<i>Loligo duvauceli</i> Orbigny, 1839	+			+		
Family Octopodidae						
<i>Octopus cyaneus</i> Gray, 1849	+	+		+		

but few give much information on the biology and ecology of the species illustrated if they occur subtidally on coral reefs and other hard substrata. However, it is clear from my own experience in the SE Gulf region of both the rocky intertidal and subtidal ecosystems (George and John 2004, 2005b; John and George 2004, 2005) that in most cases species to be found under boulders or rock slabs that are exposed low on the shore during a low water spring tide also occur regularly on permanently submerged reef platforms and coral reefs. A selection of books and other publications providing information on the marine molluscs of individual Gulf States include Basson et al. (1977) for the Gulf coast of Saudi Arabia; Deeks and Johnson (1983), Glayzer et al. (1984), Jones (1986) for Kuwait; Smythe (1972), Green (1994) for Bahrain; Biggs (1973), Smythe (1979) for the Gulf Emirates; Hosseinzadeh et al. (2001) for the Iranian coast; Mohammed and Al-Khayat (1994), Al-Ansi and Al-Khayat (1999), Al-Khayat and Al-Ansi (2008) for Qatar. Mollusc works treating the Gulf as a whole include that by Smythe (1982) and a detailed multi-authored work edited by Dance (1995).

13.3.9 Arthropoda

Some scientists believe it is likely that features attributed to the Arthropoda have developed independently on a number

of occasions and that the arthropods did not develop from a common ancestor (e.g. Fryer 1997). However it is rare for specialists to adhere to the theory of arthropod polyphyly nowadays and I will be following the classification currently given in the World Register of Marine Species (WoRMS) that uses the term phylum Arthropoda that then divides into two subphyla, the Chelicerata and the Crustacea. These two subphyla have several features in common that include the bilateral symmetry of the body which is protected by a hard exoskeleton that is periodically moulted to allow growth to occur. The body is divided into segments the anterior ones bearing paired articulated appendages that perform various functions associated mainly with feeding and movement.

The subphylum Chelicerata has two classes occurring below tide level in the marine environment and only one of these, the Pycnogonida (sea-spiders) is found in the Gulf. It is a small group whose members bear a resemblance to the spiders, hence their common name (Fry 1978, Arnaud and Bamber 1987). They have a long narrow body with the anterior part of the head bearing a cylindrical proboscis with a mouth at its tip. The posterior part of the head is elongated and bears two pairs of eyes on a rounded protruberance. The appendages on the head consist of a pair of chelifores with terminal chelae attached at the base of the proboscis and a pair of sensory, many jointed, palps situated just behind the chelifores. Also attached to the rear of the head is a pair of egg-carrying legs that are unique to the pycnogonids. As it is

the male who carries the egg mass after the eggs have been laid, these legs are better developed in males than in females. Behind the head is a trunk of 4–6 cylindrical segments with lateral extensions that bear the long eight-segmented legs each of which ends in a claw. The short abdomen bears the anus (Bamber and Nager 2010).

The species found on the coral reefs in the SE Gulf feed on sponges, hydroids, anemones and bryozoans by using their chelae to tear off tissue from their prey and pass it into the mouth. It is thus of value to search for these small invertebrates in collections of so-called ‘fouling organisms’ on coral reefs. Only four species have so far been located on the reefs of the Gulf Emirates: *Achelia* sp., *Anoplodactylus glandulifer* Stock, 1954; *Anoplodactylus* cf. *turbidus* Stock, 1975 and *Nymphon andamanense* Calman, 1923 (Fig. 13.7i).

The subphylum Crustacea is a group of successful aquatic and terrestrial invertebrates that has a large number of marine representatives of many different forms on the reefs of the SE Gulf, some of the best known being the shrimps, crabs and lobsters. The major habitat for shrimps, a commercially well-known group in the Gulf, is not on the reefs although a few species do occur there. Members of the Crustacea differ from other arthropods in having two pairs of antennae (lost in adult barnacles). The segmented body, that often has a heavily calcified exoskeleton, is usually divided into a head, thorax and abdomen with a posterior section bearing the anus (telson). In addition to the antennae the head often has a well-developed pair of laterally placed compound eyes. Behind the ventral mouth there are usually three pairs of mouthparts (mandibles and the first and second maxillae). The appendages of the thorax and of the abdomen are usually biramous and are adapted to perform a variety of functions. In some groups the anterior appendages of the thorax when thoracic segments have fused with the head also function as accessory mouthparts. There is a calcified outgrowth from the back of the head in many groups (carapace) that extends back and over the lateral flanks of the thorax to protect many of the vital organs at the front of the body. In fact the arrangement of the body and its appendages vary so much from one group to another that it is fair to say that there is no typical crustacean body plan.

Only two classes within the Crustacea occur with any frequency on the reefs in the SE Gulf, the Maxillopoda (copepods and barnacles) and the Malacostraca that contains within its ranks the majority of the benthic Crustacea. The so-called Maxillopoda do not appear to be a monophyletic group and no single character seems to define it as a group apart from the fact that most but for the barnacles (see below) feed with their maxillae and have a body plan of five cephalic segments, six thoracic segments, four abdominal segments and a telson. The subclass Copepoda are mainly small

and planktonic and need not concern us further although they do have some benthic meiofaunal representatives. One of the other subclasses/infraclasses in the group, however, the Cirripedia (barnacles), has species within the superorder Thoracica that can be found on subtidal hard substrata in the Gulf although some species in the group are confined to the intertidal zone. The sessile barnacles are possibly the most modified of all the Crustacea being headless and without an abdomen or obvious segmentation. The body of a sessile adult barnacle lies on its back surrounded by a roughly conical wall of calcareous plates that are firmly cemented to the substratum across a wide flattened base leaving a relatively small opening at the top. When feeding a barnacle thrusts its ‘feathery’ thoracic appendages out of the opening and with synchronized sweeping movements combs the seawater to remove floating particulate organic matter from it and pass it to the mouth. When not feeding the opening between the barnacle’s main wall plates is firmly closed by a moveable lid (operculum) composed of four smaller plates to deny easy access to its soft body by would-be predators (Fig. 13.7j).

The genera *Amphibalanus* (Fig. 13.7k), *Balanus* and *Megabalanus* (Fig. 13.7l) have species that can be found subtidally as part of the species assemblages on dead coral, on coral boulders and on the back reef and shoal platforms in the SE Gulf as well as on artificial hard substrata such as pier piles, buoys and undersides of pontoons. The genus *Acasta* that is present on reefs of Abu Dhabi Emirate is of particular interest as it is a barnacle that is specially adapted to live as an epizoon embedded in sponge tissue. Members of the genus have spiny plates and a more elongated body shape with a smaller base, giving the impression of a flower bud about to open. Species in this genus have also been reported from elsewhere in the Gulf (Stubbings 1961 from Kuwait; Utinomi 1969 from Iran).

In recent classifications the Malacostraca is divided into three subclasses, the Phyllocarida, Hoplocarida and the Eumalacostraca. No species within the Phyllocarida were discovered in association with the reefs in the SE Gulf although a member of the Nebaliacea (*Paranebalia* sp.) has been reported as occurring on the shallow coral reefs on the east coast of Africa (Le Vay in Richmond (ed.), 2nd edition, 2002). The Hoplocarida, on the other hand, contains the order Stomatopoda (mantis shrimps) whose members are encountered hiding under coral boulders, amongst coral rubble or in crevices on the coral reefs of the Gulf. Species in the group are dorsoventrally flattened with a short moveable carapace covering the head and its large stalked eyes, and the anterior section of the thorax. The second thoracic appendages are large and highly modified as offensive weapons (Fig. 13.8a) that are shot forward with great speed and force to kill and capture prey such as small crustaceans and molluscs



Fig. 13.8 (a) The ‘smashing’ 2nd thoracic appendages of the stomatopod *Gonodactylus chiragra*. (b) A dorsal view of a preserved specimen of *G. chiragra* displaying many of the external morphological characteristics of the order to which it belongs, including the large flattened telson. (c) *Amphithoe* sp. from amongst macroalgal holdfasts on reef shoals and platforms. (d) *Hyale* sp. removed from algal samples collected from reefs during the winter months. (e) *Leucothoe* sp. found occasionally amongst sessile macroinvertebrate collections from reefs. (f) An unidentified spheromatid (dorsal view) found amongst macroalgal samples from the reefs of Abu Dhabi Emirate. (g) *Melita* sp. was only collected from a limited

number of sites on reefs of Abu Dhabi although members of the Melitidae are said to be amongst the most frequently collected species in samples from algae, sponges and coral on the east coast of Africa. (h) An alpheid shrimp *Alpheus bellulus* alongside its host goby *Cryptocentrus lutheri*. The combination of this shrimp and goby species is common. (i) Small specimen of *Penaeus semisulcatus* partly buried on top of a shallow reef shoal platform in Abu Dhabi Emirate. (j) The long spiny antennae of *Panulirus versicolor* protruding from under an overhang. (k) A brightly coloured juvenile of *P. versicolor*. (l) Adult in the open at night (Images © D. George except h, l © C. Harris; i © C. Teasdale)

Table 13.6 Known distribution of Crustacea in the Gulf. UAE Gulf identifications by P. Rainbow; P. Clark; M. Lowe; D.George

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
Class Maxillopoda						
Subclass Thecostraca						
Infraclass Cirripedia						
Family Archaeobalanidae						
<i>Acasta</i> cf. <i>cyathus</i> Darwin, 1854	+				+	
<i>Acasta sulcata</i> Lamarck, 1818					+	+
<i>Solidobalanus ciliatus</i> (Hoek, 1913)						+
Family Balanidae						
<i>Amphibalanus amphitrite</i> (Darwin, 1854)	+	+			+	+
<i>Balanus trigonus</i> Darwin, 1854	+					+
<i>Megabalanus tintinnabulum</i> (Linnaeus, 1758)	+	+			+	
Class Malacostraca						
Subclass Hoplocarida						
Order Stomatopoda						
Family Gonodactylidae						
<i>Gonodactylus chiragra</i> Fabricius, 1781	+					
<i>Gonodactylus demani</i> Henderson, 1965	+	+		+	+	
<i>Gonodactylus smithii</i> Pocock, 1893	+					
Subclass Eumalacostraca						
Order Amphipoda						
Suborder Gammaridea						
Family Ampithoidae						
<i>Ampithoe ramondi</i> Audouin, 1826	+					
<i>Cyamadusa filosa</i> Savigny, 1816	+	+			+	
Family Colomastigidae						
<i>Colomastix</i> sp.	+					
Family Hyalidae						
<i>Hyalé</i> sp.	+					
Family Isaeidae						
<i>Photis</i> sp.	+					
Family Leucothoidae						
<i>Leucothoella bannworthi</i> Schellenberg, 1928	+					
<i>Leucothoe hyhelia</i> J.L. Barnard, 1965	+					
<i>Leucothoe</i> sp.	+					
Family Melitidae						
<i>Melita appendiculata</i> Say, 1818	+					
<i>Maera</i> sp.	+					
<i>Elasmopus pecteniscus</i> (Bate, 1862)	+	+				
Order Isopoda						
Suborder Flabellifera						
Family Cirolanidae						
<i>Cirolana</i> sp.	+					
Family Sphaeromatidae						
<i>Cymodoce fuscina</i> Schotte and Kensley, 2005						+
<i>Cymodoce richardsoniae</i> Nobili, 1906					+	
Suborder Gnathiidea						
Family Gnathiidae						
<i>Gnathia firingae</i> Müller, 1991	+					
Order Decapoda						
Suborder Pleocyemata: Caridea						
Family Alpheidae						
<i>Alpheus</i> cf. <i>djeddensis</i> Coutière, 1897	+				+	

(continued)

Table 13.6 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
<i>Alpheus cf. bellulus</i> Miye and Myake, 1969	+					
^a <i>Athanas indicus</i> (Coutière, 1903)	+					
^a <i>Athanas sibogae</i> De Man, 1910	+					
^a <i>Synalpheus fossor</i> (Paulson, 1875)	+					
<i>Synalpheus quinquedens</i> Tattersall, 1921		+			+	
^a <i>Synalpheus tumidomanus</i> (Paulson, 1875)	+					
Family Hippolytidae						
^a <i>Gelastocaris paronae</i> (Nobili, 1905)	+					
^a <i>Hippolyte ventricosa</i> H. Milne Edwards, 1837	+				+	
^a <i>Latreutes mucronatus</i> (Stimpson, 1860)	+					
^a <i>Thor spinosus</i> Boone, 1935	+					
<i>Saron marmoratus</i> (Oliver, 1811)				+	+	
<i>Saron</i> sp.	+					
Family Penaeidae						
<i>Penaeus semisulcatus</i> De Hann, 1844	+	+	+	+	+	+
<i>Megokris granulatus</i> (Haswell, 1879)					+	
<i>Metapenaeus dobsoni</i> (Miers, 1878)					+	
<i>Metapenaeus stebbingi</i> Nobili, 1904			+	+	+	
<i>Parapenaeopsis stylifera</i> (H. Milne-Edwards, 1837)					+	
Family Palaemonidae						
^a <i>Anchistus custos</i> (Forsskål, 1775)	+					
^a <i>Palaemonella ?lata</i> Kemp, 1922	+					
<i>Periclimenes obscurus</i> Kemp, 1922		+			+	
^a <i>Philarius gerlachei</i> (Nobili, 1905)	+					
^a <i>Processa australiensis</i> Baker, 1907	+					
Suborder Pleocyemata: Palinura						
Family Palinuridae						
<i>Panulirus homarus</i> (Linnaeus, 1758)						+
<i>Panulirus ornatus</i> (Fabricius, 1798)				+		+
<i>Panulirus penicillatus</i> Olivier, 1791				+		+
<i>Panulirus versicolor</i> (Latreille, 1804)	+	+	+	+	+	+
Suborder Pleocyemata: Anomura						
Family Porcellanidae						
^a <i>Aliaporcellana pygmaea</i> (De Man, 1902)	+					
<i>Pachycheles natalensis</i> (Krauss, 1843)	+				+	
^a <i>Pachycheles tomentosus</i> Henderson, 1893	+					
^a <i>Petrolisthes boscii</i> (Audouin, 1826)	+		+		+	
<i>Petrolisthes carinipes</i> (Heller, 1861)					+	
<i>Petrolisthes moluccensis</i> De Man, 1888	+					
^a <i>Petrolisthes ornatus</i> Paulson, 1875	+			+	+	
<i>Petrolisthes rufescens</i> (Heller, 1861)	+	+	+	+	+	
^a <i>Pisidia dehaanii</i> (Krauss, 1843)	+					
^a <i>Pisidia gordonii</i> (Johnson, 1970)	+					
^a <i>Pisidia inaequalis</i> (Heller, 1861)	+					
<i>Polyonyx obesulus</i> Miers, 1884	+					
Family Diogenidae						
^a <i>Clibanarius signatus</i> Heller, 1861	+					
<i>Clibanarius padavensis</i> De Man, 1888	+					
^a <i>Dardanus lagopodes</i> (Forsskål, 1775)	+					
<i>Dardanus pedunculatus</i> (Herbst, 1804)	+					+
<i>Dardanus tinctor</i> (Forsskål, 1775)	+	+			+	

(continued)

Table 13.6 (continued)

Taxa	UAE Gulf	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
^a <i>Stratiotes abbreviatus</i> (Dechance, 1963)	+		+			
^a <i>Stratiotes perspicax</i> (Nobili, 1906)	+		+			
Suborder Pleocyemata: Brachyura						
Family Dromiidae						
<i>Lewindromia unidentata</i> (Ruppell, 1830)	+		+	+		
Family Majidae						
^a <i>Acanthonyx limbatus</i> A. Milne Edwards, 1862	+			+		
<i>Micippa philyra</i> (Herbst, 1803) ^a	+		+	+		
^a <i>Cyphocarcinus capreolus</i> (Paulson, 1975)	+				+	
<i>Cyphocarcinus alcocki</i> Griffin and Tranter, 1986	+					
Family Epialtidae						
<i>Menaethiops nodulosa</i> (Nobili, 1905)						+
^a <i>Menaethiops</i> sp. nov.	+					
<i>Menaethius monoceros</i> (Latreille, 1825)		+			+	
Family Portunidae						
<i>Charybdis feriata</i> (Linnaeus, 1758)						+
<i>Charybdis (Charybdis) natator</i> (Herbst, 1794)					+	+
^a <i>Gonioinfradens paucidentatus</i> (A. Milne Edwards, 1861)	+			+		+
<i>Portunus pelagicus</i> (Linnaeus, 1766)	+	+	+	+	+	+
<i>Thalamita admete</i> (Herbst, 1803)	+		+			
^a <i>Thalamita iranica</i> Stephenson, 1945	+		+			+
<i>Thalamita rubridens</i> Apel and Spiridonov, 1998	+					
Family Pilumnidae						
^a <i>Actumnus asper</i> (Ruppell, 1830)	+		+	+		
<i>Heteropilumnus lanuginosus</i> (Klunzinger, 1913)	+					
<i>Pilumnopeus vauquelini</i> (Audouin, 1826)	+				+	
<i>Pilumnus longicornis</i> Hilgendorf, 1878	+	+		+	+	+
^a <i>Pilumnus propinquus</i> Nobili, 1905	+					+
<i>Pilumnus vespertilio</i> Fabricius, 1793		+			+	
Family Xanthidae						
<i>Actaea savignyi</i> H. Milne Edwards, 1834	+	+	+		+	+
<i>Carpilius convexus</i> Forsskål, 1775				+	+	+
<i>Chlorodiella nigra</i> (Forsskål, 1775)	+			+		+
<i>Cymo andreossyi</i> (Audouin, 1826)	+					
<i>Eriphia sebana smithii</i> (Macleay, 1838)	+			+		
<i>Etisus anaglyptus</i> H. Milne Edwards, 1834						+
<i>Etisus electra</i> (Herbst, 1801)						+
^a <i>Etisus frontalis</i> Dana, 1852	+					
<i>Etisus laevimanus</i> Randall, 1840	+			+		+
<i>Leptodius exaratus</i> (H. Milne Edwards, 1834)	+					+
<i>Phymodius drachi</i> Guinot, 1964	+					
<i>Phymodius ungulatus</i> (H. Milne Edwards, 1834)						+
^a <i>Pilodius spinipes</i> Heller, 1861	+					
<i>Pilumnopeus indica</i> (De Man, 1887)	+					
<i>Pseudoliomera ruppellioides</i> (Odhner, 1925)						+
Family Sesarmidae						
<i>Nanosesarma sarii</i> Naderloo and Türkay, 2009					+	+
Family Trapeziidae						
^a <i>Tetralia glaberrima</i> (Herbst, 1790)	+					+
<i>Trapezia cymodoce</i> (Herbst, 1801)				+		+
Family Pseudoziidae						
<i>Pseudozius caystrus</i> (Adams and White, 1849)	+					

^aSpecies of Decapoda reported by Titgen (1982) as occurring in reefal situations in Dubai Emirate, but not found during more recent general reef surveys in the Gulf Emirates

and to defend itself against predators. The rest of the following thoracic limbs are used for walking and the locomotory appendages of the long abdomen mainly for swimming and to aid its rapid movement with the help of the large flattened telson (Fig. 13.8b). Species of *Gonodactylus* are the most frequently seen mantis shrimps on the reefs of the SE Gulf (see Table 13.6).

The subclass Eumalacostraca in general contains species with the head and thorax fused together and many with a well-developed carapace that can completely cover the head and thorax. The abdomen mostly has six segments. The subclass is divided into several superorders only two of which, the Peracarida and Eucarida, concern us here as they contain between them three well known species-prolific orders, the Amphipoda, Isopoda and Decapoda, as well as some other orders of microscopic species that will not be considered further in this contribution. The Amphipoda and Isopoda within the Peracarida have species whose females brood their eggs in a pouch beneath the thorax and release miniature versions of the adult from the pouch when brooding is completed. In peracarids the first segment of the thorax is fused with the head that has unstalked eyes, there is no carapace and little obvious distinction between the thorax and abdomen, and a moveable tooth is present on the mandibles. These two peracarid orders are particularly abundant in the sea and are said to make up approximately 40% of all Crustacea, although relatively small and inconspicuous compared with many species of the Decapoda in the superorder Eucarida. The Eucarida have a strongly developed carapace that is fused with all the thoracic segments, the eyes are stalked, and the eggs are usually carried beneath the abdomen of the female, but development is indirect as there is a planktonic larval stage.

The Amphipoda can usually be recognised when seen moving underwater by the convex curvature of their bodies and particularly by their lateral compression that enables them very quickly to disappear into the smallest of niches on reef platforms when alarmed. Amphipods were found in samples of material collected from the SE Gulf under coral boulders, from the base of seaweed stipes during their winter growth period, when sampling amongst coral rubble, and from crevices opened up in the general search for sessile and mobile macroinvertebrates. It was clear to see when diving that many of the most mobile species readily escaped. All specimens belonged to families within the suborder Gammaridea that contains the majority of the amphipods. The bases of the thoracic limbs are expanded to form large coxal plates and the limbs of the abdomen are usually well developed and adapted for both swimming and crawling. Most gammarids are considered to be scavengers, eating both plant and animal remains. Ampithoidae family members are thought to construct temporary tubes on marine plants and the *Ampithoe* (Fig. 13.8c) and *Cymadusa* species collected

by me (Table 13.6) came from algal holdfasts and stipes. Most species within the Hyalidae are also found amongst algae (Fig. 13.8d). Species within the Colomastigidae and Leucothoidae (Fig. 13.8e) are inquilines in both sponges and ascidians. The Melitidae contains free-swimming species that can crawl and hide in reef niches (Fig. 13.8g). All free-living species of amphipod are heavily predated by reef fishes if they are seen by them in the open. Specialised literature is available for identification of amphipods (see A. Myers in Richmond (ed.) 2nd edition, 2002 for a list of relevant literature). Identification requires detailed microscopic examination of appendages.

The Isopoda species are generally relatively easily recognised by their body shape that is dorso-ventrally flattened in contrast to the lateral flattened amphipod body. Although no major effort was made to collect isopods they do appear to be less common on the reefs of the SE Gulf than the Amphipoda, although usually occurring in the same benthic cryptic microhabitats. They have the ability to crawl and swim using their thoracic and abdominal appendages and appear to be omnivorous scavengers. The majority of isopods seen on reefs belong to the suborder Flabellifera and certain species of the family Cirolanidae within this suborder are said to appear in great numbers on coral reefs if traps are baited with fish flesh overnight (see N. Bruce in Richmond (ed.) 2nd edition, 2002). The *Cirolana* specimens collected by me on the reefs of Abu Dhabi Emirate have yet to be identified to species level. Another family within the Flabellifera, the Sphaeromatidae has been reported from Iran (Schotte and Kensley 2005) and from amongst *Sargassum* in Kuwait (Jones 1986). A small sphaeromatid specimen found in samples collected from the reefs of Abu Dhabi Emirate (Fig. 13.8f) has not been identified so far (Table 13.6). Another suborder Gnathiidea within the Isopoda contains in the Gulf Emirates sponge samples a small species <0.5 cm long, *Gnathia firingiae* (Table 13.6), that as an adult has a body looking more like that of an insect than of a crustacean with very large mandibles, in the male in particular, and an abdomen much narrower and smaller than the thorax. The juveniles of this species are temporarily ectoparasites on reef fish, before taking up a free-living benthic existence. Adults of the species have been reported as being found in abandoned borings in dead coral, amongst coral rubble, and as inquilines in sponges (Müller 1991). As with the amphipods most isopod species are eaten by reef fishes if seen by them in the open. In order to identify isopod species there is a need for examination of appendages and other body parts at a microscopic level. A list of relevant literature can be found in Richmond (ed.) 2nd edition (2002).

The order Decapoda has one suborder, the Pleocyamata, in which most of the reef-dwelling families of the Gulf are contained and includes the shrimps, lobster and crab families. This suborder can be further subdivided into convenient infraorders four of which contain species present in the Gulf,

Table 13.7 Habitat requirements of reef Decapoda in Dubai Emirate according to Titgen (1982). N.B. Titgen placed *Actumnus asper* and *Pilumnus propinquus* in the family Xanthidae and more recent workers place them in the Family Pilumnidae. Similarly *Tetralia glaberrima* is now considered to belong in the Trapeziidae (These families are closely related)

Taxa	Habitat	Titgen notes
Order Decapoda		
SO Pleocyemata: Caridea		
Family Alpheidae		
<i>Athanas indicus</i> (Coutiere, 1903)	Amongst limestone boulders and dead coral	Lives in association with sea-urchin <i>Echinometra mathei</i> and <i>Diadema setosum</i>
<i>Athanas sibogae</i> De Man, 1910	Amongst coral and on other limestone substrata	Associated with sponges and dead coral
<i>Synalpheus fossor</i> (Paulson, 1875)	Amongst coral and on other limestone substrata	Associated with sponges and dead coral
<i>Synalpheus tumidomanus</i> (Paulson, 1875)	Amongst coral and on other limestone substrata	Associated with sponges and dead coral
Family Hippolytidae		
<i>Gelastocaris paronae</i> (Nobili, 1905)	In depths of 4–8 m	Near Jebel Ali barrier reef
<i>Hippolyte ventricosa</i> H. Milne Edwards, 1837	In subtidal algae beds on limestone substrata	
<i>Leutrules macronatus</i> (Stimpson, 1860)	Amongst seaweeds on limestone substrata	
<i>Thor spinosus</i> Boone, 1935	In depths of 8–10 m	
Family Palaemonidae		
<i>Anchistus custos</i> (Forsskål, 1775)	In shallow water	Common commensal in <i>Pinna</i> shells, where it clings to the edge of the mantle
<i>Palaemonella ?lata</i> Kemp, 1922	Rocky sublittoral in depths of 8–10 m	Often associated with sponges
<i>Philarius gerlachei</i> (Nobili, 1905)	Subtidal areas	Other Gulf locality – Arzana Island
<i>Processa australiensis</i> Baker, 1907	In depths of 8–12 m	First record in the Arabian Gulf
SO Pleocyemata: Anomura		
Family Porcellanidae		
<i>Aliaporcellana pygmaea</i> (De Man, 1902)	Found among corals, subtidally	
<i>Pachycheles natalensis</i> (Krauss, 1843)	Rocky subtidal areas in crevices and under boulders on limestone platforms	Also in Kuwait
<i>Pachycheles tomentosus</i> Henderson, 1893	In patch reefs	
<i>Petrolisthes boscii</i> (Audouin, 1826)	In depths up to 10 m	Also in Bahrain and Kuwait
<i>Petrolisthes ornatus</i> Paulson, 1875	In subtidal rocky areas	Also in Saudi Arabia and Kuwait
<i>Petrolisthes rufescens</i> (Heller, 1861)	Oyster reefs and rocky subtidal areas	Also in Bahrain and Kuwait
<i>Pisidia dehaanii</i> (Krauss, 1843)	On hard substrata subtidally	
<i>Pisidia gordonii</i> (Johnson, 1970)	Subtidal areas	Often associated with hydroids and other colonial organisms
<i>Pisidia inaequalis</i> (Heller, 1861)	On coral at 4–9 m depths	
<i>Polyonyx obesulus</i> Miers, 1884	On hard substrata	Occurs often in sponges and coral crevices
Family Diogenidae		
<i>Clibanarius signatus</i> Heller, 1861	Shallow water in subtidal rocky areas	
<i>Dardanus lagopodes</i> (Forsskål, 1775)	Depths down to 12 m	
<i>Dardanus tinctor</i> (Forsskål, 1775)	Very common in both shallow and deeper waters	Sometimes carries the anemone, <i>Calliactis polypus</i> on its shell. Also occurs in Qatar and Kuwait
<i>Paguristes abbreviatus</i> Dechance, 1963 (Now <i>Stratiotes abbreviatus</i>)	Amongst coral in shallow water	Also in Bahrain
<i>Paguristes perspicax</i> Nobili, 1906 (Now <i>Stratiotes perspicax</i>)	In depths down to 9 m	Also in Bahrain
SO Pleocyemata: Brachyura		
Family Dromiidae		
<i>Dromidia unidentata</i> (Ruppell, 1830) (Now <i>Lewindromia unidentata</i>)	In shallow waters in rocky areas	Commonly carries sponges, ascidians, and occasionally anemones on the carapace. Also in Bahrain and Saudi Arabia and elsewhere in the Gulf
Family Majidae		
<i>Acanthonyx limbatus</i> A. Milne Edwards, 1862	Often found with pearl oysters and in algae	Also occurs in Saudi Arabia

(continued)

Table 13.7 (continued)

Taxa	Habitat	Titgen notes
<i>Menaethiops</i> sp.nov.	Shallow subtidal rocky areas	Occurs where algae (e.g. <i>Sargassum</i>) are common
<i>Micippa philyra</i> (Herbst, 1803)	In depths down to 10 m	Also in Bahrain and Saudi Arabia
<i>Cyphocarcinus capreolus</i> (Paulson, 1975)	Shallow subtidal rocky areas	Also in Kuwait
Family Portunidae		
<i>Charybdis paucidentata</i> (A. Milne Edwards, 1861)	In depths down to 15 m, often on pearl oyster beds	Also in Saudi Arabia
<i>Portunus pelagicus</i> (Linnaeus, 1766)	Sometimes found on backreef platforms	Fished commercially in the Gulf. Also in Bahrain, Saudi Arabia and Kuwait
<i>Thalamita admete</i> (Herbst, 1803)	Commonly occurs under coral rock boulders in shallow water	Also in Bahrain and elsewhere in the Gulf
<i>Thalamita iranica</i> Stephenson, 1945	Shallow subtidal waters amongst coral	Probably a Gulf endemic species. Very common in Dubai and also found in Bahrain
Family Xanthidae		
<i>Actaea savignyi</i> H. Milne Edwards, 1834	Found on hard substrata in both shallow and deeper waters	Also occurs in Bahrain, Kuwait and elsewhere in the Gulf
<i>Actumnus asper</i> (Ruppell, 1830)	Offshore in depths down to 12 m	Often found with pearl oysters and in shell gravel. Also in Bahrain and Saudi Arabia
<i>Chlorodiella nigra</i> (Forsskål, 1775)	Commonly associated with corals	
<i>Eriphia sebana smithii</i> (Macleay, 1838)	Occurs on coral reefs and their rocky substrata	Large aggressive species. Poisonous. Found also in Saudi Arabia
<i>Etisus frontalis</i> Dana, 1852	On subtidal hard substrata	
<i>Pilodius spinipes</i> Heller, 1861	On subtidal hard substrata	
<i>Pilumnus propinquus</i> Nobili, 1905	On subtidal hard substrata	It is the most abundant <i>Pilumnus</i> species in the Dubai area. Also found elsewhere in the Gulf
<i>Tetralia glaberrima</i> (Herbst, 1790)	Coral reefs on <i>Acropora</i>	Species is an obligate coral commensal, usually associated with <i>Acropora</i> spp. Also occurs in Saudi Arabia

the Caridea (shrimps), Palinura (lobsters), Anomura (porcelain and mole crabs, hermit crabs) and the Brachyura (true crabs). The most comprehensive study of decapods of the SE Gulf was undertaken by Titgen (1982) from where stems information given in Table 13.7.

The Infraorder Caridea family Alpheidae (snapping or pistol shrimps) has three genera that are found regularly on the coral reefs and reef platforms of the SE Gulf, *Alpheus*, *Athanas* and *Synalpheus*. Although SCUBA-divers can readily hear the snapping noises made by the well-developed large clawed limbs of the first thoracic segment (chela), they are generally not readily visible since they tend to be small cryptic shrimps. It is thought that the snapping noises made by them are defensive rather than offensive, their primary function being a threat display between individuals to announce their territories (Nolan and Salmon 1970). Jones (1986) distinguished *Athanas* from the other two genera by the fact that when the shrimp is viewed from above the eyes at the end of its eye stalks can be seen on either side protruding beyond the front of the carapace with its pointed central tip (rostrum) extending forward between them. In *Alpheus* and *Synalpheus* the eyes are hidden below the carapace when

viewed from above. These two genera are distinguished from each other by the fact that the *Alpheus* carapace has a rounded front end whilst that of *Synalpheus* is angular. Some *Alpheus* species cohabit with shrimp gobies (Randall 1995). On the partially sand-covered reef platforms of coastal back reefs and offshore shoals of Abu Dhabi Emirate, shrimps such as *Alpheus* cf. *djeddensis* and *A.* cf. *bellulus* (Table 13.6) have been seen by myself and diving colleagues on many occasions busily ‘bulldozing’ coarse sand with its relatively large chela from the entrance to the burrows of the goby *Cryptocentrus lutheri* whilst the sharp-eyed fish at the burrow entrance keeps watch for possible predators of its smaller ‘housekeeper’ (Fig. 13.8h). *Synalpheus* species are also known to associate with other macroinvertebrates such as large sponges, hydroids, and corals like *Stylophora* although the exact nature of the association is not clear. Similarly species of *Athanas* have been found living amongst the spines of *Diadema* and *Echinometra* sea urchins (Titgen 1982) that are at present prolific on the shallow reefs of the SE Gulf.

Compared with the Alpheidae species within the Hippolytidae have much smaller chela on the first thoracic segment and tend to be free-living amongst algae (and

seagrasses) on the reef platforms when algae are at their peak during the cooler winter months. Most are cryptically coloured to match their surroundings and are thus difficult to see. Little is known about their feeding, but it seems likely that they feed mainly on plant detritus.

Many species of the family Penaeidae (shrimps and prawns) are important to the commercial fisheries of many States within the Gulf and one species *Penaeus semisulcatus*, is frequently found in small numbers in the seagrass beds on top of offshore shallow reef shoals (Fig. 13.8i). The feeding ecology of *P. semisulcatus* has recently been studied in the inshore waters of Qatar by Al-Maslamani et al. (2007).

In the family Palaemonidae individuals have the first two thoracic appendages with chelae, the second pair often being larger. Many species within the group living on coral reefs have a commensal relationship with larger macroinvertebrates such as sponges, hydroid colonies, anemones, the sea urchin *Diadema setosum* and sea cucumbers. A few species seem to be free-living scavengers. It is also possible that some are carnivorous and pick off individual polyps from hydroid colonies with their chelae.

The infraorder Palinura contains only one species of lobster (*Panulirus versicolor*) that can be found on the coral reefs of the Gulf although other species of *Panulirus* have been reported from non-coral rocky areas along the Iranian coast and also from Saudi Arabia (Table 13.6). *P. versicolor* belongs to the family Palinuridae, members of which are known as the spiny lobsters, the common name deriving from the pair of long spiny antennae that species possess. These antennae waving slowly in the water column are sometimes all that can be seen of *P. versicolor* protruding from cavities under coral mounds during daylight hours (Fig. 13.8j). Spiny lobsters are large dorso-ventrally flattened animals, up to 40 cm in body length, with a thick protective exoskeleton, but with no large claws (Fig. 13.8l). They are active mainly at night where they scavenge for food on reef fronts and platforms, but are possibly also opportunistic carnivores feeding on other smaller crustaceans and molluscs. The body colour patterns of *P. versicolor* are sharply defined and bright, especially in juveniles (Fig. 13.8k) and have led to it being called the painted spiny lobster. The flesh of this species is highly prized as a food item by man and thus a specimen fetches a high price when seen in local fish markets. As an adult the spiny lobster's only known predator, apart from man, is the octopus, although their planktonic larvae are very vulnerable to predation by suspension feeding macroinvertebrates. Spiny lobster juveniles are sometimes captured and eaten by predatory crabs if they cannot escape rapidly backwards by strong flapping movements of the abdomen aided by their broad tail fan.

The infraorder Anomura is a well-known decapod group with many representatives on the reefs of the SE Gulf. Only

two marine families are of importance on these coral reefs, the Porcellanidae (porcelain crabs) and the Diogenidae (hermit crabs).

The so-called porcelain crabs superficially resemble the brachyuran crabs (true crabs, see later), but the abdomen is not so reduced as in the brachyurans although it is flexed under the cephalothorax as in the true crabs. The last pair of appendages of the abdomen is usually reduced although still present. Another feature that distinguishes them from the brachyurans is that they apparently have only three pairs of thoracic walking legs as opposed to the four pairs of the brachyurans since their fourth pair is concealed under the carapace. Porcelain crabs are small, delicate, and flattened with large chelae and long maxillipeds with numerous fine hairs used for filter-feeding by combing plankton and suspended organic matter from the water column and then flexing towards the mouth where the food particles are scraped off the hairs. Surprisingly the large chelae do not appear to be used for capturing prey but more usually for offensive behaviour in territorial disputes, although they are capable of picking up suitable food during scavenging expeditions from their cover. The limbs are easily lost but can be replaced during successive moults. The crabs are rarely located on reef fronts, but are common under coral boulders on back reefs and on reef shoal platforms as well as amongst consolidated coral rubble. The commonest genera located on present day coral reefs in the Gulf Emirates are *Pachycheles* and *Petrolisthes*. Few published records of porcellanid crab species exist for reefs elsewhere in the Gulf apart from records of *Petrolisthes* species (Table 13.6). Many of the species recorded by Titgen (1982) on reefs in Dubai may no longer exist on the now depauperate reefs of the Gulf Emirates.

Hermit crabs (Diogenidae) are often located by SCUBA-divers in reefal situations as a result of noticing the unusually rapid intermittent movements of gastropod shells of various sizes across the substratum. The soft abdomen of this type of crab is not hidden beneath the cephalothorax, but is asymmetrically modified to fit into the protective spiral coils of shells of dead gastropods where it is held in place by the rear cephalothoracic appendages and modified abdominal appendages. The frequent asymmetry of the claws and walking legs of hermit crabs help them to fit snugly into the selected shell. Diogenids often have the left claw larger than the right, but in the case of *Dardanus lagopodes* (Fig. 13.9a) they are approximately the same size. The restrictions placed on the growth of a crab by the size of its shell home mean that the crab has to move to a larger shell at each moult. Hermit crabs are mainly scavengers and can be found in greatest numbers on the reef flats and on sheltered reef slopes in the SE Gulf. As mentioned earlier in the Cnidaria account larger hermit crabs such as *Dardanus pedunculatus* and *D. tinctor* can be found occasionally with commensal anem-



Fig. 13.9 (a) The hermit crab *Dardanus lagopodes* has walking legs that have distinctive wide dark red/black bands on the carpus. The spiny chelae are approximately the same size and the eye-stalks are light yellow in contrast to their black eyes. (b) Frontal view of the hermit crab *Dardanus tinctor* carrying anemones (*Calliactis polypus*) on its gastropod shell home. One of the anemones is sweeping its tentacles across the substratum in search of food. (c) The xanthid *Etisus laevimanus* on a shallow offshore reef platform in Abu Dhabi. The spoon-shaped tip of the 'thumb' of the left claw of this individual is visible. (d) A specimen of the swimming crab *Portunus segnis* eating bait pillaged from a basket trap (gargoor) in Abu Dhabi. (e) A male *P. segnis* defending a smaller female after her moult whilst remaining in a 'pseudocopulatory' position. (f) *P. segnis* in a defensive mode. (g) This beautiful xanthid crab species *Carpilius convexus* is in danger of disappearing from the Gulf

due to collecting for the aquarium trade. (h) An unknown pilumnid crab, possibly *Actumnus* sp., located amongst coral on a shallow coastal platform in Abu Dhabi Emirate. (i) The off-white translucent gelatinous branching structure of the ctenostomatid bryozoan *Zoobotryon verticellatus* appears very plant-like when seen underwater. (j) The cheilostomatid *Celleporaria* cf. *pigmentaria* forms distinctive black mounded calcified colonies that are hard and 'spiky' to the touch and are often found on dead coral. (k) This species of the cheilostomatid *Biflustra* forms rigid foliaceous cream-coloured colonies in current-swept deeper offshore reef localities. (l) A calcified encrusting cheilostomatid bryozoan, *Schizoporella errata*, under a sheltered reef overhang is being overgrown by ascidian colonies (Images d, e, i, j, l © D. George; a, b, g © C. Harris; c, f © C. Teasdale; k © F. Dipper; l © Nautica Environmental Associates)

ones (*Calliactis polypus*) firmly attached to their gastropod shell homes (Fig. 13.3a) from which position they can bend to allow their tentacles to trail across the substratum gathering organic debris as the crab moves forward (Fig. 13.9b). These two crab species that are difficult to distinguish from each other underwater (see Lewinsohn 1982; McLaughlin 2002) are likely to derive protection from predators from this association as in laboratory conditions crabs have been observed to transfer the anemones they are carrying on to new larger shells when they move home.

The infraorder Brachyura is a large group of some 50 families known as the true crabs and is characterised by the short symmetrical abdomen being much reduced in size and tucked tightly under the dorso-ventrally flattened thorax. The majority of those found on coral reefs in the Gulf have well developed chelae modified in various ways to suit their feeding preferences. True crabs have a wide range of feeding habits depending on the species, some being active carnivores and scavengers whilst others are omnivores or primarily herbivores. Stephensen (1945) drew together all the previous information then available on the identity of brachyurans from the Gulf in his monograph on the Brachyura of Iran that was itself based on the benthic material collected by the Danish Scientific Investigations on behalf of the Iranian government. Most of the specimens were collected using bottom trawls, dredges and grabs from offshore soft substrata, although a few species relevant to this study were collected by dip net and hand from subtidal hard substrata. In recent times most brachyuran material from Iran has been collected remotely using bottom trawls and grabs from vessels operating offshore (Naderloo and Sari 2007) or from muddy substrata of mangrove forests and tidal flats (Naderloo and Türkay 2009). On the west coast of the Gulf, Jones (1986) is a useful guide to the brachyurans to be found in shallow back reef areas of Kuwait and the SCUBA-diver investigations in Basson et al. (1977) are of value for reefs in Saudi Arabian waters. The studies of Hogarth (1988, 1989, 1994) in Oman show that there is a considerable number of species in common between the decapods of Oman and the Gulf.

The large portunid swimming crab *Portunus segnis* is a fast-moving aggressive predator (Lai et al. 2010) that is common throughout the Gulf (see Table 13.6) and is often found in the shallows on back reefs and amongst seagrass beds on top of reef shoals (Fig. 13.9d–f). It has its hind limbs specially flattened for swimming and is the only crab that is taken commercially within the Gulf although other species such as the portunid *Charybdis natator* and the xanthid stone crab *Etisus laevimanus* (Fig. 13.9c) are collected occasionally for human consumption or are used as bait (Carpenter et al. 1997). Of the aggressive portunids, species of *Thalamita* are the most common on coral reef flats of the Gulf Emirates. The latest contribution to portunid taxonomy in the region

was by Apel and Spiridonov (1998) who produced a large paper on the taxonomy and zoogeography of the portunid crabs of the Gulf and adjacent waters.

The Xanthidae is the commonest family of crabs to be found on the reefs of the SE Gulf and individuals are usually located in reef crevices, under coral boulders, or sometimes even foraging for food in the open on back reef flats or amongst coral rubble (Table 13.6). One visually attractive stone crab, *Carpilius convexus* (Fig. 13.9g), found on Gulf reefs is unfortunately sometimes taken by divers collecting for the aquarium trade and is becoming a rarity.

The Pilumnidae (hairy crabs) are closely related to the Xanthidae and are small crabs usually covered with a fine down of hairs over their bodies and limbs that tends to trap sediment thereby further helping to camouflage their outline. They can be found on back reefs in the SE Gulf where they hide in crevices, under coral boulders, and amongst coral rubble during the day, but emerge at night to feed on a variety of other macroinvertebrates including sponges and polychaetes as well as on pieces of algae that they pull apart with their relatively large claws. Species within the genera *Actumnus* (Fig. 13.9h), *Heteropilumnus*, *Pilumnopeus* and *Pilumnus* have been located during investigations on the reefs of Abu Dhabi Emirate, with *Pilumnus longicornis* being the most commonly encountered. Titgen (1982) on the other hand stated that *P. propinquus* was the most common *Pilumnus* species in Dubai Emirate and does not mention *P. longicornis* – this may be a case of mistaken identity.

The Trapeziidae (coral crabs) are always found amongst branching corals. *Trapezia cymodoce* is known to associate with *Pocillopora* in the Western Indian Ocean and *Tetralia glaberrima* with *Acropora* species (Jones 2002). The relationship between the crabs and branching corals is thought to be a commensal one as the corals provide cover from predators for the crabs amongst their branches and the crabs use their chelae to fend off potential predators of coral soft tissues. Evans et al. (1973) found *T. glaberrima* during their marine investigations off the coast of Abu Dhabi Emirate and Titgen (1982) reported it as occurring on *Acropora* during his studies in Dubai Emirate. Earlier records of the occurrence of this species in the Gulf were from Iran (Stephensen 1945) and from Saudi Arabia (Basson et al. 1977). Another species *Trapezia cymodoce* appears never to have been recorded from the SE Gulf, but it has been found in the past both in Iranian (Stephensen 1945) and in Saudi Arabian waters (Basson et al. 1977) (Table 13.6). The possible reason for its absence is the rarity of *Pocillopora* in the SE Gulf.

Majidae (spider crabs), so called because of their relatively long slender legs compared with their body, do not seem to be well represented on the coral reefs of the Gulf Emirates, although Titgen (1982) recorded four species during his study of decapods from the reefs of Dubai Emirate (see Table 13.7).

Table 13.8 Bryozoa of the Gulf Emirates reefs. Identifications by K. Tilbrook with the assistance of M. Spencer Jones

Order Ctenostomatida
<i>Zoobotryon verticellatus</i> (Delle Chiaje, 1828)
ctenostomid
Order Cyclostomatida
<i>Disporella novaehollandiae</i> (d'Orbigny, 1853)
Order Cheilostomatida
<i>Aetea</i> sp.
<i>Antropora minor</i> (Hinks, 1880)
<i>Beania</i> sp.
<i>Bicellaria</i> cf. <i>levinseni</i> Harmer, 1926
<i>Biflustra</i> sp.
<i>Celleporaria</i> cf. <i>pigmentaria</i> (Waters, 1909)
<i>Celleporaria</i> sp.1
<i>Celleporaria</i> sp.2
<i>Drepanophora indica</i> Hayward, 1988
<i>Jellyella tuberculata</i> (Bosc, 1802)
<i>Parasmittina</i> sp.1
<i>Parasmittina</i> sp.2
<i>Parellisina curvirostris</i> (Hincks, 1871)
<i>Poricella robusta</i> (Hincks, 1874)
<i>Poricellaria ratoniensis</i> (Waters, 1887)
<i>Rhynchozoon</i> sp.1
<i>Rhynchozoon</i> sp.2
<i>Savignyella lafontii</i> (Audouin, 1826)
<i>Schizomavella</i> sp.
<i>Schizoporella errata</i> (Waters, 1878)
<i>Schizoporella</i> sp.1
<i>Scrupocellaria</i> cf. <i>spatulata</i> (d'Orbigny, 1851)
<i>Scrupocellaria</i> sp.1
<i>Synnotum aegyptiacum</i> (Audouin 1826)
<i>Thalamoporella</i> cf. <i>harmeri</i> (Levinsen, 1909)
<i>Thalamoporella</i> cf. <i>tubifera</i> (Levinsen, 1909)
<i>Turbicellepora</i> cf. <i>ampla</i> (Kirkpatrick, 1888)
<i>Turbicellepora</i> sp.1

Spider crabs tend to decorate themselves with pieces of sponge and algae that they attach to hooked setae on top of their triangular-shaped carapace (see Jones 2002). Species of the Dromiidae (sponge crabs) also adopt the same strategy to hide themselves from predators, but hold living encrusting sponge pieces in place on top of their hairy carapace, using specially adapted rear thoracic limbs, until the sponge starts to overgrow the carapace. When the crab moults, pieces of sponge are transferred from the moulted exoskeleton on to its new carapace as soon as it has hardened sufficiently.

13.3.10 Bryozoa

The phylum Bryozoa (often known as sea-mats) is a poorly known group of macroinvertebrates within the Gulf. All marine forms are sessile, modular, colonial suspension-

feeding animals; each basic bilaterally symmetrical module (autozoid) with a characteristic eversible food collecting and respiratory organ known as a lophophore. The lophophore consist of a crescentic or circular arrangement of ciliated tentacles that surrounds the mouth. The mouth leads into a voluminous u-shaped gut within the body cavity and then opens to the exterior through an anus just outside the lophophore introvert. The zoid may secrete a gelatinous (e.g. *Zoobotryon*) or a calcareous rigid capsule around it (e.g. *Disporella*) that supports the colony as it develops by asexual budding from the ancestral zoid that has itself been formed from a larva produced by sexual means. The single orifice of the protective capsule is usually towards one end and it is through this that the lophophore can be everted by hydrostatic pressure when feeding or withdrawn rapidly into the safety of the capsule (that may or may not have a hinged operculum) by a retractor muscle when the zoid is not feeding or approached by a predator. Some species have several types of zoid specialised to form a particular function for the colony. Recent bryozoans are usually classified into three Orders: Ctenostomatida (non-calcified and lacking operculum); Cyclostomatida (completely calcified protective wall to zoid and circular orifice is terminal); Cheilostomatida (calcified protective wall to zoid not always complete and orifice is subterminal or frontal, nearly always with a hinged operculum). The Cheilostomatida is by far the largest group of bryozoans on the coral reefs of the SE Gulf (see Table 13.8).

The majority of genera in the SE Gulf are two-dimensional encrusters in crevices, under overhangs and coral boulders as well as on skeletal coral surfaces on reef fronts, reef shoals and outer regions of back reef flats. Encrusting colonies help to stabilise coral rubble, particularly dead *Acropora* branches, and sometimes drifts of dead shells on reef shoal platforms. Other genera, however, contain species that form three-dimensional arborescent or foliaceous branching growths some of which are flexible whilst others are rigid and calcified.

Only one species of ctenostomatid was identified from the reefs of the SE Gulf during the NHM survey (Table 13.8) although another, as yet unidentified, species was collected. The identified species, *Zoobotryon verticellatus*, forms a gelatinous translucent three-dimensional branching colony that can reach very large dimensions for a bryozoan (0.5 m). It can be found in areas where wave movement is slight in lagoons and on the lee side of some reef shoals. It can also be a fouling species of some consequence in marinas and on pier piles (Fig. 13.9i) and has been said to sometimes clog the seawater intake pipes of coastal power stations and desalination plants (ADCO employee, personal communication). Similarly only one species of cyclostomatid was recorded from the SE Gulf, this being the relatively widely distributed species



Fig. 13.10 (a) Calcified encrusting cheilostomatid bryozoan, *Schizoporella errata*. (b) An unidentified, but commonly occurring, cheilostomatid bryozoan on shallow sheltered reefs and hard substrata in marinas. (c) *Phoronopsis californica*? photographed on the east coast of the UAE, but has been seen also in Abu Dhabi Emirate. (d) The crinoid *Oligometra serripinna* attached to the soft coral *Junceella juncea* at a depth of 14 m off Hengam Island, Iran. (e) *Lamprometra palmata* emerges at dusk from crevices in shallow reefs and positions itself on top of prominent features with its arms spread at right angles to the current to catch passing plankton. (f) The starfish *Aquilonastra burtoni* is often located under loose coral boulders and under overhangs in reef shallows. (g) *Astropecten phragmorus* is seen rarely on hard substrata, but more often on coral rubble and coarse sand adjacent to reefs.

(h) *Linckia multifora* with arms of unequal length probably due to previous fission and subsequent regrowth of one of its arms. (i) *Pentaceraster mammillatus* with an interesting graphic design of lines on its aboral surface seen at 12 m depth off Kish Island, Iran. (j) *Linckia guildingi* prefers coarser sediments around the base of shallow reefs, photographed at 12–15 m off Kish Island, Iran. (k) The multi-armed predator of coral, *Acanthaster planci*. It has only been recorded twice from the Gulf. (l) *Ophiothrix (Ophiothrix) savignyi* is seen commonly amongst sessile macroinvertebrate colonies, particularly sponges such as *Aplysinella rhax*, both in crevices and in the open, and shows considerable colour pattern variation on its dorsal surface (Images © D. George except i, j © H. Rezai; a © F. Dipper; c © C. Harris; d © K. Samimi-Namin)

Disporella novaehollandiae that forms small whitish-coloured roughly circular encrusting domed patches consisting of heavily calcified adjacent, but unfused, individual tubes protecting the zooids. These patches occur primarily on shallow reef flats but also on large algal stipes and seagrass blades. Some examples of cheilostomatids in the SE Gulf, many of which have been photographed *in situ* are *Celleporaria* cf. *pigmentaria* (Fig. 13.9j); *Biflustra* sp. (Fig. 13.9k); *Schizoporella errata* (Figs. 13.9l and 13.10a); an unidentified, but commonly occurring, species of cheilostomatid in shallow sheltered reef situations and in marinas (Fig. 13.10b). *Synnotum aegyptiacum* forms an erect branching colony that has been likened to a string of glass beads. It is often difficult to distinguish underwater since it frequents areas of dead coral also favoured by hydroids with which it often intermingles. *Jellyella tuberculata* is a species that is not found directly attached to the hard substrata of coral reefs but rather to the stipes and fronds of *Sargassum* and other algae that occur on shallow coral reefs and become particularly prominent during the cooler winter and spring months when algae are at their peak of development (see Chap. 14 on Algae).

A book by Ryland (1970) provides a good introduction to the phylum and his contribution on Bryozoa (Ryland 1984) has a useful key to higher taxa of the phylum with special reference to coral reefs. Studies on bryozoans of coral reefs closer to the Gulf include one on the Cheilostomatida from Mauritius (Hayward 1988) and a biogeographical analysis of the cheilostomatids of the Indo-West Pacific by Tilbrook and De Grave (2005). A contribution by Thornely (1912) on Bryozoa in the Indian Ocean was produced at approximately the same time as Waters (1909, 1910) was studying the Bryozoa of the Sudanese Red Sea. Powell (1967) published on Bryozoa of the Southern Red Sea and followed it with a checklist of Indo-Pacific bryozoans in the Red Sea as a whole (Powell 1969). Bryozoans collected from the reefs of the Gulf Emirates are listed in Table 13.8.

13.3.11 Phoronida

The small phylum Phoronida, commonly known as horse-shoe-worms, contains species that are sometimes mistaken for bryozoans since they also have a ciliated lophophore used for suspension feeding and respiration. However, phoronids have a bilaterally symmetrical elongated body with an enlarged bulb-like posterior end that is used as an anchor. Their gut is U-shaped and extends throughout the body with the anus opening close to the lophophore at its anterior end. They live within a chitinous tube to which sediment adheres during the hardening process of the sticky body secretions. Some species live vertically in sandy sediments and amongst coral rubble whilst others cluster in groups on hard surfaces or even bore into limestone, dead coral and bivalve shells by

means of chemical secretions. Although their lophophore can be withdrawn rapidly into the protection of the tube they are nonetheless vulnerable to predators such as fish. However, phoronids are able to regenerate their anterior end within a few days if it is damaged. Those wishing to know more about the group should read Emig (1979) and visit the Phoronida World Database (Emig 2007).

Phoronid species are seen commonly on the east coast of the UAE (C. Harris, personal communication), but their presence has yet to be confirmed in the Gulf Emirates and elsewhere in the Gulf, although I believe that I have seen a specimen in sand amongst seagrass adjacent to a coral reef in Abu Dhabi Emirate. Many of the specimens that occur in sand and coral rubble adjacent to coral reefs on the east coast of the UAE are unmistakable due to their beautiful black arrays of lophophore tentacles (Fig. 13.10c). The species may be *Phoronopsis californica* Hilton, 1930 but there is also a distinct possibility (C. Emig, personal communication) that it is a black variety of *Phoronis australis* Haswell, 1883 that appears to be a generally less robust-looking translucent pinkish white species, that occurs in the same sedimentary habitat, but is usually embedded in large numbers in the tube of a cerianthid cnidarian. Until specimens are available from the area for detailed examination by an expert on the group the matter remains unresolved.

13.3.12 Echinodermata

The phylum Echinodermata is one of the most conspicuous and familiar macroinvertebrate groups within the Gulf. There is an excellent collection of literature available to aid in their identification and good and well-maintained specimen collections within the larger Museums and Institutions that have been involved with work in the Gulf and the Indo-West Pacific. It is a fully marine phylum whose members are mainly bottom dwellers that have a basic 5-rayed symmetry as adults that is radial in most, but bilateral in some. They have an internal skeleton of calcareous plates/ossicles, and a unique water-vascular system that extends out through the skeleton to form tube feet that are used for locomotion and food gathering. Excellent introductory accounts of the phylum can be found in Nichols (1969) and Clark A.M. (1977) and an introduction specifically to the echinoderms of coral reefs (Clark 1976) is also of value. The higher classification of the group is relatively simple with most echinoderm publications directing readers straight to the five main classes occurring in shallow waters that are easy to distinguish from one another, even in the field. These are the Crinoidea (featherstars), Asteroidea (starfishes), Ophiuroidea (brittlestars), Echinoidea (sea-urchins), and the Holothuroidea (sea-cucumbers).

Table 13.9 Habitat requirements of Echinodermata associated with Gulf reefs. Majority of information extracted from Price's 1983 publication. Species marked with an asterisk (*) are additional species found in the SE Gulf since Price's study

Taxa	Habitat
Class Crinoidea	
<i>Decametra mollis</i> (A.H. Clark, 1909)	Coral reef base, 15 m
Class Asteroidea	
<i>Astropecten phragmorus</i> Fisher, 1913	Subtidal rock and sand, 0–15 m
<i>Pentaceraster mammillatus</i> (Audouin, 1826)	Subtidal coarse sand or coral rubble on or near coral reefs, 4–15 m
<i>Leiaster leachi</i> (Gray, 1840)	Coral reefs, 7–15 m
* <i>Linckia guildingi</i> Gray, 1840	Sand and coral rubble at base of reefs, 5–15 m
<i>Linckia multifora</i> (Lamarck, 1816)	Coral reef and subtidal sand, 3–15 m
<i>Asteropsis carinifera</i> (Lamarck, 1816)	Coral reef, 2–7 m
<i>Aquilonastra burtoni</i> (Gray, 1840)	Coral reef, subtidal rock, 0–10 m
<i>Euretaster cribrosus</i> (von Martens, 1867)	Coral rubble near reef base, 20 m
Class Ophiuroidea	
<i>Amphiura crispera</i> Mortensen, 1940	Coral reef, 5 m
<i>Ophiactis savignyi</i> (Müller and Troschel, 1842)	Coral reef, subtidal rock, epizoic on sponges, 0.5–15 m
<i>Macrophiothrix elongata</i> H.L. Clark, 1938	Coral reef, subtidal rock, 0–15 m
<i>Ophiothela danae</i> Verrill, 1869	Coral reef, epizoic on gorgonians, 12–32 m
<i>Ophiothela venusta</i> (de Loriol, 1900)	Coral reef, epizoic on gorgonians
<i>Ophiothrix</i> (<i>Ophiothrix</i>) <i>savignyi</i> (Müller and Troschel, 1842)	Coral reef, subtidal rock, 0–32 m
* <i>Ophiothrix</i> (<i>Acanophiothrix</i>) <i>purpurea</i> von Martens, 1867	Amongst sessile organisms and rubble on coral reefs 0.5–15 m
<i>Ophionereis dubia</i> (Müller and Troschel, 1842)	Coral reef, subtidal rock, 0.5–7 m
* <i>Ophiocoma scolopendrina</i> (Lamarck, 1816)	Under coral rubble on shallow reef shoals and coastal platforms, 0–2 m
Class Echinoidea	
<i>Prionocidaris baculosa</i> (Lamarck, 1816)	Coral reef, 5–32 m
<i>Diadema setosum</i> (Leske, 1778)	Coral reef, subtidal rock, 0.5–8 m
<i>Echinometra mathaei</i> (de Blainville, 1825)	Coral reef, subtidal rock, 0.5–31 m
<i>Metalia sternalis</i> (Lamarck, 1816)	Coral reef flat (platform), sand
Class Holothuroidea	
<i>Labidodemas semperianum</i> Selenka, 1867	Coral reef, 7 m
<i>Holothuria</i> (<i>Cystipus</i>) <i>rigida</i> Selenka, 1867	Coral rock, subtidal rock
<i>Holothuria</i> (<i>Halodeima</i>) <i>atra</i> Jaeger, 1833	Subtidal sand-covered rock and sand, grass beds etc., 3–4 m
<i>Holothuria</i> (<i>Mertensiothuria</i>) <i>leucospilota</i> (Brandt, 1835)	Coral reef, 6–13 m
<i>Holothuria</i> (<i>Thymiosycia</i>) <i>arenicola</i> Semper, 1868	Coral reef, mixed sand and rock, 0–7 m
<i>Holothuria</i> (<i>Thymiosycia</i>) <i>hilla</i> Lesson, 1830	Coral reef, 1–15 m
<i>Holothuria</i> (<i>Thymiosycia</i>) <i>impatiens</i> (Forsskål, 1775)	Coral reef, 7 m
<i>Stichopus hermanni</i> Semper, 1868	Coral reef, reef rubble, 5–7 m
<i>Ohshimella ehrenbergii</i> (Selenka, 1868)	Coral, subtidal rock, 0.3 m
<i>Leptosynapta chela</i> Mortensen, 1926	Coral reef flat sand, 1.5–8.8 m

The Crinoidea are an ancient group and unique in the echinoderms in that the body of members in the group have what would normally be considered as being the ventral side in most other classes facing upwards into the water column with both their mouth and anus on the upward facing side. They basically have five arms but these in many species are forked repeatedly to form numerous branches with feathery extensions called pinnules on either side. Organic matter and plankton in the water column is caught on these side extensions by tube feet and transferred down an upward-facing ciliated groove in the arms to the mouth. Most suspension feeding crinoids are nocturnal in habit in well-lit shallow waters and only

emerge from crevices in the reef at dusk to take up a prominent positions in the water current on top of corals and other objects. They cling to the structures with special appendages known as cirri from the dorsal central plate and feed on the plankton that tends to rise to the surface waters at dusk.

Crinoids are not a well-represented group in the Gulf compared with in the Red Sea and according to Price (1981, 1983) only one species of featherstar (*Decametra mollis*) was found on the reefs during his work along the Gulf coast of Saudi Arabia (Table 13.9). I was unsuccessful in locating any crinoids during my recent research on the coral reefs of the Gulf Emirates, although local divers have reported seeing

them on wrecks in deeper water offshore (C. Harris, personal communication), and Hughes Clarke and Keij (1973) found comatulid crinoids (unidentified?) in dredge samples taken near rocks at several unidentified localities in the southern Gulf. Only one species (*Heterometra savignii*) has been reported from the coral reefs off the east coast of Qatar by Al-Ansi and Al-Khayat (1999) and records of this species in the Gulf may well turn out to be *H. africana* according to Gislén (1940), and Clark and Rowe (1971). Featherstars, however, were located off Bahrain and on reefs along the Iranian coast within the Gulf in the late 1930's according to Gislén (1940) and recently reported in Iran (K. Samimi-Namin, personal communication) (Fig. 13.10d). It should come as no surprise that they occur in Iranian coastal waters within the Gulf as they are seen regularly amongst corals on the east side of the Musandam Peninsula (Oman) and along the east coast of the UAE (personal observation). To date six crinoid species have been reported from reefal areas within the Gulf: *Decametra mollis* (A.H. Clark, 1909), *Heterometra africana* (A.H. Clark, 1911), *Heterometra savignii* (J. Müller, 1841), *Himerometra persica* (A.H. Clark, 1907), *Lamprometra palmata* (J. Müller, 1841) (Fig. 13.10e) and *Oligometra serripinna* (Carpenter, 1881) (Fig. 13.10d).

Species within the Asteroidea usually have five sturdy arms (sometimes more) radiating from the central part of the body that has a mouth in the middle of its ventral surface and an anus centrally placed on the dorsal side, but a few species have no anus. The arms, which generally taper towards their extremities, have prominent grooves on their undersides bearing rows of tube feet that are used for locomotion and in carnivorous species help to secure their prey. Asteroids often regenerate lost or damaged arms and a few species (e.g. *Linckia multifora*) reproduce by fission as well as sexually. Although the majority of starfish species occur on reefal hard substrata, many can be found on soft substrata adjacent to coral reefs searching for mollusc prey within the sediment. Predatory starfish within the Gulf feed on a variety of different prey items including sponges, corals, polychaetes, bivalve molluscs and crustaceans. However, many predators are also scavengers.

According to Clark and Rowe (1971) and Price (1982) relatively few starfish species have been recorded in the Gulf compared with those found in other areas of shallow water in the Indo-West Pacific. It is by no means certain whether all of Mortensen's (1940) ten asteroid records from Iranian coastal waters were collected within the Gulf or from the Iranian coastline outside the Gulf fronting the Gulf of Oman, and most of them were not taken from reefal hard substrata. It can be said with certainty, however, that species he identified as *Asterina burtoni* (now known as *Aquilonastra burtoni* – see Table 13.9), *Astropecten phragmorus*, *Linckia multifora*, and *Pentaceraster mammillatus* can be found close to or on reef substrata. Information extracted from Price (1981) would suggest that he

only recorded seven species from the coral reefs along the Gulf coast of Saudi Arabia (Table 13.9). Evans et al. (1973) during their extensive early work along the coastline of Abu Dhabi Emirate collected four species of asteroid (*Astropecten pugnax*, *A. indicus*, *A. phragmorus* and *Aquilonastra burtoni*) that were identified by A M Clark at the NHM, but only two of those (*Aquilonastra burtoni* and *Astropecten phragmorus*) were members of reef assemblages.

During my recent work on the coral reefs of Abu Dhabi Emirate only three species of asteroid *Aquilonastra burtoni* (Fig. 13.10f), *Astropecten phragmorus* (Fig. 13.10g) and *Linckia multifora* (Fig. 13.10h) were recorded. However, recent investigations of the Qatar east coast benthic macroinvertebrate biota of coral reefs (Al-Ansi and Al-Khayat 1999), and also of oyster beds (Al-Khayat and Al-Ansi 2008), listed *Pentaceraster mammillatus*, and an unidentified species of *Ophidiaster* in addition to those I recorded in Abu Dhabi Emirate. *P. mammillatus*, one of the commonest asteroids on the oyster assemblages there, is a known predator of pearl oysters and has also been recently photographed *in situ* along the Gulf coast of Iran (Fig. 13.10i) as has *Linckia guildingi* (Fig. 13.10j) (K. Samimi-Namin, personal communication). According to local press reports in recent years numbers of the coral polyp-eating crown-of-thorns starfish (*Acanthaster planci*), which is common in the Gulf of Oman (Fig. 13.10k), have been seen by SCUBA-divers attacking corals along the Iranian Gulf coast and in Kuwait.

Ophiuroidea is the largest of the classes of echinoderms. Members of the group, unlike the Asteroidea, have a distinctive central disc-shaped body with mostly five long narrow and fragile, articulated, arms sharply set-off from it (see Nichols 1969 for a detailed comparison of the arm structure of the two classes). They have a centrally placed mouth surrounded by tooth-like plates on the ventral side of the body and lack an anus, thus requiring undigested waste from the large sac-like stomach to pass back out through the mouth. Locomotion of brittlestars is achieved mainly by arm flexing combined with the use of the spines on their calcareous plates for anchoring as the body is drawn forward. The small tube feet (podia) on the undersides of the arms play little part in locomotion, their main function being to aid feeding. Most species are scavengers, surface deposit feeders and/or suspension feeders on minute planktonic organisms and particulate organic detritus in the water column, although a few of the larger species prey on worms, bivalves and crustaceans. Pentreath (1970) made an elegant study of the feeding mechanisms in some ophiuroids.

Many ophiuroids are confined to sand and muddy substrata in the Gulf although a range of species can be found on all types of hard substrata including coral reef fronts, reef shoal platforms and back reefs. It is not unusual to see brittlestars associated with sponges and epizoa on gorgonians, although in most cases all that can be seen are



Fig. 13.11 (a) The brightly coloured bodies of *Ophiothela venusta* are unmistakable, but the species is not often seen in the SE Gulf. When located on deeper parts of reefs they are invariably wrapped around the branches of an octocoral such as *Menella* sp. (b) The bright orange specimen seen on a sponge may be *Ophiothrix* (*Acanthophiothrix*) *purpurea*, but could just be a colour variant of *O. (Ophiothrix) savignyi*. (c) *Ophiocoma scolopendrina* was located in the shallows of an offshore reef shoal platform in Abu Dhabi Emirate. (d) The same species seen feeding on organic matter trapped in the surface water film on a calm day in the sublittoral shallows of the Red Sea. (e) *Echinometra mathaei* occurs in such large numbers on the reefs in Abu Dhabi Emirate that dead *Porites* mounds are reduced in size surprisingly rapidly by the scraping movements of the lantern teeth of the urchins. (f) *Diadema setosum* grazing on mat- and turf-algae. Occasionally predominantly white specimens of this urchin are seen and this 'albino' specimen has

a bulging anal sac with the characteristic red ring around its anus readily visible. (g) *Prionocidaris baculosa* has characteristic robust primary spines, with longitudinal lines of thorns. The spines are coated with a range of encrusting invertebrates and calcareous algae. (h) An 'army' of specimens of this species grazing on algae at 8 m depth off Hengham Island, Iran. Several of these urchins have their spines covered with brittlestars some of which have their arms erected into the water column as they feed on plankton in the passing current. (i) *Holothuria (Mertensiothuria) leucospilota* seen on sand in the shallows of a reef shoal platform in Abu Dhabi Emirate is able to elongate its body to at least twice its contracted length. (j, k) *Stichopus herrmanni* has a square body shape when seen in cross-section and prominent longitudinal rows of papillae. It is quite common on reefs and amongst coral rubble in the Gulf Emirates and Iran (Images © D. George except h, k © K. Samimi-Namin)

ophiuroid arms protruding from cracks and crevices or from between tightly packed sessile macroinvertebrates on reefs. In the SE Gulf the most commonly encountered reef-dwelling ophiuroids were *Ophiothrix* (*Ophiothrix*) *savignyi* (Fig. 13.10l), *Ophiactis savignyi*, *Macrophiiothrix elongata*, and *Ophionereis dubia*. *Ophiothela venusta* (Fig. 13.11a) was present but rarely seen. Additional specimens of ophiuroids from Abu Dhabi Emirate collected by Evans et al. (1973) and identified by A.M. Clark at the NHM included *Ophiopeza fallax* and *Ophiothrix* aff. *exigua*, although it is not known whether these were collected from coral reefs. I also may have seen a specimen of *Ophiothrix* (*Acanthophiothrix*) *purpurea* (Fig. 13.11b) amongst others on a sponge on reefs in the Emirate, and a specimen of *Ophiocoma scolopendrina* (Fig. 13.11c) on a shallow reef shoal platform, but unfortunately specimens are not available to corroborate these two sightings. Interestingly I have encountered *O. scolopendrina* in the immediate sublittoral of the Red Sea sweeping its arms across the water surface on a calm day as the water lapped over its hiding place under a rock (Fig. 13.11d); presumably there is enough organic material trapped in the surface water film to make this activity worthwhile. Magnus (1967) also observed such behaviour in this species.

Al-Khayat and Al-Ansi (2008) noted *Ophiothrix* (*Acanthophiothrix*) *purpurea* on the oyster assemblages of Qatar and a species additional to those mentioned above, *Ophiura kinbergi*, was recorded from reefs around Qatar's Halul Island by Al-Ansi and Al-Khayat (1999), but is more usually found on sand and in seagrass beds. Further to the north on the west coast of the Gulf in Saudi Arabia, Basson et al. (1977) and Price (1981, 1983) recorded two species, *Amphiura crista* and *Ophiothela danae*, that were not seen on the SE Gulf reefs. *O. danae* like *O. venusta* is usually found attached to gorgonians on deeper parts of reefs. Jones (1986) also noted these two species as occurring in reefal areas of Kuwait along with *Ophiothrix* (*Ophiothrix*) *savignyi*, *Macrophiiothrix elongata* and *Ophionereis dubia*. Little has been published on the identity of ophiuroids from the extensive Iranian coastline since the work of Mortensen (1940) and many of his specimens were collected remotely from non-reefal substrata.

The spiny calcareous plates of the Echinoidea form a rigid casing (test) around the body. There are no arms as in the previously mentioned groups, but even so the radial pentamerism of the test in coral reef-dwellers is generally very obvious from the arrangement of the plates and tube feet, with the mouth placed centrally on the ventral surface and the anus centrally on the dorsal side ('regular urchins'). The well-developed and highly muscular mechanism operating the five teeth surrounding the mouth in regular urchins is often referred to as Aristotle's lantern because of its resemblance to the shape of an old-fashioned lantern.

Regular urchins use their teeth to scrape off algal turf from the dead coral skeletons and from reef limestone platforms as well as to assist them in consuming seagrasses. Many species that bury themselves in soft sediments tend to have a secondarily bilaterally symmetrical shape to their test whilst still retaining their pentamerism ('irregular urchins'). Their lantern is not well developed since they tend to ingest organic matter gleaned by their tube feet whilst ploughing through the sediment.

The sea-urchins are not a well represented group on the coral reefs of the SE Gulf in terms of species, only two species being seen with any regularity: *Echinometra mathaei* and *Diadema setosum*. *E. mathaei* (Fig. 13.11e) in particular can now be seen in much greater abundance than previously (e.g. Hughes Clarke and Keij 1973; Evans et al. 1973) on the reefs since the massive death of the corals on the reefs in 1996 and 1998 allowed the invasion of their calcareous skeletons by cyanobacteria and mat- and turf-forming algae including calcareous red algae such as *Lithophyllum kotschyanum* on all of which this urchin feeds voraciously (see George and John 2004, 2005a, b; John and George 2003). *D. setosum* tends to be more of a low-light algal feeder and frequently stays immobile in large crevices and under overhangs in the reef shallows during the strong sunlight of the day, protected from predators by its long sharp spines (Fig. 13.11f). The length of the spines of *D. setosum* put it at a disadvantage, compared with *E. mathaei* with much shorter spines, when trying to manoeuvre and feed amongst the three-dimensional collapsing thickets of dead branching *Acropora* that are still common in the reef shallows of this region. For instance *E. mathaei* is able to graze along individual branches of the dead *Acropora* in thickets and is capable of removing a layer of the calcareous *L. kotschyanum*. Other echinoids that have been recorded from deeper reef substrata in the SE Gulf are *Prionocidaris baculosa* (Fig. 13.11g) (Hughes Clarke and Keij 1973; George 2005) and *Temnotrema toreumaticus* found by Hughes Clarke and Keij (1973) and originally identified by them as *T. scillae*.

The first detailed field study of the echinoderms of the Gulf coast of Saudi Arabia was made by Le Baron Bowen Jr. and his collected material from Tarut Bay (mainly from the Ras Tanura peninsula) later identified by A.H. Clark (Clark and LeBaron Bowen 1949). This publication was the first confirmed report of *Diadema setosum* within the Gulf. Price (1983) in his detailed study of echinoderms along the Gulf coast of Saudi Arabia additionally found *Metalia sternalis* in sand on a coral reef platform. Few studies have been made on echinoids of hard substrata in Kuwait apart from work on the biology and ecology of *Echinometra mathaei* and *Diadema setosum* (Downing 1992; Downing and El-Zahr 1987; Downing and Roberts 1993; Alsaffar and Lone 2000). There appear to be no published studies of

echinoids of the Iranian coast since the Danish Scientific Investigations (Mortensen 1940) and many of the species identified were collected from soft substrata. However, underwater photographs taken recently by K. Samimi-Namin (personal communication) show clearly that *E. mathaei*, *Diadema setosum* and *Prionocidaris baculosa* are present in some abundance. An apparently unreported phenomenon in the Gulf that he photographed shows a large group of grazing *P. baculosa* with brittlestars (*Ophiothrix* (*Ophiothrix*) *savignyi*?) attached to their substantial spines and suspension feeding on plankton flowing past the urchins in the water current (Fig. 13.11h). This type of behaviour is not unknown amongst brittlestars and another species *Ophiothrix* (*Ophiothrix*) *fragilis* that is common elsewhere, and often occurs in large aggregations on level substrata where currents flow, is known to suspension feed on particulate matter in a similar way and has been studied in detail by SCUBA-divers (Warner 1971, 1986; Warner and Woodley 1975).

The sometimes leathery, armless, bilaterally symmetrical soft body of a Holothuroidea species is unique in the echinoderms in that it is usually cucumber-shaped and capable of extension or contraction since its internal skeleton is reduced to microscopic ossicles embedded in the body wall. These calcareous structures have a range of forms within a species (e.g. table, plate, button, rod, anchor) that is constant and they are thus used in species identification. In evolutionary terms members of the group lie on their sides with their mouth at one end and their simple gut terminating in a cloaca and anus at the other. The mouth is surrounded by oral arborescent food-capturing tentacles (modified tube feet) that are used for surface deposit feeding or in a few species for suspension feeding. The form and type of these oral tentacles is also a useful clue when attempting to identify sea-cucumbers. Apart from the highly modified oral tube feet, the tube feet are used mainly for slow locomotion over the benthos and their arrangement on the body is variable – some with three rows of tube feet running along the ventral surface of the body from mouth to anus and those on the upper surface modified as sensory papillae, others with five bands of tube feet along the body, or in yet others the tube feet may be scattered over the body. In one order, the Apodida, no tube feet are present and movement of the body is by muscular contraction of the body wall in combination with the tentacles.

Many species are able to protect themselves from attack by prospective predators by everting the hind part of the gut including their internal respiratory trees (branching off the cloaca), which they are able to regrow. In addition certain species of some genera (e.g. *Holothuria*, *Pearsonothuria*) have long sticky (and possibly toxic) threads, known as ‘Cuvierian tubules’, that can be inverted through the cloaca

and anus and entangle natural predators such as crabs, lobsters, fish and turtles. These natural defences do not deter man from drying and cooking them and large *bêche-de-mer* fisheries occur in some parts of the world, although within the Gulf this happens only to a very limited extent. An interesting account of the biology and ecology of tropical holothurians was given by Bakus (1973).

Only five species of holothuriodean were noted on reefs during the NHM’s investigations of subtidal hard substrata in Abu Dhabi Emirate, three of these belonging to the large family Holothuriidae: *Holothuria* (*Halodeima*) *atra*, *Holothuria* (*Halodeima*) *edulis*, and *Holothuria* (*Mertensiothuria*) *leucospilota* (Fig. 13.11i) and one to the Stichopodidae: *Stichopus herrmanni* (Fig. 13.11j, k). All of these were found either on sand between coral, on detritus-covered dead coral, on coral rubble or under boulders on reef shoal platforms or back reefs covered with a thin layer of sand. The fifth species (*Leptosynapta chelae*), a small (2–3 cm long), thin-walled sipunculan-like colourless synaptid that adhered to the fingers when handled, was found in a layer of coarse sand covering a creviced reef platform. Elsewhere in the SE Gulf Al-Ansi and Al-Khayat (1999) recorded *Holothuria* (*Halodeima*) *atra* on the coral reefs of Qatar and Al-Khayat and Al-Ansi (2008) the same species amongst Qatar’s oyster assemblages.

As a result of the research of Basson et al. (1977), Price 1981, 1982, 1983 the sea-cucumbers of the Gulf coast of Saudi Arabia are relatively well-known. I have extracted a list of species that are associated with the reefal environments from these publications and find that ten species were likely to have been associated with the coral reef environment at that time (Table 13.9). Most of them belonged to the genus *Holothuria*, several of which are additional to those species recorded more recently in the SE Gulf. Other species not recorded further south in the Gulf included *Labidodemus semperianum* and *Ohshimella ehrenbergi*. Price (1986) studying echinoderms from Kuwait, identified two species, *Pentacta loeppenthini* (now known as *Plesiocolochirus loeppenthini* according to Rowe and Gates 1995) and *Hemithyone semperi* not previously found during his research along the Gulf coast of Saudi Arabia.

Heding (1940) examined the holothurians collected by the Danish Scientific Investigations in Iranian waters and checked those from the littoral areas of the Iranian coastline identified by Koehler and Vaney (1908). Only six species were found in the vicinity of or on hard substrata of Iranian coastal waters within the Gulf and these have all been found in other Gulf countries since that time. A recent paper (Tehranifard et al. 2006) on the reproductive cycle of *Stichopus herrmanni* from Kish Island, Iran is of interest. Another species, *Pearsonothuria graeffei*, occurs on the east coast of the UAE and of the Musandam peninsula of Oman (personal observation), but has not as yet been recorded in the Gulf.

13.3.13 Ascidiacea

Only one group of reef-associated benthic macroinvertebrates within the phylum Chordata is of direct interest and that is one of the three classes of the exclusively marine subphylum Urochordata, commonly called tunicates because the body of a urochordate is encased within a cellulose-like surface layer known as a tunic. The class in question, the sessile Ascidiacea (sea-squirts), has often colourful solitary and colonial members that are present and sometimes conspicuous on almost all types of hard substrata including reefs within the Gulf, yet have been little studied there in detail compared with in other regions of the world (see later). As with the sponges, pharmaceutical companies have shown a special interest in this group because of the possible medicinal value of some of its chemical compounds.

The tunic of an adult ascidian, that may sometimes contain stellate calcareous spicules (e.g. *Didemnum* spp.), has two openings one of which is an inhalent (oral) siphon the other the exhalent (cloacal) siphon. Suspended within the body from the oral opening is a multiperforated ciliated (branchial) sac into which seawater and particulate matter is drawn through the oral opening. In the sac particulate matter is filtered out in a mucous net that is rolled up and streamed into a relatively simple digestive tract with a large stomach where useful organic matter is absorbed and waste material then expelled to the exterior through the cloacal siphon. In some colonial forms of these filter-feeders, much as in the more evolutionarily primitive sponges, the expelled material from each zooid is passed into channels serving many zooids that are embedded in a common tunic and out through a communal opening to the exterior. Observations made in the field can sometimes lead to colonial forms being provisionally identified by a casual observer as sponges. Ascidiaceans are hermaphrodites and produce tadpole-like larvae, with chordate characteristics, that swim in the water column before settling to the bottom and metamorphosing into small ascidiaceans. Some colonial forms also reproduce asexually by budding from their zooids.

The class Ascidiacea is divided into three orders, based mainly on the characteristics of the branchial sac, the largest of which being the Aplousobranchia that contains almost two thirds of tropical species. The order Phlebobranchia has mostly solitary species and the Stolidobranchia a mix of solitary and colonial forms. Ascidiaceans from the shallow hard substrata including coral rock of the western Indian Ocean have been studied in most detail from the east coast of Africa during the latter half of the twentieth century and continuing through to recent times (Millar 1956, 1961, 1962, 1975; Monniot 1965, 1997, 2002; Monniot and Monniot 1976; C. Monniot et al. 1991, 2001; Monniot and Monniot 1997a, b).

Provisional identifications of ascidian specimens collected during the NHM's on-going research on macroinvertebrates of subtidal hard substrata (mainly of coral reefs and coral assemblages) in Abu Dhabi Emirate have been made (see George 2005; George and John 2004; John and George 2004 and Table 13.10), but many have yet to be identified. The majority of the species are considered to be 'fouling organisms' if found on pier piles, jetties, buoys or marina pontoons and on the numerous pleasure craft that move infrequently from their moorings within the marinas. However, all these species also occur in association with the coral reefs of the Emirate, although usually not as abundantly as on artificial hard substrata in sheltered localities. They occur on dead coral, under overhangs, in crevices and fissures on the reef fronts. On offshore shallow reef shoals ascidiaceans can be found as pads with adhering sand on shallow horizontal platform surfaces (Fig. 13.12a) as well as under coral boulders (Fig. 13.13a) and overhangs (Fig. 13.13b, e), on coral rubble, on macroalgal stipes, and on seagrasses growing in sand accumulations on top of the shoals (Fig. 13.12b). On reef flats behind the reef fronts of coastal reefs they occur under coral boulders. Some of the most commonly seen species by SCUBA-divers in the open on the reefs in Abu Dhabi Emirate belong to the genera *Didemnum* (Fig. 13.12c–g), *Phallusia* (Fig. 13.12i), and *Botryllus* (Fig. 13.12j, l), although other genera are encountered on occasions (Fig. 13.12h, k).

Elsewhere in the Gulf Lane (1986) identified five species and two more genera collected from intertidal and subtidal rock substrata in Kuwait (Table 13.10). The ascidian experts Monniot and Monniot (1997) made a detailed study of specimens collected for them from reef rubble, artificial hard substrata, sea grass beds and mangrove in the shallow waters of Bahrain, and identified a total of 15 species and an additional two genera that were too immature to identify to species level (Table 13.10). Al-Ansi and Al-Khayat (1999) recorded the genera *Polyclinum*, *Didemnum* and *Phallusia* from the reefal areas off the east coast of Qatar and Al-Khayat and Al-Khayat (2000) *Phallusia nigra*, *Styela canopus*, *Didemnum* sp. and *Herdmania* sp. from unspecified east coast offshore substrata. Al-Khayat and Al-Ansi (2008) noted *P. nigra*, *S. canopus* and *Didemnum* sp. from the oyster assemblages off the Qatar east coast. No published records could be found of ascidiaceans occurring off the Gulf coast of Saudi Arabia other than a reference in Basson et al. (1977) to their presence as a group on the coral reefs there. Only one published reference (Millar 1975) was found to the species of Ascidiacea present along the Iranian Gulf coastline, although recent underwater photographs kindly sent to me by K. Samimi-Namin show that didemnids and styelids are present amongst coral assemblages on the hard substrata there (Figs. 13.12d and 13.13d).

Table 13.10 Known distribution of reef ascidians in the Gulf

	UAE	Qatar	Bahrain	Saudi Arabia	Kuwait	Iran
Order Aplousobranchia						
Family Polyclinidae						
<i>Aplidium</i> cf. <i>rubripunctum</i> C. Monniot and F. Monniot, 1997	+		+			
<i>Aplidium</i> sp.					+	
<i>Polyclinum constellatum</i> Savigny, 1816	+	+	+		+	+
Family Polycitoridae						
<i>Eudistoma</i> sp.	+					
Family Didemnidae						
<i>Didemnum candidum</i> Savigny, 1816	+		+		+	
<i>Didemnum</i> cf. <i>granulatum</i> Tokioka, 1954	+					
<i>Didemnum obscurum</i> F. Monniot, 1969	+		+			
<i>Didemnum perlucidum</i> F. Monniot, 1983	+					
<i>Didemnum yolky</i> C. Monniot and F. Monniot, 1997	+		+			+
<i>Didemnum</i> sp.	+	+				
<i>Diplosoma listerianum</i> (Milne Edwards, 1841)	+		+			
<i>Lissoclinum fragile</i> (Van Name, 1902)			+			
<i>Polysyncraton thallosomorpha</i> F. Monniot, 1993	+					
Order Phlebobranchia						
Family Ascidiidae						
<i>Ascidia</i> sp.	+					
<i>Phallusia nigra</i> Savigny, 1816	+	+	+		+	+
Family Perophoridae						
<i>Ecteinascidia thurstoni</i> Herdman, 1890			+			
Order Stolidobranchia						
Family Styelidae						
<i>Botryllus gregalis</i> (Sluiter, 1898)	+		+			
<i>Botryllus niger</i> (Herdman, 1886)	+		+			
<i>Botryllus</i> spp.	+					
<i>Eusynstyela</i> cf. <i>hartmeyeri</i> Michaelsen, 1904	+		+			
<i>Polyandrocarpa</i> sp.	+				+	
<i>Polycarpa</i> sp.	+					
<i>Styela canopus</i> Savigny, 1816	+	+	+		+	+
<i>Symplegma bahraini</i> C. Monniot and F. Monniot, 1997	+		+			+
<i>Symplegma brakenhielmi</i> (Michaelsen, 1904)			+			
Family Pyuridae						
<i>Herdmania momus</i> (Savigny, 1816)	+		+		+	
<i>Pyura</i> cf. <i>gangelion</i> (Savigny, 1816)						+
pyurid	+					

Little is known about predators of ascidians in the Gulf although the flatworm *Pseudoceros*, pleurobranchid sea slugs, crabs and starfish have been observed to browse on ascidians elsewhere as have certain fish (e.g. Millar 1971; Parry 1984; Monniot et al. 1991).

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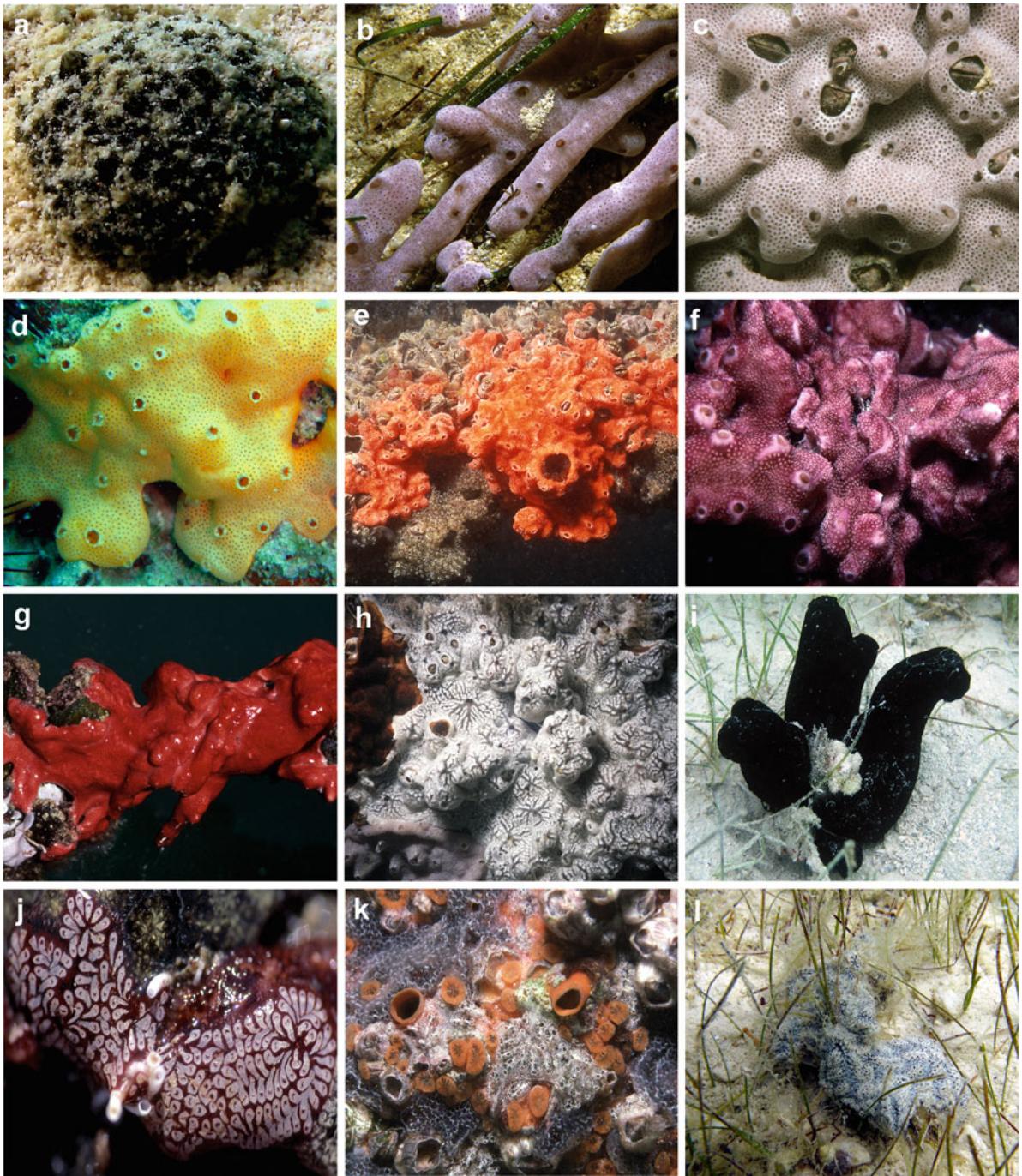


Fig. 13.12 (a) An as yet unidentified species of ascidian (possibly *Eudistoma* sp.) forming a domed colony on top of a shallow reef shoal platform that has a thin layer of mobile coarse sand. It is likely that the blue-black colouration is due to cyanobacteria in the surface tissues. (b) *Didemnum* sp. enclosing the blades of the seagrass *Halodule uninervis*. (c) *Didemnum perucidum* encroaching around barnacles (*Amphibalanus amphitrite*) on the underside of a sheltered overhang. (d, e) *Didemnum* yolky colonies display two predominantly different colours in the shallow reefal areas of the SE Gulf. (f) The colouration of *Didemnum* cf. *granulatum* appears to be constant within the Gulf Emirates. (g) An unknown *Didemnum* sp. on *Acropora* coral rubble.

(h) *Polysyncraton thallomorpha*, a brittle white didemnid with characteristic grey markings on its upper surface is seen occasionally under sheltered overhangs in Abu Dhabi Emirate. (i) *Phallusia nigra*, a member of the Ascidiidae, occurs in prominent positions on coral reefs throughout the Gulf. (j) The styelid *Botryllus niger* is often seen coating coral rubble and other hard substrata. (k) An unidentified translucent ascidian colony on dead coral bored by the orange sponge *Cliona* sp.. (l) *Botryllus* cf. *gregalis* is most often seen in amongst seagrass beds on reef top platforms or amongst seagrass at the base of reefs (Images © D. George except i, l © C. Teasdale; d © K. Samimi-Namin)

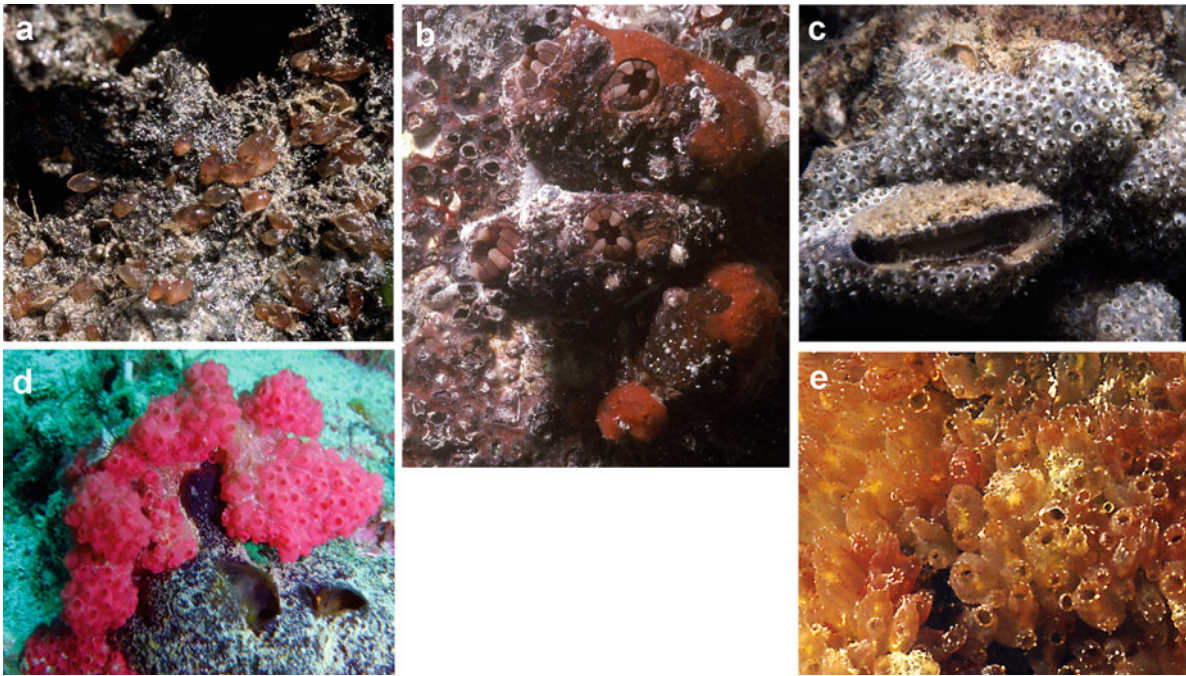


Fig. 13.13 (a) The individual zooids of this *Eusynstyela cf. hartmeyeri* colony found under a coral slab on a reef platform are linked together by thin translucent stolons. (b) Oral and cloacal siphons of these three individuals of *Polycarpa* sp. are the only parts visible under a covering of sponges and other epibionts on their thick rough tunics. (c, d) The two *Symplegma* species recorded in the SE Gulf are difficult to distinguish from

each other without detailed examination of their internal structure, and colony colouration varies from grey to red. (e) An as yet unidentified ascidian on SE Gulf reefs that occurs occasionally in large aggregations hanging in sheltered positions under rocks where there is a reasonable current flow combined with large amounts of organic material in the water column (Images a, b, e © D. George; c © C. Teasdale; d © K. Samimi-Namin)

A. Cabrinovic (Echinodermata). J. Chimonides and T. Conyers made major contributions to analysis of the species and site information. Invertebrate specialists from other Institutions helped with literature and identification problems with Crustacea (Dr P. Hogarth and Dr P. Ng), opisthobranch Mollusca (Dr N. Yonow and Dr B. Dayrat), and Phoronida (Dr C. Emig). Several friends and colleagues have graciously filled gaps in photographic coverage: Dr F. Dipper, C. Harris, C. Teasdale, K. Samimi-Namin, Dr H. Rezai, and staff members of Nautica Environmental Associates. Their photographic copyrights are acknowledged in the relevant Figure captions. Finally I would like to thank Prof. J. George for undertaking the onerous task of the initial construction of the Tables and word processing the original list of References.

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David M. John

14.1 Introduction

The extreme conditions in the Gulf makes it a very inhospitable environment for marine organisms including hard reef-building corals, other animals and benthic plants (including seaweeds). The annual fluctuations in seawater temperature and salinity in its extensive shallows are more extreme than encountered in coastal waters elsewhere. The low biological diversity of the Gulf is not only a consequence of the amplitude (at least 25°C) but several other factors, including the very high summer seawater temperature (>35°C) especially in the southern Gulf. Inshore salinity is also important and sometimes reaches 55 ppm in the summer and is significantly lower in the most northerly parts where there are inputs from rivers in Iraq and Iran, the most significant being the Tigris/Euphrates. Two episodes of coral bleaching in the southern Gulf in summer 1996 and 1998 resulted in widespread mortality of reef-building corals. Later bleaching events occurred in 2002 (mainly in the southern Gulf), 2007 (mainly Iran) and throughout the Gulf in 2010 (see Baker et al. 2008; Riegl and Purkis 2009, chapters 5 and 6). These were all the result of prolonged periods of seawater temperature above the long-term average maximum (George and John 2005).

A consequence of these seawater temperature anomalies was a 'phase shift' with seaweeds displacing assemblages of hard corals as the dominants over shallow rocky shoals and on platforms fringing the shore. Over these shallow areas there develops in winter dense beds or 'forests' of foliose brown seaweeds beneath which is an understory of mat- or turf-forms and calcareous red algae known as 'corallines'. The low growing mat or turf formers and corallines persist throughout the year and are amongst some of the first colonizers of dead coral skeletons and damaged portions of living corals. There is some evidence to suggest that well-established seaweeds inhibit or

slow the rate of coral recruitment. Re-establishment of corals is underway since the major episodes of coral death (see Burt et al. 2009), but further recovery will be inevitably delayed if there are to be further positive temperature anomalies (Riegl and Purkis 2009; see Chap. 5). Such anomalies have been predicted to recur at intervals of 10–15 years (Riegl 1999; Purkis and Riegl 2005; Riegl and Purkis 2009) and shorter regeneration times, due to global change, are predicted to lead to irreversible changes in communities (see Chap. 9). The water temperature anomaly in the summer of 1996 was the first to occur since 1981 (George and John 2005; based on satellite data of SST which have been available since 1981).

Seaweed assemblages also develop on partially or intermittently sand-buried hard surface in wave-sheltered shallows behind rocky submarine platforms. Smaller epiphytic algae are common on the blades of those seagrasses which frequently dominate sandy backreef areas. These epiphytes are also common on foliose brown seaweeds including those which occur in such areas where growing attached to sponges, rocks and coral debris washed over the reef platform.

The most detailed accounts of seaweeds associated with coral reefs are those dealing with the southern Gulf. De Clerk and Coppejans (1996) investigated seaweeds in the Jubail Marine Wildlife Sanctuary in Saudi Arabia and Basson et al. (1977) considered seaweeds when describing biological assemblages ('biotopes') along the coast of Saudi Arabia and around its offshore islands. These Saudi Arabian studies are of particular significance since undertaken before the most recent episodes of mass coral mortality. Most other studies in the Gulf have focussed on intertidal seaweeds and taxonomy with little or no mention of ecology (see below). The only other early study of special significance is Børgesen's account of Iranian seaweeds (Børgesen 1939) since it included ecological observations and is the only authoritative treatment of the genus *Sargassum* in the Gulf.

The following account of the distribution of seaweed-dominated assemblages associated with living or dead

D.M. John (✉)
Natural History Museum, Cromell Road, London SW7 5BD, UK
e-mail: d.john@nhm.ac.uk

corals draws heavily on the findings of surveys carried out over a 12-year period (1996–2008) along the coast of Abu Dhabi (UAE) and several offshore islands and shoals (e.g. Hail Shoal, Bu Tinah Shoals, Delma Island). The first of these surveys (March 1996) was carried out just 4 months prior to the first of a series of catastrophic episodes of coral bleaching and death. Described is the impact of these episodes on seaweeds and seaweed development is followed over periods when conditions have become more conducive for coral recruitment and survival. The foliose seaweeds described and illustrated are those that are best developed over the winter months and are common in the southern Gulf. Also considered are mat- or turf-forming seaweeds and small epiphytes on foliose brown seaweeds. Special attention is focussed on crustose calcareous seaweeds ('corallines') since they are of special ecological importance by contributing to reef building and assist in stabilizing coral rubble (Fig. 14.11).

The corallines have been little studied in the Gulf and the following account is largely based on an investigation of Abu Dhabi material by Dr Yvonne Chamberlain (formerly Portsmouth University, UK), a leading specialist in this group. Information is also provided on the distribution within the Gulf of the coral-associated seaweeds.

14.2 Earlier Phycological Investigations

Knowledge of the Gulf seaweeds dates back to 1775 when a list appeared in an account of a Danish expedition; probably this anonymously published list was compiled by Per Försskal (John and George 2003). Endlicher and Diesing (1845) mention six species of brown and red seaweeds from the islands of Kharg and Kish in present day Iran. Almost a century later, Børgesen (1939) published the first comprehensive account of seaweeds in the Gulf and mentioned 77 species from the islands of Kharg and Bishire in Persia (now Iran) and 23 species from the islands of Bahrain (as 'Bahrein'), Qais, Farur and Qishm. His study was based mainly upon material collected by 'Mag. Kjøie' and the account includes a description of seaweed belts on the intertidal 'coral reef' around Kharg Island. He shows photographs (pp. 50, 52, Figs. 14.2 and 14.3) and the 'utmost' part of this reef and the innermost part where *Cladophora nitellopsis* is mentioned as forming yellowish-green spongy masses next to the shore (p. 50) 'in which the tepid water is retained during ebb-tide'. Undoubtedly the more interesting and extensive areas of living coral were in shallow rocky areas and yet these are not mentioned in detail. Nonetheless, Børgesen states (p. 51) that 'Mag. Koie gathered a great number of fragments of corals from a depth of 1–2 m with a lot of small creeping algae'; most of these 'creeping' algae are common and widely distributed in the Gulf. The material was collected during a visit by the 'Danish Fishery-Investigations'

expedition (1936–1937) to Iran and also included information on collections sent to Børgesen for identification and comment. These included collections from near the islands of Qais, Farur and Qishm and Børgesen considered them to be of special interest since showing that further out [closer to Strait of Hormuz] in the Gulf (p. 52) 'the vegetation [seaweeds] there becomes more luxuriant and richer in species' and were 'nearly all the same as those found at Dwarka'.

The following is a list of Gulf countries and key publications dealing with their seaweeds: Bahrain: Basson et al. (1989); Dubai, UAE: Dipper and Woodward (1989); Kuwait: Newton (1953, 1955a, b), Jones (1986), Al-Hasan and Jones (1989); Qatar: Dorgham (1990), Heiba et al. (1990); Saudi Arabia: Basson (1979a, b), Basson et al. (1977), De Clerk and Coppejans (1996), Abdel-Kareem (2009a, b); Abu Dhabi, UAE: John (2005); John and George (2003); Iran: Nizamuddin and Gessner (1970), Sohrabipour and Rabei (1996, 1999, 2007, 2008), Sohrabipour et al. (2004), Dadolahi-Sohrab et al. (2011). No records have been traced for Iraq or the Emirate of Ras al-Khaimah (UAE) and only two seaweeds are known from Dubai. The paucity of seaweed records for Emirate of Dubai is surprising since there are discontinuous patches of caprock lying within 1 km of the shore along the westernmost 10 km of its coastline (Riegl 1999). Also the amount of hard-bottom habitat has been vastly increased in the past decade by the construction of over 65 km of protective rocky breakwaters (Burt et al. 2009). The majority of the papers mentioned above deal with seaweeds from the intertidal zone and occasionally include drift plants and ones collected in the shallows. The only papers mentioning seaweeds growing on healthy, dead or recovering coral reefs are those dealing with Saudi Arabia (Basson et al. 1977; De Clerk and Coppejans 1996) and the Emirate of Abu Dhabi, UAE (EAD 2008; George and John 1999, 2005; Grandcourt 2007; John 2005; John and George 2003).

Much of the Gulf coast is under-explored phycologically and hence information on the seaweed flora remains very incomplete. The number of seaweeds recorded by Basson (1992) in the Gulf was about 320 and over 75 additional species are included by Silva et al. (1996) in a checklist of Indian Ocean seaweeds. The number of seaweeds known from the Gulf is currently over 250 taxa with a good proportion of these subtidal in distribution. Only considered in this chapter are those seaweeds commonly associated with coral reefs or areas formerly dominated by living corals and closely associated habitats.

14.3 Seaweed Growth and Seasonality

Over the past 15 years episodes of coral bleaching and death have led to the loss or a significant decrease in coral cover in shallow inshore rocky habitats, especially in the southern Gulf.

The demise of the coral has provided new opportunities for colonization and development of seaweeds which have dramatically increase in cover-abundance. The most conspicuous are the foliose brown seaweeds and these seasonally form dense ‘forests’ or beds in areas formerly dominated by hard corals. These seaweeds beds are absent in chronically sea urchin-grazed areas where the only conspicuous seaweeds are crustose corallines. Seaweeds do not normally grow on living corals but rather colonize dead corals or dead portions of otherwise living corals (Fig. 14.2d). Many shallow rocky platforms and the wave-exposed seaward margins of platforms fringing the shore in Abu Dhabi were dominated by hard corals prior to the summer of 1996. Since 1996 these rocky areas commonly become covered by dense beds of brown seaweeds from about October to April (Fig. 14.3a, b). Beneath the canopy dominants there is a usually diverse understory of less conspicuous seaweeds. In Abu Dhabi the seasonal assemblages are dominated by such foliose brown seaweeds as *Cystoseira trinodis* and species of *Sargassum* (principally *S. latifolium*). Often only the basal parts of the *Sargassum* species survive over the summer and new branches rapidly grow from these early in the autumn. Some seaweed survives over the summer as reasonably healthy individuals and include *Canistrocarpus cervicornis*, *Lobophora variegata*, *Cystoseira myrica*, *Padina boergesenii* and *Spyridia filamentosa*. Unlike most other brown seaweeds *Hormophysa cuneiformis* and *Sargassopsis decurrens* are more common on partially sand-buried rocks and coral rubble (Figs. 14.4b, d, e and 14.7b) than on more continuous rocky areas where competition for space is intense during the summer. *Hormophysa cuneiformis* is one of the brown seaweeds to occasionally survive the summer as large and relatively healthy individuals (Fig. 14.7b). The seaweed assemblages on the sides of floating pontoons, buoys and other artificial surfaces show a similar seasonality.

The convoluted and inflated brain-like bladders of *Colpomenia sinuosa* are frequently observed on coral skeletons (Fig. 14.2c) and other hard surfaces (Fig. 14.6e). This very distinctive brown seaweed is common in Abu Dhabi between about February and May when the seawater temperature is below 25°C. These bladders are frequently observed floating in the sea and large numbers are cast up on beaches in April and May.

A similar seasonal phenomenon has been observed along the Saudi Arabian coast. De Clerk and Coppejans (1996) observed a distinct summer die-back thus leaving shallow rocky platforms dominated by corallines and low turf- and mat-forming seaweeds. Similar seasonal changes occur in Kuwait where Al-Hasan and Jones (1989) mention shores dominated by *Sargassum aquifolium* (as *S. binderi*) in the autumn and large masses of this seaweed drifting ashore when it becomes ‘defoliated’ in late winter. Unfortunately most of the observations on Kuwaiti seaweeds concern those growing

in the intertidal zone. Vast masses of decaying seaweeds are washed up on sandy beaches and intertidal platforms in Abu Dhabi as a consequence of the seasonal die-back.

Large expanses of shallow water frequently remain at low tide on the shoreward side of often wide rocky platforms that are common along parts of the Abu Dhabi coast. The seaward margin of these platforms is often slightly raised to form a narrow shoal. Such shallow-water areas are inhospitable environments for seaweeds because of high light levels and raised seawater temperature during slack water, especially away from the seaward margin of the platforms. Many of the ‘red’ seaweeds growing in this stressful environment are straw-coloured and there are few brown seaweeds except close to the seaweed margin. Occasionally on these platforms there are quite extensive areas covered by the flattened and nodulated branches of the coralline alga *Lithophyllum kotschyianum* (Fig. 14.11e, g). The absence or low abundance of the seasonally developed seaweeds in some rocky areas is due to a variety of factors including grazing by sea urchins (Fig. 14.2g, h) and demersal fish.

The primary space opened up by the demise of the hard corals soon becomes colonized by corallines, turf- and mat-forming seaweeds (principally red seaweeds). These mainly perennial seaweeds eventually dominate many coral-free areas and are most conspicuous in the summer when foliose brown seaweeds are absent or in reduced abundance (Fig. 14.4a–f).

14.4 Coral-Reef Associated Seaweeds: Past and Present Distribution

The following account is based mainly on the findings of submarine surveys carried out along the coast of Abu Dhabi (UAE) and on several offshore island and shoals (Fig. 14.1). Also mentioned are ecological observations on the seaweeds of Saudi Arabia (Basson et al. 1977; De Clerk and Coppejans 1996) and Iran (Børgesen 1939, as Persia). Just seven seaweeds were recorded from Abu Dhabi prior to 1996 (Silva et al. 1996) and subsequent surveys have increased this number to over 120 (see EAD 2008; John 2005).

Until March 1996 most shallow hard substratum in Abu Dhabi were dominated by assemblages of corals. These corals formed isolated patches, and fringed parts of the mainland coast, islands and offshore shoals. Before the summer of 1996, the branched acroporid corals (notably *Acropora clathrata* and *A. downingi*) formed dense and very extensive ‘thickets’ in shallow areas, especially on the more wave-exposed upwind fringes of offshore shoals and island. The robust poritid and faviid corals dominated in deeper water where they grew on rocky slopes and somewhat horizontal rocky surfaces. Coral assemblages were also common along the edges of the channels in ‘khors’, on artificial structures

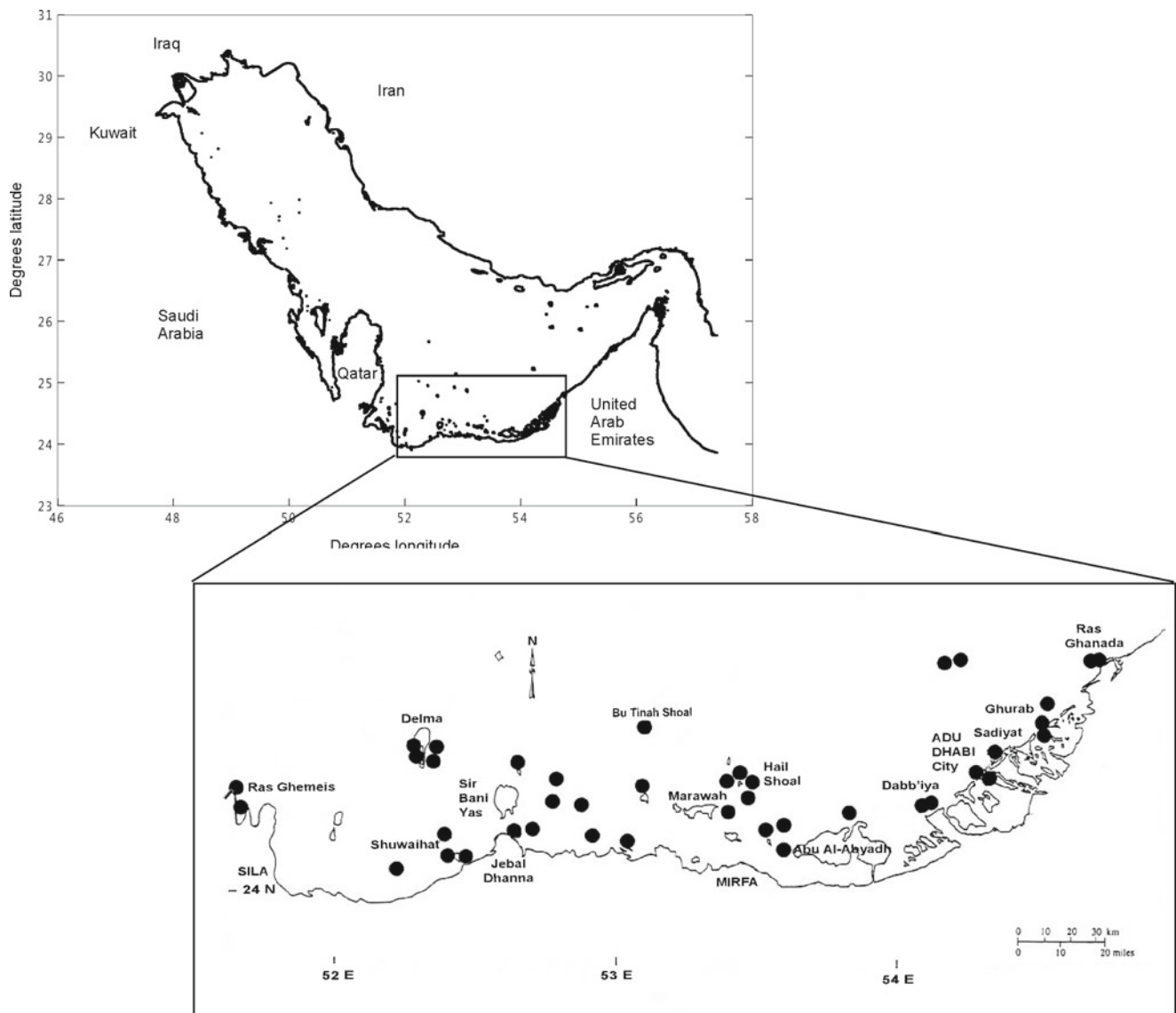


Fig. 14.1 Map of Abu Dhabi showing the position of subtidal sites surveyed between March 1996 and March 2008. Many of these sites were sampled on several occasions

including stone breakwaters and causeways, and on the outermost margin of shallow rocky platforms which sometimes extend for more than a kilometre from the coast.

Seaweeds were a subordinate and an inconspicuous component of healthy coral reefs examined in Abu Dhabi before the summer of 1996. They were normally confined to damaged areas on corals (Fig. 14.2e, f) or else were confined to the more shaded basal parts. Otherwise small beds of seaweeds were common in the shallows (often <1 m below low water) where coral cover was low and any present usually formed only small colonies. Many shallow limestone platforms examined in March 1996 in Abu Dhabi were covered by very dense thickets of *Acropora*, often these were a metre or more in height and in places were several hundred square

metres in extent. One of most common fleshy seaweed associated with these reefs was *Lobophora variegata* whose overlapping, fan-shaped, prostrate fronds were commonly observed on steeply sloping and coral-free rocky ledges (Fig. 14.6f). DeClerk and Coppejans (1996: 228) mention that in Saudi Arabia this brown seaweed seems ‘...to grow very well between the branches of *Acropora*, where it completely covers its basal parts...never develops so extensively on the ‘*Porites*-dominated reefs’.

Very commonly associated with healthy coral reefs was the morphologically very variable *Lithophyllum kotschyannum*. This crustose coralline initially forms a crustose layer from which arises slightly compressed or obviously flattened, convoluted, interweaving and somewhat fan-shaped branches.

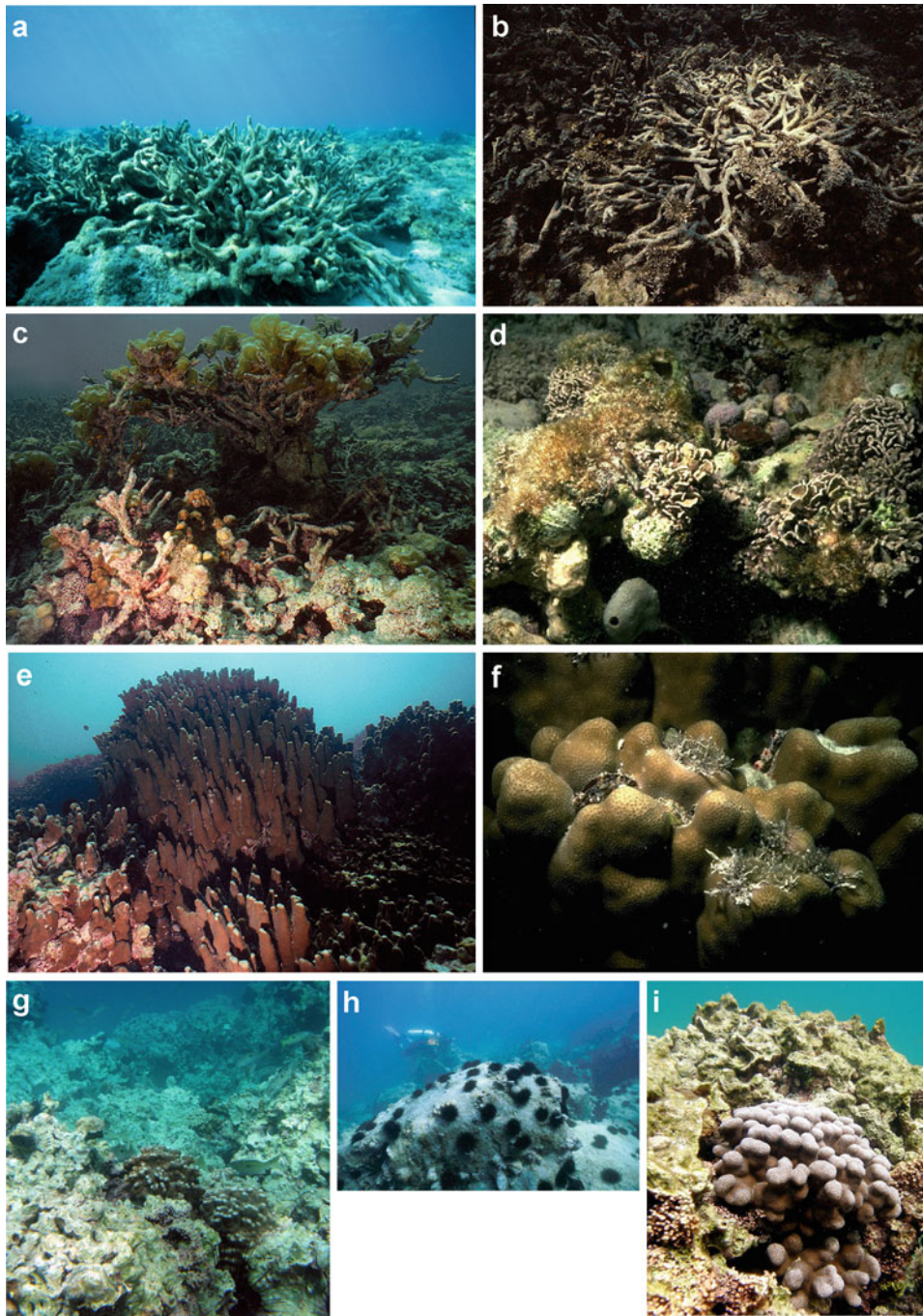


Fig. 14.2 (a) General view of skeletons of *Acropora* covered by a whitish layer of sediment and the fine filamentous brown alga *Hinckesia mitchelliae*; (b) Dead branches of *Acropora* colonized by clumps of seaweed and various fouling animals; (c) Dead branches of *Acropora* covered by crustose coralline algae (mainly *Lithophyllum kotschyanum*) and the uppermost dead branches colonized by the bladder-like brown seaweed *Colpomenia sinuosa*; (d) Close view of branches showing clumps of the coralline *Lithophyllum kotschyanum*, the foliar-appendages of small clumps of the brown seaweed *Sargassum latifolium* and mats of filamentous red seaweeds; (e) Large clump of *Porites* covered by

growths of the crustose coralline *Lithophyllum kotschyanum* especially towards the base (bottom left); (f) Damaged area of *Porites harrisoni* covered by low mat of 'red' seaweeds; (g) An intensively sea urchin grazed limestone platform devoid of seaweeds other than crustose corallines and showing the long-spined urchin *Diadema setosum* (bottom right); (h) Rocky area dominated by crustose corallines and grazed by the shorter spined sea urchin *Echinometra mathaei*; (i) Close view of reef surface showing a relatively new colony of *Porites* and the irregularly branched clumps of the coralline *Lithophyllum kotschyanum* (Photos (a-f, h), D. George; (g, i) C. Teasdale)

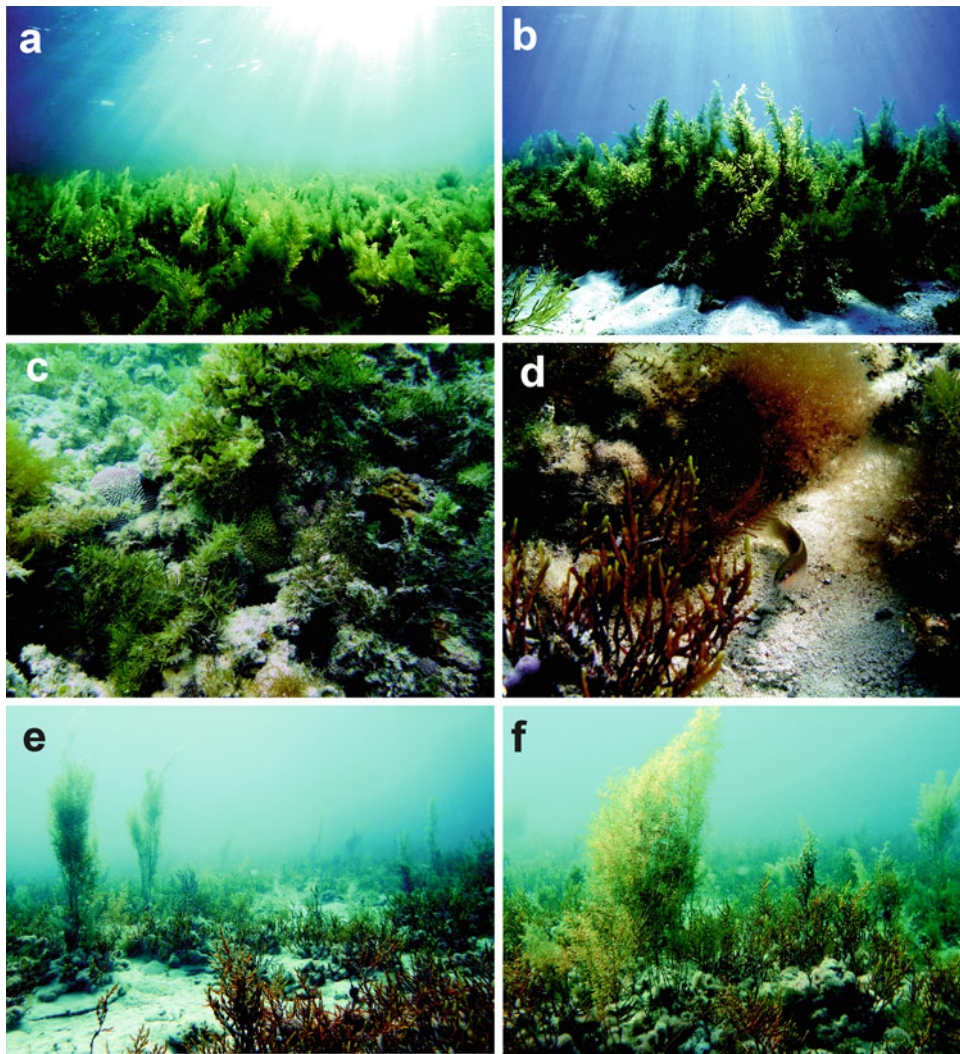


Fig. 14.3 Winter period – (a) Seaward sloping rocky platform covered by a ‘forest’ dominated by *Sargassum* and other brown foliose seaweeds; (b) Shallow seaward area of a rocky platform showing a *Sargassum*-dominated assemblage and giving way to a sand-lined channel; (c) Close view of an eroded rocky platform covered by mats and clumps of filamentous seaweeds and small colonies of hard corals; (d) Back area behind a raised rocky platform showing partially sand-covered rocks on which in the foreground is *Hormophysa cuneiformis*,

in middle ground *Acanthophora spicifera* and *Jania rubens*, and in the background *Laurencia obtusa* and bushy clumps of *Spyridia filamentosa*; (e) General view of a back area showing in the foreground *Hormophysa cuneiformis*, large clumps of *Cystoseira trinodis* and mats and clumps of smaller seaweeds; (f) Closer view of back area showing several large clumps of the brown seaweed *Cystoseira trinodis* and many smaller clumps of *Hormophysa cuneiformis* as well as mats of other algae (principally *Jania rubens*) (All photos by C. Teasdale and V. Pappin)

It is mentioned by Vogt (1996) as having a 72% cover at the ‘reef edge’ (2 m depth) on Karan Island, Saudi Arabia and its cover decreased down the reef slope as coral cover increased until at a depth of 6 m depth the cover of *L. kotschyanum* was just 6% and that of coral was 42%. If corals are damaged then crustose corallines such as *L. kotschyanum* can very soon begin to colonize. Vogt and Al-Shaik (2005) mention that large dead colonies of *Platygyra daedalea* were partly overgrown by *L. kotschyanum* and these colonies were at a depth of 2 m depth along the reef edge on Karan Island, Saudi Arabia They suggested that these *Porites* colonies were (p. 206) ‘at least several decades if not more

than a hundred years’ old and their death suggested that conditions had changed (prior to 1992 when observations made) and were favouring a ‘shift at the reef edge from a coral to a coralline algae dominated zone’. Frequently encountered in Abu Dhabi is *Sporolithon ptychoides* (Fig. 14.11f, h), another crustose coralline seaweed. Yet another *Sporolithon*, *S. molle* (Heydrich) Heydrich, is recorded in Saudi Arabia by De Clerk and Copejans (1996) who mention (p. 273) it as growing in the ‘...infralittoral, along surf-exposed coasts. Often forming a distinct zone on the reef flat’. Other crustose corallines associated with coral reefs include *Lithothamnion muelleri* (Fig. 14.11i) and a species of *Neogoniolithon*;

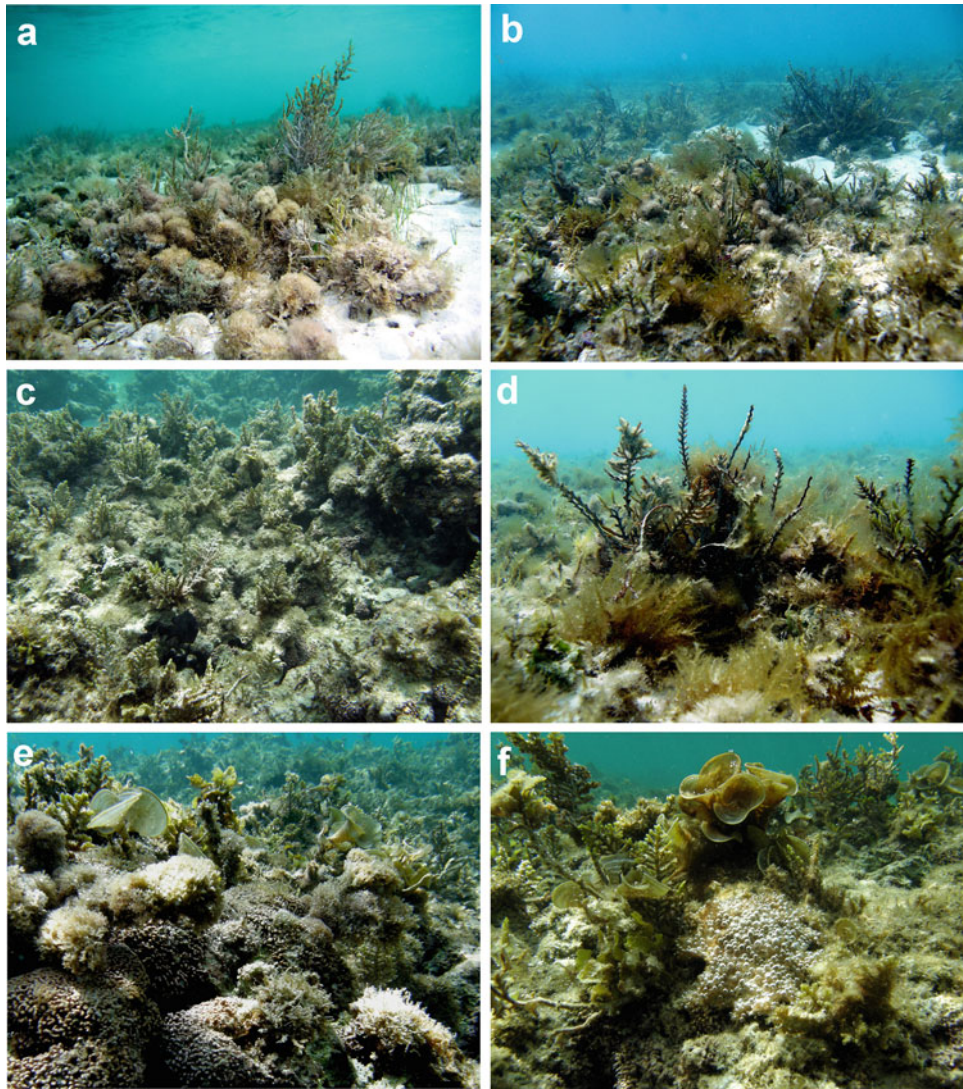


Fig. 14.4 Summer (mostly July) – (a) Back area of a rocky platform showing a few clumps of brown seaweed (*Hormophysa cuneiformis*, *Cystoseira trinodis*) and hard surfaces covered with algal mats dominated by the articulated coralline *Jania rubens*; (b) Back area of a rocky platform showing clumps of *Sargassopsis decurrens*, small individuals of *Cystoseira myrica* and many mostly red seaweeds including *Champia parvula* and *Jania rubens*; (c) Shallow area of a rocky platform showing several small clumps of the brown seaweed *Cystoseira myrica* and turfs or mats of filamentous algae; (d) Close view of back area of a

rocky reef showing moribund clumps of *Sargassopsis decurrens* and mats of fine filamentous seaweeds, including some growing epiphytic on *Sargassopsis*; (e) Seaward side of a rocky platform showing the crustose coralline *Lithophyllum kotschyanum*, mats of fine filamentous seaweeds and small clumps of *Cystoseira myrica* and *Padina boergesenii*; (f) Seaward side of a rocky platform showing clumps of the brown seaweed *Padina boergesenii*, basal portions of foliose brown seaweeds and much of the rock surfaces covered with algal mats (All photos C. Teasdale and E. Palmer)

these corallines were most common on steep sloping, coral-dominated platforms and on dead or damaged corals. Low mats or turfs of such red seaweeds as *Gelidium pusillum*, *Wurdemannia miniata*, *Gelidiella myriocladia*, *Jania pumila* and *Polysiphonia kampsaxi* were common on damaged areas of *Acropora* (Fig. 14.2b, d) and *Porites harrisoni* (Fig. 14.2f). Often these low-growing seaweeds were also common in the sublittoral fringe on wave-exposed rocky shores and in very shallow water where coral cover was low.

Some mat or turf-forming red seaweeds are especially conspicuous within the territories of small pugnacious fish where they are given some protection from grazing by non-territorial fish. Occasionally on damaged corals there are soft reddish or purplish tufts or mats of blue-green algae. Frequently shallow sand-lined channels run across the raised seaward margin of rocky platforms and into the more wave-sheltered areas lying behind. The sheltered landward side of such platforms represents an inhospitable environment,

especially if there is little or no water exchange at low tide. Often in this sheltered habitat there are extensive areas of sand which are commonly colonized by seagrass beds dominated by *Halodule uninervis*, especially if the sand is relatively mobile. Some of the seaweeds on hard substrata in such areas over the winter are *Hormophysa cuneiformis*, *Canistrocarpus cervicornis*, *Padina boergesenii* and species of *Sargassum* and *Cystoseira*. These brown seaweeds are only common and abundant on the landward side of offshore shoals (Figs. 14.2e, f and 14.7a) where they grow attached to coral rubble and other sand-buried hard substrata, including much fissured limestone and recently formed diagenetic hard substrata. Other seaweeds present include those forming low mats or tufts and these are attached to shells, sponges and partially sand-buried coral debris (Fig. 14.8b, c). Small creeping forms are mentioned by Børgesen (1939) on Karg Island (Iran) where they were observed in the early months of 1937 on coral fragments at depths ranging from 1 to 2 m and included *Herposiphonia tenella* (now *Herposiphonia secunda* f. *tenella*), *Centroceras clavulatum*, *Griffithsia tenuis* (now *Anotrichium tenuis*), *Gelidium crinale* (probably a form of *Gelidium pusillum*) and a species of *Gelidiella* sp. (probably *G. myriocladia*). Many of the seaweeds recorded by Børgesen from Karg Island have also been observed growing on coral fragments and other hard surfaces in Abu Dhabi.

Two years after the death of the *Acropora*-dominated reefs in 1996 there followed an even more severe episode of coral bleaching and subsequent death. The first catastrophic event in Abu Dhabi caused considerably more damage to corals lying to the west of Abu Dhabi City where it was estimated that about 98–99% of the *Acropora* bleached and died in the summer of 1996 (John and George 2003, 2005). There was some damage to corals to the east of Abu Dhabi city as well as those in Dubai. The more severe episode of coral bleaching in 1998 delayed further recovery of the *Acropora*-dominated reefs and now caused major damage to the mound- or boulder-forming *Porites*. These colonies tend to be in deeper water and were little impacted by the 1996 seawater temperature anomaly (George and John 1999, 2005). The demise of Abu Dhabi's coral reefs has had a dramatic and well-documented impact on the distribution and abundance of seaweeds (John 2005; George and John 1999, John and George 2003). The causes of these episodes of coral bleaching are considered in detail elsewhere (George and John 1999, 2004; see Chaps. 2 and 5).

Very shortly after bleaching the coral skeletons became covered by a layer (Fig. 14.2a) of fine silt associated with fast-growing filamentous seaweeds (principally *Hincksia mitchelliae*; Fig. 14.12b). Living corals usually produce sufficient mucus to prevent silting and fouling by sessile organisms, including opportunistic seaweeds. These finely divided seaweeds contribute to siltation of the coral skeletons

by entrapping sediment particles. The coral skeletons were colonized by a succession of slower-growing red or pinkish-red crustose corallines and various turf- or mat-forming seaweeds (Fig. 14.2b–d) following the initial flush of fast-growing filamentous forms. Vogt and Al-Shaik (2005) mention that in August 1999 the coral skeletons in the lagoon at Karan Island, Saudi Arabia were covered by *Lithophyllum kotschyanum* and they did not observe significant numbers of macroalgae. They predicted (p. 206) 'that *L. kotschyanum* will overgrow most of the hard substratum provided by coral skeletons, thus becoming the dominant benthic species in the lagoon. This prediction seems to continue a previous trend that led to the dominance of the same coralline algae on the reef edge'; their observations were made in summer when most foliose seaweeds were absent or moribund. Corallines and other seaweeds are usually inconspicuous components of healthy coral reefs although quickly colonize the dead branches of *Acropora* and the mounds of dead *Porites*. The dark reddish crusts of *Peyssonnelia simulans* (Fig. 14.9g) are common on heavily shaded surfaces and the prostrate form of the brown seaweed *Lobophora variegata* where shading is less (Fig. 14.6f); both these seaweeds persist throughout the year. One of the most conspicuous of the brown seaweeds to develop on coral skeletons is *Colpomenia sinuosa*. The convoluted, sacks or bladders formed by this seaweed are often abundant from about February to April in Abu Dhabi and frequently developed over the branches of dead *Acropora* (Fig. 14.2c). There was little development of other brown seaweeds on the dead branches of *Acropora* although the basal leaf-like appendages of *Sargassum* were observed on a few occasions (Fig. 14.2d) along with the fan-shaped fronds of *Padina boergesenii*. The most common turf- or mat-forming seaweeds on the upper surfaces of coral skeletons were *Gelidiella myriocladia* and *Wurdemannia miniata* (Figs. 14.2f and 14.10g).

Bioerosion by boring sponges and bivalves, as well as grazing by sea urchins (principally *Echinometra mathaei*), seriously weakened the dead *Acropora* branches and impacted upon the structural integrity of the thickets. As a consequence, the 3-dimensional thickets of *Acropora* gradually disintegrated and collapsed sooner in more wave-exposed localities. The disintegration was probably delayed by the jacket of crustose corallines (principally *Lithophyllum kotschyanum*) formed around dead branches. Crustose corallines might not only delay collapse but assisted in stabilizing the coral debris. Four years after the main period of *Acropora* death in Abu Dhabi there were discovered a few almost intact thickets in March 2001 at some wave-sheltered sites. When the coral thickets collapsed the debris often accumulated in depressions on the reef flat before becoming eventually washed into back reef areas. Seaweeds that commonly grew on these coral fragments included *Dictyosphaeria cavernosa*, *Colpomenia sinuosa*, *Hincksia mitchelliae*, *Jania*

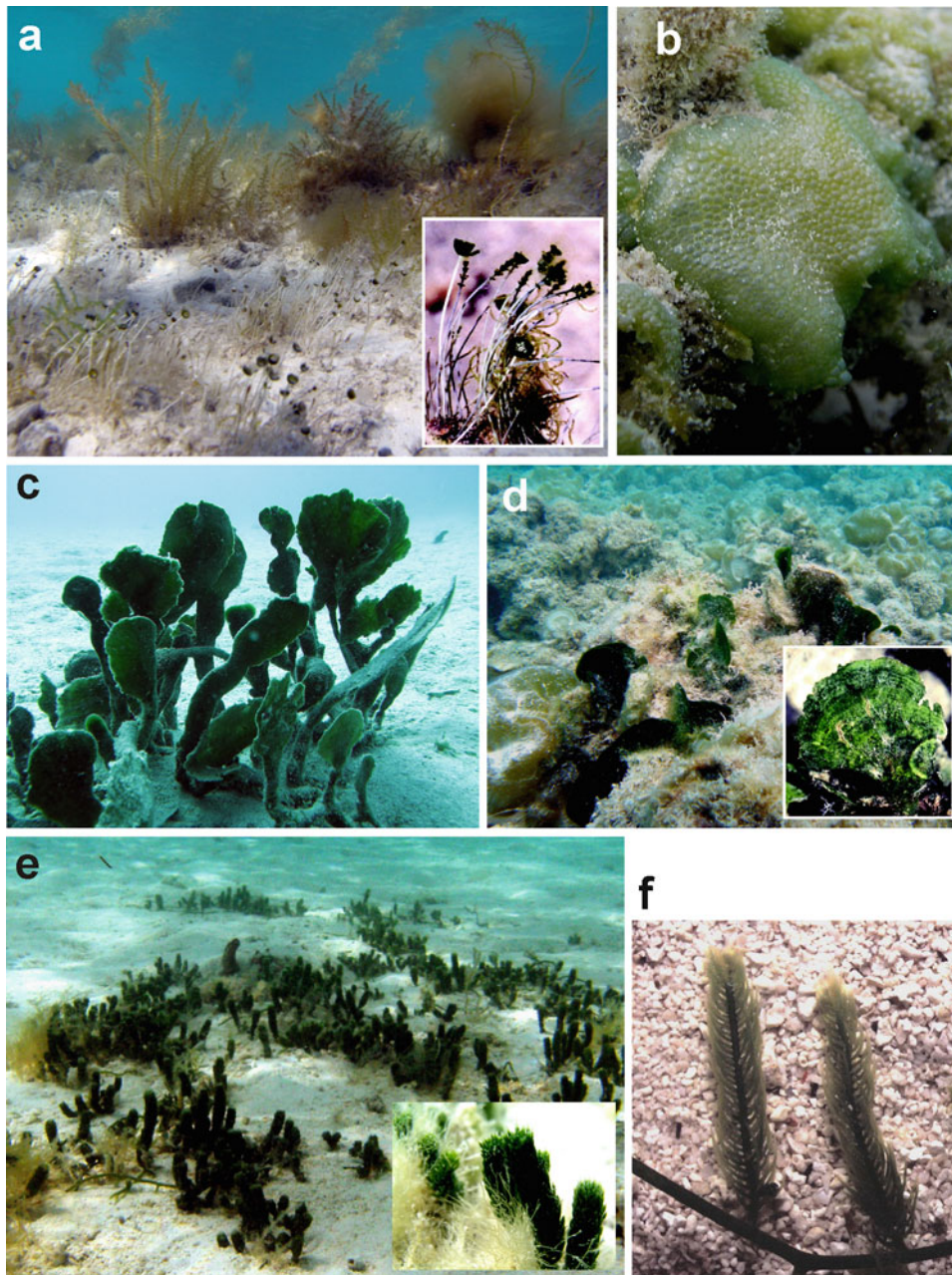


Fig. 14.5 (a) Small umbrella-shaped green seaweed *Acetabularia calyculus* growing on partially sand-buried surfaces in back area of a rocky platform, inset is a close view of a group of individuals; (b) Colony of the green seaweed *Dictyosphaeria cavernosa*; (c) Club-shaped form of the green seaweed *Avrainvillea amadelpha*; (d) *Avrainvillea amadelpha* growing on the seaward side of a rocky platform in amongst a mat of filamentous alga, inset shows a flattened

growth form; (e) *Caulerpa sertularioides* f. *farlowii* growing on the floor of a sand-lined channel in a wave-sheltered back area behind a rocky platform, inset shows the erect fronds with dense, radially arranged pinnules; (f) Typical form of *Caulerpa sertularioides* showing the pinnules disposed in a single plane on the erect fronds and arising from a creeping stoloniferous base (Photos (a–e) C. Teasdale, E. Palmer; (f) D. John)

rubens, *Jania pumila* and *Polysiphonia kampsaxii* (Figs. 14.5b and 14.10e, h).

The collapse of *Acropora*-dominated reefs and the eventual loss of the debris resulted in the exposure of the underlying limestone or other hard surfaces. Some of the initial algal colonizers of these surfaces were fast-growing filamentous

forms followed by mat- and turf-forming seaweeds, coral-ines and a few foliose brown seaweeds. The latter seaweeds caused a dramatic transformation of the seascape in winter when they formed dense submarine ‘forests’.

Soon after bleaching and death the massive *Porites* and *Platygyra* mounds became colonized by seaweeds and

invertebrate animals. In some places the grazing activities of the sea urchins caused the erosion of the surface of the corals (Fig. 14.2g, h). In areas where sea urchin numbers were low there was evident coral recruitment and undoubtedly there was intense competition for space between seaweeds, hard corals and other sessile invertebrate animals. If recruitment of hard corals were to continue then it will lead to a decline in the extent of the seasonally-developed seaweed beds. Such a slow change back to coral domination is proceeding at some sites but at different rates depending on local circumstances.

14.5 Reef-Associated Algal Assemblages

The following account is of seaweed assemblages or 'biotopes' associated with low rocky shoals or platforms which were once dominated by corals. It is based on the findings of submarine surveys carried out along the Abu Dhabi coast (since 1996) including offshore islands and shoals (Fig. 14.1). Seaweed assemblages are frequently well-developed along the wave-exposed and sometimes seawardly sloping margins of rocky platforms fringing the coast, islands and offshore shoals. In these areas the crustose coralline *Lithophyllum kotschyanum* and turf- and mat-forming 'red' seaweeds are usually dominant over the summer. This coralline and dense seaweed turfs and mats, mainly composed of *Gelidiella myriocladia*, *Gelidium pusillum* and *Wurdemannia miniata*, also developed on dead *Porites lutea*. Some newly settled and regenerating colonies of *Porites* were observed in March 2008 during a survey of Hail Shoal (=Al Heel) in Abu Dhabi. Other encrusting or prostrate forms associated with rocky areas include corallines (e.g. *Sporolithon ptychoides*, *Lithothamnion muelleri*, *Neogoniolithon misakiense*), *Lobophora variegata* and *Peyssonnelia simulans*. In winter the dominant foliose seaweeds are typically *Cystoseira trinodis*, *Sargassum* spp. (principally *S. latifolium*) and occasionally *Hormophysa cuneiformis* (usually in deeper areas). Other brown seaweeds common during the winter include *Cystoseira myrica*, *Canistrocarpus cervicornis*, *Padina boergesenii* and other *Sargassum* species (e.g. *S. aquifolium*, *S. angustifolium*). All that remains in summer of several of these seaweeds are the holdfasts and moribund main axes which are frequently heavily epiphytised by smaller forms (e.g. *Jania rubens*, *Sphacelaria rigidula*, *Herposiphonia secunda* f. *tenella* and thin crusts of the coralline *Hydrolithon*). The stiff brown filaments of *Sphacelaria rigidula* form small tufts or completely cover older branches so giving them the appearance of a 'cat's tail'. *Digenea simplex* and *Hormophysa cuneiformis* are two of the most conspicuous seaweeds surviving over the stressful summer months and are accompanied by turf- or mat-forms as well as crustose corallines; these latter low growing seaweeds form the understory in

beds of brown seaweeds. Occasionally rocky areas are covered by enormous numbers of sea urchins (*Echinometra mathaei*, *Diadema antillarum*) and here crustose corallines are the only conspicuous seaweeds present. In some deeper areas where sand predominates, partially sand-buried hard surfaces are frequently colonized by *Canistrocarpus cervicornis*. This brown seaweed is occasionally abundant on the rocky floor of shallow channels running across the reef platform and is especially abundant where the tidal current is strong. According to De Clerk and Coppejans (1996), *Canistrocarpus* persists through the summer in Saudi Arabia although no information is given on its abundance.

Shallow (0.5–2 m) channels or depressions lying close to the seaward margin of rocky platforms are often sandy floored and contain partially sand-buried coral/rock rubble. During the winter months the larger and stable portions of coral or rock debris often support seaweeds (e.g. *Canistrocarpus cervicornis*, *Jania rubens*) in this area that is subject to much sand scour. In more wave-sheltered areas seaweed diversity increases during the winter and typically present are *Cystoseira trinodis*, *C. myrica*, *Hormophysa cuneiformis*, *Digenea simplex*, *Padina boergesenii*, several species of *Sargassum* (e.g. *S. latifolium*, *S. boveanum*) and *Sargassopsis decurrens*. These foliose seaweeds are frequently epiphytised by smaller red seaweeds such as *Herposiphonia secunda* f. *tenella* and the crusts of corallines such as *Hydrolithon farinosum* and *H. improcerum*, along with various sessile animals. Where smaller fractions of less stable rubble predominate, the associated seaweeds include *Acanthophora spicifera*, *Laurencia obtusa*, *Palisada perforata*, *Chondria dasyphylla*, *Hypnea cornuta* and *Cystoseira myrica*; some of these species persist over the summer. Common on dead *Porites* mounds was the crustose coralline *Lithophyllum kotschyanum* and 'red' mat-forming seaweeds along with clusters of the jewel box bivalve (*Chama reflexa*). As mentioned earlier, the distinctive sack-like *Colpomenia sinuosa* develops in abundance between about February and April. Turfs or mats are common and are composed of several smaller algae, including *Jania pumila*, *Gelidium pusillum*, *Gelidiella myriocladia* and *Wurdemannia miniata*, which also grow on small pieces of coral rubble.

Shallow back reef areas (0.5–1.5 m), that are well away from the margin of the rocky platforms are often floored by areas of hard rock, dead corals, cemented together masses of coral/shell fragments and sand which often forms a thin covering over many of the hard surfaces. During the winter clumps of foliose brown seaweeds are patchily distributed in this back reef areas and are attached to partially sand-buried rubble and sand-free low-lying rocky surfaces. The most common species present in this area are *Hormophysa cuneiformis*, *Sargassum latifolium*, *Sargassopsis decurrens* and *Cystoseira trinodis*. Brown tufts of *Sphacelaria rigidula* are frequently epiphytic on *Sargassum* and pinkish crusts of

Hydrolithon (Fig. 14.7g) are common both on *Sargassum* and *Hormophysa cuneiformis*. Turfs or mats of red seaweeds are frequent on partially sand-buried rocks and are often accompanied by the brown seaweed *Padina boergesenii*. The crustose coralline *Lithophyllum kotschyianum* and the prostrate or peltate brown lobes of *Lobophora variegata* are common on steeply sloping rock surfaces such as low rocky ledges. The green seaweed *Dictyosphaeria cavernosa* and the straw-coloured clumps of the red seaweed *Palisada perforata* are common in very shallow water (Fig. 14.9h). Other seaweeds frequently encountered in these back reef areas include *Cystoseira myrica*, *Canistrocarpus cervicornis*, *Jania rubens*, *Chondria dasyphylla*, *Polysiphonia kampsaxii* and *Colpomenia sinuosa*; the latter usually between February and April. Similar platforms are described by Basson et al. (1977) surrounding the Jana and Karan islands, off the Saudi Arabian coast. These platforms are described as covered by scattered colonies of the most resistant coral species with these are more abundant towards the edge where there are horizontal areas of rock covered by actively growing corals. One of the few seaweeds mentioned by Basson was *Hydroclathrus clathratus* which formed (p. 130) 'great net-like masses on dead corals and coral rock, especially in the back-reef zone'; this brown seaweed is yet to be recorded from Abu Dhabi.

Deeper (0.5–10 m depth) back reef and channels running through the rocky platforms, have rocky ledges, large areas of sandy and often much partially sand-buried debris. Any larger rocks and dead coral blocks present support a richer seaweed flora compared to small and less stable hard surfaces. Seaweeds typically present includes *Cystoseira trinidadis*, *Hormophysa cuneiformis*, *Digenea simplex*, various *Sargassum* species (e.g. *S. latifolium*), *Sargassopsis decurrens* and *Padina boergesenii*. New branches on *Hormophysa cuneiformis* are very noticeable in early winter (about November) since devoid of epiphytes unlike the older branches which are frequently heavily encrusted by invertebrate animals, pink crusts of the coralline *Hydrolithon* and possess clumps of the articulated coralline *Jania rubens*. During summer the moribund branches of many brown seaweeds are often covered by the fine brown filaments of *Hinckia mitchelliae*, the crusts of *Hydrolithon* spp. and various filamentous red seaweed. Sometimes the persistent bases of the foliose seaweeds are completely enclosed by sponges. Clumps of such seaweeds as *Acanthophora spicifera*, *Laurencia obtusa*, *Palisada perforata*, *Chondria dasyphylla* and *Cystoseira myrica* are often attached to partially sand-buried portions of coral rubble and other hard surfaces; some of these seaweeds survive throughout the summer. In some cases the seaweed grow to such a large size that they become dislodged along with their attachment surface (Fig. 14.9b). Such individuals are frequently transported across the back reef and often carve out a furrow in the sandy seabed. *Gelidium pusillum* is one of the most common sea-

weeds on rubble and rocks and is also a components of the algal turf (Fig. 14.10d).

Large and isolated mounds of *Porites*, usually on rocky areas surrounded by sand, are sometimes encountered in sheltered or moderately wave-exposed areas. Some of these mounds of dead *Porites* have similar seaweeds assemblages to those encountered on the fringing rocky platforms. Frequently associated with these mounds are the sea urchins *Echinometra mathaei* and *Diadema setosum* as well as turf or mat-forming red seaweeds and crustose corallines (mainly *Lithophyllum kotschyianum*). Other seaweeds include *Lobophora variegata*, *Peyssonnelia simulans*, *Jania pumila*, *Polysiphonia* sp., *Canistrocarpus cervicornis* and the distinctive bladder-like *Colpomenia sinuosa*.

14.6 Algal-Animal Interaction

A feature of coral reefs is the complexity of the interactions between its inhabiting organisms, including competition between the space-occupying sessile groups. Various competitive strategies adopted by seaweeds include temporal escape from grazing or competition by rapid growth and regeneration. For example, filamentous seaweeds are the initial colonizers of dead or dying corals and these also form a felt covering over surfaces in areas chronically grazed by the sea urchins *Echinometra mathaei* and *Diadema setosum*. Slower growing seaweeds are unlikely to survive the ravages of herbivores and are therefore absent or rare in sea urchin and herbivorous fish-grazed areas unless they possess a defence against grazing. Crustose coralline seaweeds are structurally adapted to withstand most types of grazing and therefore are conspicuous where grazing pressure is intense. The surfaces of *Lithophyllum kotschyianum* and other crustose corallines are still often eroded by the grazing activities of *Echinometra mathaei*, especially where these corallines are growing over dead *Porites*. Parrotfish seem to be the only fish that actively consume crustose corallines. Few marine mammals feed on the foliose brown seaweeds and their biomass probably makes a significant contribution to the microbial loop.

The absence or rarity of larger foliose seaweeds on coral skeletons is the result of a combination of factors. Undoubtedly intense competition for space is important, including that between crustose corallines and other algal life forms (e.g. mat- or turf-formers). The success of the crustose corallines might be due to them continuously slough-off their outermost layers so preventing fouling by other seaweeds and sessile animals (Littler and Littler 1997). The often prolific development of foliose seaweeds during the winter results in a canopy which shades the crustose corallines and this has been shown to significantly reduce their growth (see de Figueredo et al. 2001). Seaweeds have been shown to outcompete corals

for space and to kill them by canopy shading (Johannes et al. 1983; Miller and Hay 1996), although Coles (1988) discovered that seasonal canopy development did not seem to significantly reduce live coral coverage in a 2-year study carried out in Saudi Arabia. Competition for primary space is evident in Abu Dhabi where there has been a significant increase in the cover-abundance of the seasonally developed seaweeds following the demise of the corals. Still requiring investigation in the Gulf are any changes in reef-dependent fish related to the increase in the extent and abundance of the brown seaweed in winter. According to Coles (1988), there is a dramatic decrease in fish abundance in Saudi Arabia on nearshore reefs during winter although it is unclear whether this was linked to seasonal changes in the seaweeds. McClanahan et al. (1999) have shown experimentally that the dominance of fleshy seaweeds on reefs along the Kenyan coast had caused a significant decline in fish that graze algal turfs or mats and in other groups including predators of invertebrates. Such findings imply that dense seaweed beds might suppress some fish groups as well as reduce coral growth (Tanner 1995; Miller and Hay 1996, but see Coles 1988) and limit coral recruitment and juvenile survivorship (see Lirman and Biber 2000).

14.7 Seaweed Taxonomy

The principal marine primary producers in the Gulf are seaweeds, phytoplankton, the symbiotic dinoflagellates (zooanthellae) associated with hard corals (principally the *Symbiodinium* D algal symbiotic lineage, Baker et al. 2005), the seagrasses (only three), the mangrove *Avicennia marina* and the halophytes that form the saltmarsh community. Seaweeds are largely restricted to rocks or other hard surfaces and smaller forms are frequent on seagrasses, foliose brown seaweeds, the pneumatophores of *Avicennia* and a wide range of sessile animals. The seaweeds mentioned in the following account are those commonly associated with healthy coral reefs, former coral-dominated areas and other closely associated habitats. All the photographs are of seaweeds and submarine habitats in Abu Dhabi, UAE.

Seaweeds are an unnatural grouping of oxygen-producing organisms with the groups having different phylogenetic histories although do have similar ecological requirements. All contain chlorophyll but the green colour is often masked by accessory pigments. Colour linked to a suite of other characters is used to separate the seaweeds into the following groups: Chlorophyta (green seaweeds), Phaeophyta (brown seaweeds), Rhodophyta (red seaweeds), Xanthophyta (yellow-green algae), Cyanobacteria (=Cyanophyta, blue-green algae). The Cyanobacteria are not considered here since are not common in coral reef habitats in the Gulf.

Although colour is a character that can be used to recognize seaweeds, it can be difficult in the field to decide to which group a specimen belongs. For example, brown seaweeds may range from blackish-brown to yellowish-orange or straw-coloured depending on the amount of brown pigment. Similarly red seaweeds or blue-green algae contain the pigments phycoerythrin (red colour) and phycoerythrin (blue colour) and can vary in colour from dark purplish-red to light pink or almost greenish depending on the relative proportions of these pigments and the green chlorophyll.

Some seaweeds show the phenomenon of iridescence caused by having a layered cell wall or cell inclusions causing some light to be defracted when they are submerged (or wet). These seaweeds are either completely iridescent, only iridescent at the branch tips or have a banded or spotted appearance.

14.7.1 Phylum Chlorophyta (Green Algae)

Characteristically a bright green since no secondary pigments mask the chlorophyll colour. Range from single cells, simple or branched filaments of cells aligned in a single series to compact spongy forms to flattened fronds or tubes. A few are lime-impregnated.

Class Bryopsidophyceae

Order Bryopsidales

Family Udoteaceae

Avrainvillea amadelpha (Montagne) A. & E.S. Gepp (Fig. 14.5d)

Fronds spongy, narrow or widely anvil to fan-shaped and arise on long or short stipes, sometimes densely packed and frequently several erect fronds arising from a long, bulbous and rhizomatous base. DeClerk and Coppejans (1996: 209) recognize the following extreme growth forms along with many intermediates: on coral boulders a form having a dark-green to brownish form with short stipes bearing numerous, densely packed, narrow, anvil-shaped to fan-shaped fronds (often eroding at upper margin); on softer substrata a form with a rhizomatous holdfast bearing on long stipes (2–8 cm long), several olive-green (sometimes with faint concentric striations) and anvil-shaped to markedly fan-shaped fronds (not marginally eroding). These forms are common in Abu Dhabi with the long stipe form frequent in sandy areas on the reef flat and in back reef areas where usually associated with seagrass, and the short stipe form more common towards the edge of rocky platforms and is therefore subject to more wave-exposure. Also DeClerk and Coppejans (1996) report the shorter stipe form to be more frequent on the wave-exposed seaward side of coral reefs and to a depth of about 1 m. Also known in the Gulf from Bahrain and Kuwait.

Family Caulerpaceae

Caulerpa serularioides (Gmelin) Howe (Fig. 14.5e, f)

Erect fronds flattened, pinnate, with the pinnules cylindrical and disposed in a single plane (type variety) or radially arranged (forma *farlowii* (Weber-van Bosse) Børgesen), arise from a creeping stolon-like base and attached at intervals by rhizoids. Very common in sandy areas where often amongst seagrass in channels and sand-lined depressions behind shallow reef platforms. DeClerk and Coppejans (1996) mentions it around Qurma island in the Jubail Marine Wildlife Sanctuary, Saudi Arabia and that the type form grows in deeper water (2 m downwards) than the variety (as 'ecad') *farlowii*. Also known in the Gulf from Bahrain, Kuwait, Iran and Saudi Arabia.

Class Ulvophyceae**Order Dasycladales****Family Polyphysaceae**

Acetabularia calyculus Quoy & Gaimard (Fig. 14.5a)

Umbrella-like, often whitish and calcified, usually about 2–4 cm high. Commonly on small stones, worm tubes and shell fragment embedded on the floor of shallow sand-lined tide pools on the lower shore and very common in shallow areas behind shallow reef platforms but easily overlooked. Also known from Bahrain, Kuwait, Qatar and Saudi Arabia.

Order Siphonocladales**Family Siphonocladaceae**

Dictyosphaeria cavernosa (Forsskål) Børgesen (Fig. 14.5b)

Globular and irregularly lobed, hollow, stiff and brittle, formed of large and conspicuous macroscopic cells (1–3 mm across), often older plants are eroded at the top. Occurs on rocks near low water, often fringing rocky tide pools, but sometimes in shallow water on hard substrata and coral skeletons where frequently accompanied by *Palisada perforata* and *Digenea simplex*. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

14.7.2 Phylum Phaeophyta (=Heterokontophyta) (Brown Algae)

Characteristically brown in colour due to the presence in quantity of pigments masking the green coloured chlorophyll. Varying from filaments of cells in a single series through to strap-like forms or those with leaf-like appendages and of considerable size with a distinct holdfast, stipe or stem and frond(s).

Order Ectocarpales**Family Acinetosporaceae**

Hincksia mitchelliae (Harvey) P.C.Silva (Fig. 14.12b)

Soft light brown to yellowish-brown mats or tufts, varies from a low mat to woolly tufts up to 30 cm in length, with

fine alternately or laterally branched filaments arising from a base of creeping filaments. Reproductive organs known as plurilocular sporangia, usually arise in series from lower cells of branches, typically elongate and cylindrical to ellipsoidal with base and apex obtuse. Often develop rapidly on newly exposed rock surfaces and coral skeletons, sometimes covers extensive areas and commonly epiphytic on foliose brown seaweeds, especially species of *Sargassum* and *Hormophysa cuneiformis*. Also known from Bahrain, Iraq, Iran, Kuwait, Qatar and Saudi Arabia. Various small filamentous algae (e.g. *Myriactula arabica*, *Ectocarpus cryptophilus*) are mentioned from Iran by Børgesen (1939) and these were usually epiphytes on foliose brown seaweeds.

Order Sphacelariales**Family Sphacelariaceae**

Sphacelaria rigidula Kützting (Figs. 14.7g and 14.12)

Small tufts or compact cushions (up to 5 cm high) and filaments stiff, sparingly and irregularly divided. Vegetative reproduction by Y-shaped propagules. Occurs as an epiphyte on foliose brown seaweeds, particularly *Sargassum* spp., *Hormophysa cuneiformis* and *Cystoseira trinodis*, often most common on moribund branches during summer. Also known from Bahrain, Kuwait, Iran, Qatar and Saudi Arabia.

Order Scytosiphonales**Family Scytosiphonaceae**

Colpomenia sinuosa (Mertens ex Roth) Derbes & Solier 'Oyster thief' (Fig. 14.6c)

Initially form sack-like crinkled balls and with age becoming irregularly lobed, convoluted and brain-like, sometimes reaching 30 cm across. Occur on wave-exposed rocks in the sublittoral fringe but the largest individuals develop on shallow wave-sheltered rocky platforms, including the skeletons of the coral *Acropora*. Known from November in the Gulf but only common and abundant between February and April in Abu Dhabi; frequently observed floating in the sea and sometimes cast up ashore in vast numbers with the drift of other seasonally developed seaweeds. Also known from Bahrain, Kuwait, Iran, Qatar and Saudi Arabia.

Order Dictyotales**Family Dictyotaceae**

Canistrocarpus cervicornis (Kützting) De Paula & DeClerk (Fig. 14.6a, b)

Synonym *Dictyota cervicornis* Kützting

Reaching to about 20 cm long, light brown. Occurs on low rocky platforms and sand-embedded rocks in back areas and in seagrass beds where sometimes entangled with blades. Dense and fairly extensive populations have been observed in Abu Dhabi, especially covering the rocky floor of channels running through the reef platform and subject to consid-

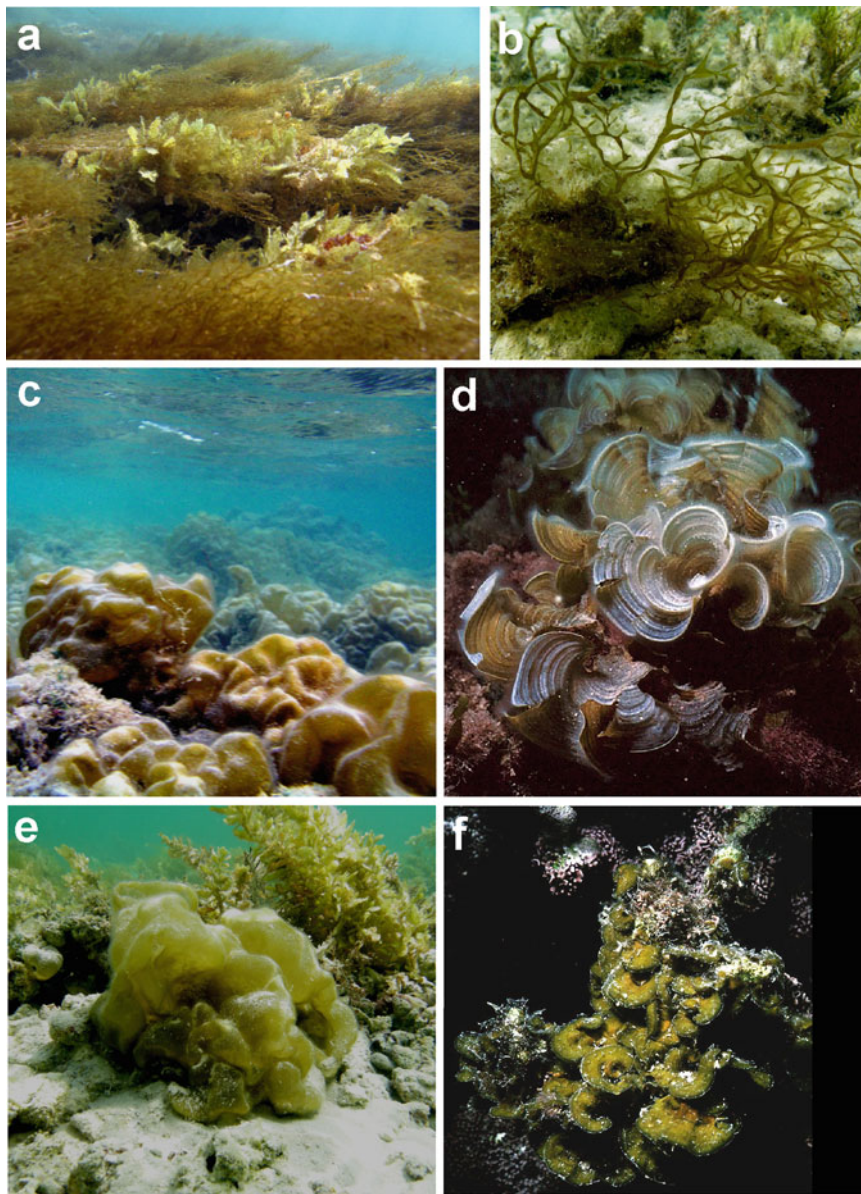


Fig. 14.6 (a) The brown seaweeds *Canistrocarpus cervicornis* and *Sargassum latifolium* in a rocky channel where there is considerable water flow at certain states of the tide; (b) *Canistrocarpus cervicornis* growing in a back area behind a raised rocky platform; (c) The season-

ally-developed sack-like *Colpomenia sinuosa* growing in a back area; (d) Clump of the brown seaweed *Padina boergesenii*; (e) Close view of a single colony of *Colpomenia sinuosa*; (f) Peltate growth form of *Lobophora variegata* (Photos (a–e) C. Teasdale; (f) D. George)

erable water flow at certain states of the tide. Also known from Iran, Kuwait, Qatar and Saudi Arabia.

Lobophora variegata (Lamouroux) Womersley ex Oliveira (Fig. 14.6f)

Fronds rounded to fan-shaped in outline, overlapping and peltate, about 1–5 cm wide, sometimes completely crustose, brown and sometimes having darker zig-zag bands on surface, attached by rhizoids. One of the few fleshy algae reported growing on living corals in Saudi Arabia. DeClerk and Coppejans (1996) report it as seeming to ‘grow very well

between the branches of *Acropora*, where is completely covers its basal parts. It never develops so extensively on the *Porites*-dominated reefs’. Common in Abu Dhabi where on steeply sloping rocky areas shaded by dead or living corals and in winter under the canopy of foliose brown seaweeds; often more conspicuous in summer following the die-back and loss of the canopy-dominants. Also known from Bahrain, Iran and Saudi Arabia.

Padina boergesenii Allender & Kraft ‘Peacock weed, turkey-tail’ (Figs. 14.4e and 14.6d)

Fan-shaped or funnel-shaped lobes, dark concentric dark rows of hairs, with upper surface often whitish due to strong calcification. Occurs in Abu Dhabi on exposures of reef rock down to about 5 m below low water, sometimes on fairly stable and partially sand-buried rocks, frequently in depressions on shallow and almost flat rocky platforms and more wave-sheltered areas behind, occasionally amongst the seagrass; uncommon over the summer. Only known in the Gulf from Abu Dhabi and Saudi Arabia. De Clerk and Coppejans (1996) recognize different growth forms in Saudi Arabia with the form on reef surfaces having narrower and darker blades compared to those in more sheltered sites. Similar growth forms are recognized in Abu Dhabi. The only other *Padina* known so far from the Gulf is *Padina minor* and is reported from Saudi Arabia by DeClerk and Coppejans (1996).

Order Fucales

Family Sargassaceae

Cystoseira myrica (Gmelin) Agardh (=Polycladia myrica (S.G. Gmelin) Draisma et al.) (Figs. 14.4b, e and 14.7d, f) Branches fairly rigid and stiff, sometimes reaching a length of 30 cm, dark brown to blackish-brown, covered by numerous, short, fairly rigid spines; branches alternately pinnate and the pinnae becoming gradually shorter towards apices so each branch has a triangular outline; spiny oval air bladders often present. The perennial basal portion and main branches bear many small spiny branchlets and air bladders which are cast ashore when these are lost during autumn. Most commonly on the reef flat and back-reef areas where the hard substratum is normally sand-free and survives over the summer as small individuals. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Cystoseira trinodis (Forsskål) Agardh (=Sirophysalis trinodis (Forsk.) Kuetzing) (Figs. 14.3c, f, 14.4a, 14.7a, c, e) Branches slender (almost 0.8 m long), brown to yellowish-brown, bear spine-like outgrowths, with ultimate branchlets having spindle-shaped air bladders in 2s or 3s; leaf-like appendages often present, narrow, about 3 mm wide and 3–5 cm long, smooth-margined. Occurs with other foliose brown seaweeds where forming dense ‘forests’ on shallow submerged rocky platforms, also on partially sand-buried rocks in areas behind the shallower platforms and survive into the summer. Often the principal branches of *Cystoseira trinodis* survive over the summer when frequently heavily epiphytised by the filamentous brown alga *Sphacelaria rigidula*. Sometimes the bladders are cast up on some beaches in Abu Dhabi in early summer. Also occurs in very similar habitats in Saudi Arabia where DeClerk and Coppejans (1996) mentions (p. 234) that it grows ‘..in the relatively deeper infralittoral zone (2–5 m depth) along surf-exposed coasts: Abu Ali Island, Ras az-Zaur and around the patch reefs, attached to coral fragments on sand, seaward of the

reef or on sand-covered hard substrate, frequently associated with *Hormophysa cuneiformis* and *Sargassum decurrens*’. Also reported in the Gulf from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Hormophysa cuneiformis (Gmelin) P.C.Silva (Figs. 14.3e–f, 14.4a, 14.7a, b)

Branches three-winged, fairly rigid, more or less segmented, margins distinctly dentate, reaching about 50 cm in length, irregularly pinnate or whorled. Sometimes individuals survive over the summer but often many branches are lost in autumn leaving only the basal branches that frequently becomes heavily epiphytised. Occurs in the shallow-water beds of foliose brown seaweeds, usually best developed in areas behind shallower rocky platforms where growing on partially sand-buried rocks; most conspicuous during the summer when the cover of most other brown seaweeds is low. Also reported from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Sargassum angustifolium Agardh (Fig. 14.8e, f)

Branches delicate, about 1 mm in diameter, reaching over 0.5 m in length, round in cross section, light to dark brown, oppositely arranged and usually alternately divided; leaf-like appendages very narrow, 1–3 mm in diameter, <50 mm long, margins dentate and having a pointed tip. Most common over the winter where grows with other *Sargassum* species on shallow rocky platforms which were formerly dominated by hard corals. Also reported also from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Sargassum aquifolium (Turner) Agardh ‘Binder’s *Sargassum* (Fig. 14.8i)

Synonym *Sargassum binderi* Sonder

Branches robust, <0.5 m long, round in section, light brown to yellowish-brown, radially arranged; leaf-like appendages broad and oval, 1–2 cm wide and to about 5 cm long, crisp, margins smooth or conspicuously toothed and blunt; hairs spots present or absent (cryptostomata); bladders small, spherical and stalked (sometimes with a distinct flattened margin). Infrequent in Abu Dhabi and only reported to be locally abundant in the Jubail Wildlife Sanctuary in Saudi Arabia (DeClerk and Coppejans 1996: 238). Also known also from Bahrain, Iran, Qatar and Saudi Arabia. Doubt attaches to the identity of material referred to this species in the Gulf. Often it is described as having cryptostomata on the leaf-like appendages although DeClerk and Coppejans (1996) did observe them on material from Saudi Arabia (as *Sargassum binderi*).

Sargassum boveanum J.Agardh (Fig. 14.8g, h)

Branches elegant and supple, less than 1 mm in diam. and up to 70 cm long, light to dark brown, sometimes at intervals are olive-shaped to subspherical swellings, with prominent main axes and side branches alternate and short; leaf-like appendages

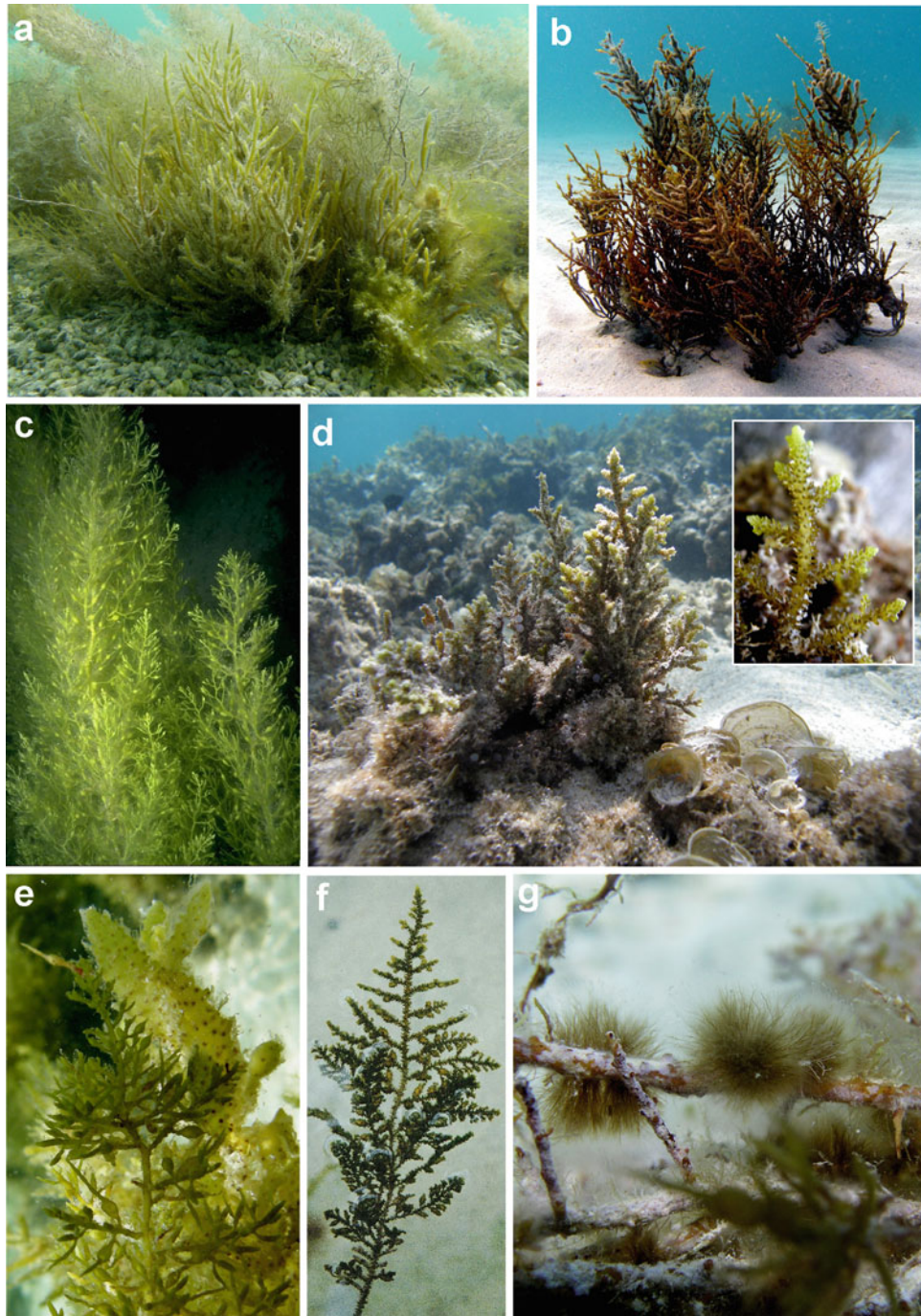


Fig. 14.7 (a) The brown seaweed *Hormophysa cuneiformis* (foreground) and *Cystoseira trinodis* (background) during winter; (b) Clump of *Hormophysa cuneiformis* on sand-covered rocks during summer at ~5 m; (c) Two individuals of the brown seaweed *Cystoseira trinodis*; (d) *Cystoseira myrica* in middle ground and the turkey-tail seaweed *Padina boergesenii* in foreground; insert shows close of pyramidal branch apex of *C. myrica* and with tubercles visible; (e) Close view of

a branch of *Cystoseira trinodis* and a foliar appendage of *Sargassum latifolium*; (f) Well-developed individual of *Cystoseira myrica* showing its typical outline; (g) Old branches of *Hormophysa cuneiformis* covered by clumps of the filamentous brown seaweed *Sphacelaria rigidula* and the pinkish crusts of the coralline *Hydrolithon* (Photos (a–e) C. Teasdale; D. George; (f, g) D. John)

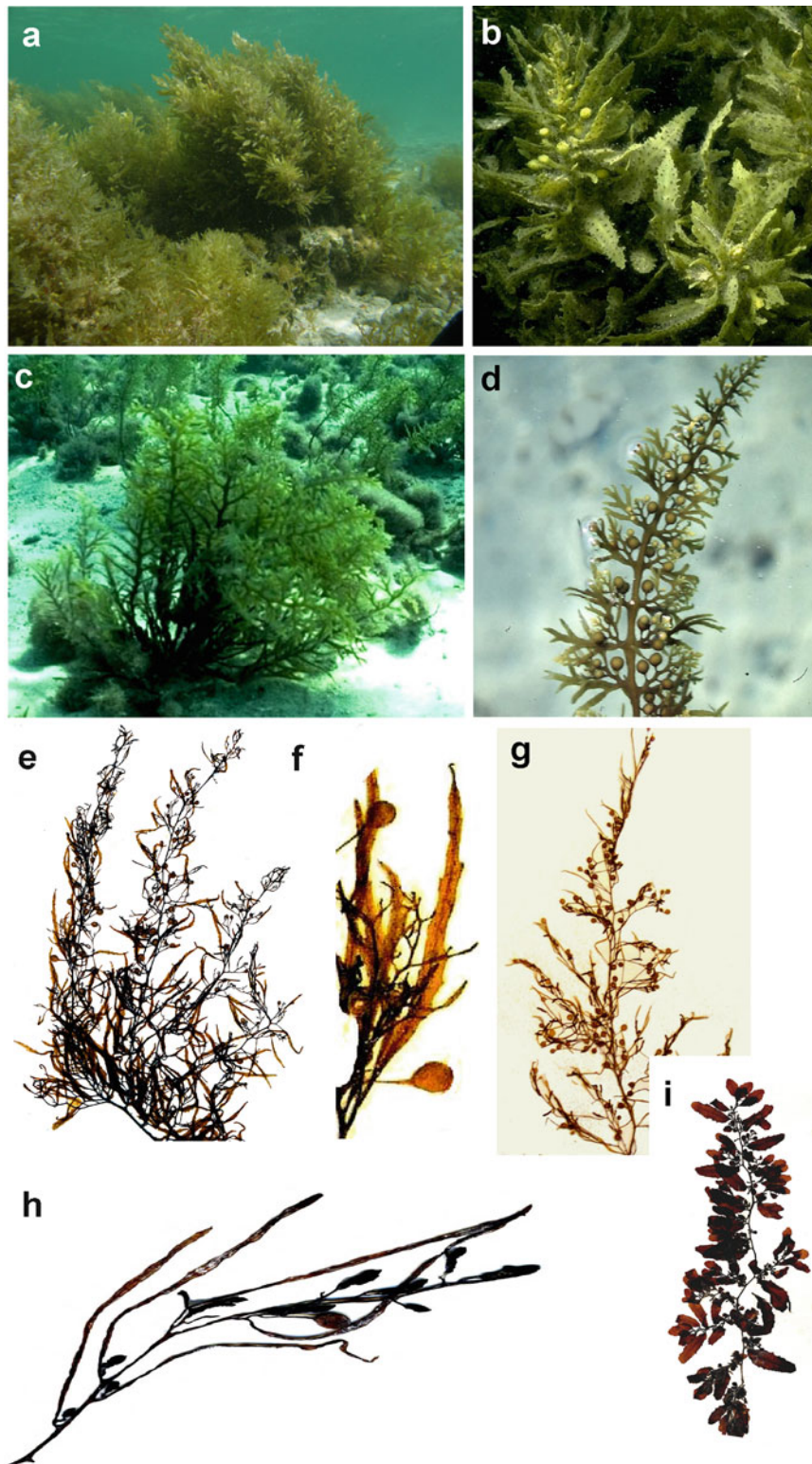


Fig. 14.8 (a) Well-developed clump of *Sargassum latifolium* in a back reef area; (b) Close view of the lance-shaped leaf-like appendages of *Sargassum latifolium* showing the toothed margin, acute apex and very prominent cryptostomata; (c) Typical clump of *Sargassopsis decurrens* on partially sand-covered rocks in a back reef area; (d) Close view showing the stiff and fern-like form of *Sargassopsis decurrens* with the long triangular shape of the main axis as a result of the compressed lateral branchlets decreasing in length towards apex; (e) Habit of

Sargassum angustifolium; (f) Narrow, linear, toothed-margined and pointed leaf-like appendages of *Sargassum angustifolium* with small and inconspicuous cryptostomata; (g) Thin and elegant habit of *Sargassum boveanum*; (h) Linear and smooth or undulate margined leaf-like appendages of *Sargassum boveanum* with inconspicuous cryptostoma and spindle-shaped receptacles (reproductive organs); (i) Habit of *Sargassum aquifolium* (Photos (a) C. Teasdale; (b) D. George; (d-i) D. John)

linear, 0.5–1 mm wide and up to 35 mm long, with margins smooth or slightly undulate and apices rounded; hair spots inconspicuous; bladders stalked, spherical or mucronate. The type variety and var. *aterrimum* are associated with the seasonally-developed beds of foliose brown seaweeds. Also known from Bahrain, Kuwait, Qatar and Saudi Arabia.

var. *aterrimum* Grunow

Similar to the type variety but differs in having long side branches and so the main axes are not especially conspicuous. The leaf-like appendages are without hair spots and the bladders are spindle-shaped. Also known also from Saudi Arabia.

Sargassopsis decurrens (R. Brown ex Turner) Trevisan (Figs. 14.3b, d, and 14.8c, d)

Branches flattened above, very rigid, with lateral alternate branches arising on each side of axis and gradually narrowing towards apex; bladders sometimes present, small and stalked. Most common on partially sand-buried rocks and coral debris in areas behind shallow rocky platforms where frequently associated with *Hormophysa cuneiformis*. Reported also from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Sargassum latifolium (Turner) Agardh (Figs. 14.6a, 14.7e, 14.8a, b, 14.9a)

Branches elegant, up to about 0.5 m long, compressed to almost cylindrical, 2–4 mm broad, with branches arising in a zig-zag fashion and leaf-like appendages arising alternately; leaf-like appendages generally lance-shaped, 0.5–1 cm wide and reaching 6 cm in length, with conspicuous marginal teeth and very prominent hair spots (to 1 mm in diam.); bladders subspherical to spindle-shaped, without an apical mucron. Commonly the dominant species forming the dense seasonally-developed on rocky platforms and on other hard substrata at depths ranging from about 0.5–3 m along the Abu Dhabi coast. Also reported by DeClerk and Coppejans (1996: 242) as the most common *Sargassum* species in the Jubail Wildlife Sanctuary in Saudi Arabia and the only one to remain fully developed over the summer period. Also known from Bahrain and Iran.

Several other *Sargassum* species have been reported on rare occasions in the Gulf and from just one or two countries. Børgesen (1939) reports four additional *Sargassum* species from Iran (*S. cervicorne* Greville, *S. swartzii* (Turner) Agardh, *S. asperifolium* (Herring & Martius) J. Agardh, *S. acutifolium* Greville) and Abdel-Kareem (2009a) reports five species (*S. denticulatum* (Försskal) Børgesen, *S. natans* (L.) Gaillon, *S. vulgare* Agardh, *S. acinaciforme* Montagne, *S. crassifolium* J. Agardh) from Saudi Arabia and regarded these as ‘new records’ for the Gulf. Two of these species (*S. acinaciforme*, *S. crassifolium*) had been reported earlier from Iran by Børgesen albeit with doubt. *Sargassum crassifolium* and *S. denticulatum* had also been reported from Qatar by

Dorgham (1990) although were regarded as rare and were only found amongst drift seaweeds. It is notoriously difficult to identify *Sargassum*'s and the study by Børgesen (1939) should be regarded as the the only authoritative treatment of the genus in the Gulf. He sent his Iranian material to William Setchell (Berkeley, USA) who at the time was a leading authority on tropical *Sargassum* species. The identifications were checked by Børgesen against material in the Jacob Agardh collection in the Lund Herbarium (Sweden) following a suggestion by Setchell that ‘you may find it advantageous to compare your specimens with those in Herb. Agardh’.

14.7.3 Phylum Rhodophyta (Red Algae)

Characteristically red in colour since the green chlorophyll pigment is masked by a combination of the red pigment phycoerythrin and the blue pigment phycocyanin. Often under high light conditions individuals become bleached to a brownish or straw colour. Varying from filaments consisting of a single series of cells through to compact tissues in the form of cylindrical or flattened branches and sometimes membrane-like. Some members are impregnated with lime and are referred to as ‘coralline’ seaweeds since they have been commonly mistaken for hard corals. Reproduction and life history in this phylum is often very complex and is not considered here in any detail.

Order Ceramiales

Family Rhodomelaceae

Acanthophora spicifera (Vahl) Børgesen (Figs. 14.3d and 14.9b, e, j)

Bushy, somewhat stiff to cartilaginous, reaching about 15 cm long, dark purple to straw-coloured; branches cylindrical and sparsely branched, bearing side branches of rather similar length and these beset with small spines. Occurs on the edges of submarine rocky platforms and is common on partially sand-buried hard surfaces behind such platforms. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Chondria dasyphylla (Woodward) Agardh (Fig. 14.9e, k)

Bushy clumps, up to 20 cm high, pink to straw-coloured, very supple; branches up to 2 mm in diam., irregularly divided, without a dominant axis, bearing soft spindle-shaped branchlets. Common along with *Laurencia obtusa* in back-reef habitats and readily distinguished from it by having short, rigid side branchlets which are not basally constricted. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Digenea simplex (Wulfen) Agardh (Fig. 14.8e)

Branches brush-like in appearance, erect and stiff, about 30 cm high, reddish to a dull brown, irregularly divided and

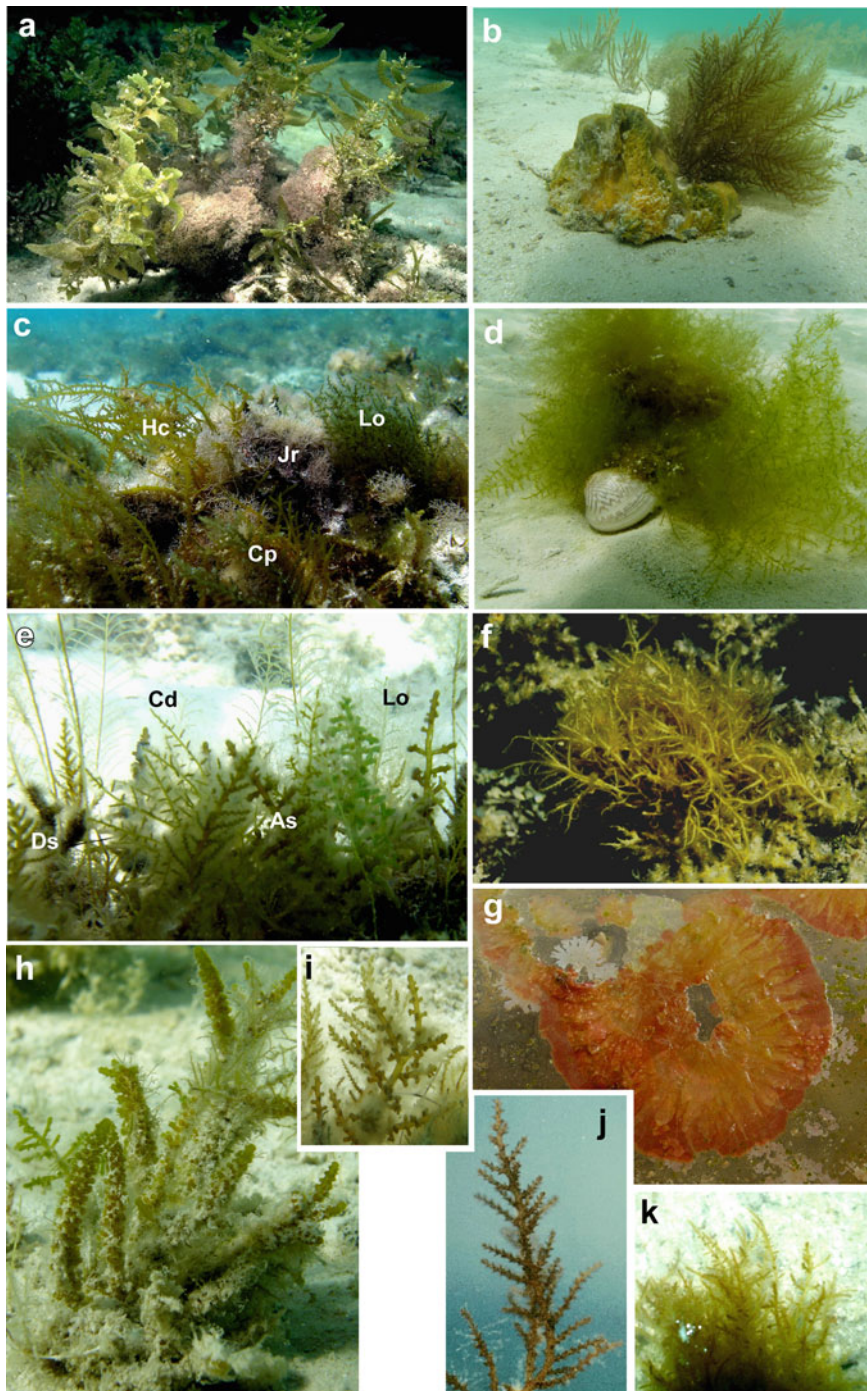


Fig. 14.9 (a) *Sargassum latifolium* in a back area behind the raised rocky reef platform and heavily epiphytised by the articulated coralline *Jania rubens*; (b) Clump of the 'red' seaweed *Acanthophora spicifera* growing in a back reef area on a dislodged sponge; (c) Assemblage of the 'red' seaweeds *Hypnea cornuta* (Hc), *Jania rubens* (Jr), *Laurencia obtusa* (Lo) and *Champia parvula* (Cp); (d) Clump of *Chondria dasyphylla* growing on a bivalve shell in a back reef area; (e) Shallow water assemblage of 'red' seaweeds in a very shallow back reef area, includes-

Digenea simplex (Ds), *Chondria dasyphylla* (Cd), *Acanthophora spicifera* (As) and *Laurencia obtusa* (Lo); (f) Habit of the filamentous 'red' seaweed *Spyridia filamentosa*; (g) The reddish crust of *Peyssonnelia simulans*; (h) Clump of the 'red' seaweed *Palisada perforata*; (i) Habit of *Laurencia obtusa* with an erect branch having whorls of short club-shaped branchlets; (j) Main axis of *Acanthophora spicifera* showing the short and spiny lateral branchlets; (k) Clump of *Chondria dasyphylla* (Photos (b–e, h, i) C. Teasdale; (a–f) D. George; (g, j, k) D. John)

covered by short bristle-like branchlets. Occurs in the sublittoral fringe and shallowest parts of the rocky reef flats, commonly covered by small epiphytes. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Laurencia obtusa (Hudson) Lamouroux (Figs. 14.3d and 14.9e, i)

Bushy clumps, up to 20 cm high, greenish to reddish-brown, somewhat cartilaginous; branches to 2 mm in diam., round in cross section, opposite and sometimes alternately or irregularly divided, almost in whorls, often lateral branches becoming shorter towards apex and covered by short, somewhat club-shaped branchlets with an invaginate apex. Common on coral fragments and other partially sand-buried surfaces in shallow areas behind rocky platforms. Also known from Bahrain, Kuwait, Qatar and Saudi Arabia.

Herposiphonia secunda (Agardh) Ambronn forma *tenella* (Agardh) Wynne (Figs. 14.10f and 14.12f)

Creeping filaments, reddish-purple, commonly epiphytic, less than 1 cm high; creeping filaments attached by rhizoids, bearing from almost every segment an erect branch, often three simple erect branches lying between a subdivided branch, with apex of divided and prostrate filaments incurved. Commonly epiphytic on brown seaweeds and occasionally on other hard surfaces. Also known also from Bahrain, Qatar and Iran.

Palisada perforata (Bory de Saint-Vincent) K.W.Nam (Fig. 14.9h)

Synonym *Chondrophyucus papillosus* (Agardh) Garbary
Branches cylindrical, stiff to cartilaginous, somewhat straw- or orange-coloured, irregularly divided, beset with small branchlets (sometimes swollen) decreasing in length towards apices so having a narrow pyramidal outline. Occurs most commonly in lower shore tide pools, but also in shallow parts of rocky submarine platforms and areas behind these platforms, frequently associated with *Dictyosphaerium cavernosa* and *Digenea simplex*. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Polysiphonia kampsaxii Børgesen (Figs. 14.10e and 14.12f)

Forming tufts or mats, up to about 4 cm high; filaments polysiphonous, segments up to one times longer than broad, with creeping filaments attached by unicellular rhizoids and giving rise to spirally divided erect branches. Occurs with other mat-forming species on rocks and coral skeletons and sometimes epiphytic; most common in areas behind shallow rocky platforms. Reported also from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Spyridia filamentosa (Wulfen) Harvey (Figs. 14.3d, 14.9f, 14.12i)

Bushy, distinct and irregularly divided branches, pink to straw-coloured, with a $\times 10$ hand lens the branches appear segmented since corticated by regularly disposed cells, beset by small branchlets arising at right angles to main axes and giving plant a somewhat 'fuzzy' appearance. Occurs on small, sand-embedded hard surfaces in tide pools and common on shallow rocks in areas behind shallow rocky platforms; sometimes amongst seagrass beds and often epiphytic on seagrass blades. Also known from Bahrain, Iran, Kuwait, Qatar and Saudi Arabia.

Order Rhodymeniales

Family Champiaceae

Champia parvula (Agardh) Harvey (Figs. 14.3b, 14.9c)

Small clumps or solitary, soft and gelatinous, pinkish to straw- or orange-coloured, up to about 10 cm high; branches to 1 mm wide, arising alternately, oppositely or whorled, divided by diaphragms into barrel-shaped segments, near apices segments shorter compared to broader and longer segments below. Most common on rocky ledges and intermittently sand-buried hard surfaces behind shallow rocky platforms. Also known from Iran, Kuwait and Saudi Arabia. Other *Champia* species are reported from the Gulf including *C. indica* Børgesen (Iran, Kuwait) which is more robust than *C. parvula* and whose segments are half as long as broad or shorter.

Order Gelidiales

Family Gelidiellaceae

Gelidiella myrioclada (Børgesen) Feldmann & Hamel (Fig. 14.9f, i)

Creeping tufts or mats, with the creeping system attached by wedge-shaped haptera, bearing numerous erect axis, 1–4 cm high, round in cross section, simple or irregularly or pinnately branched, with apices pointed and terminating in a single apical cell. Common along with other mat-forming seaweeds on shallow rocky surfaces including coral skeletons. Known also from Saudi Arabia.

Gelidium pusillum (Stackhouse) Le Jolis (Fig. 14.10c, d)

Creeping, felty mats of minute erect branches (less than 1 cm high) arising from a creeping basal system of branches, with erect branches flattened, constricted, irregularly divided and rounded at apex, brownish to reddish-purple in colour. Occurs from sheltered to very wave-exposed shores as a felty covering over rocks, barnacles and molluscs or mixed with other turf-forming seaweeds in shallow areas on the landward side of raised rocky platforms. Known also from Kuwait, Iran and Saudi Arabia.

Order Gigartinales

Family Cystocloniaceae

Hypnea cornuta (Kützting) J. Agardh (Fig. 14.9c)

Bushy, reaching about 15 cm high, pink to straw-coloured; branches sparingly alternately divided, bearing short, simple, upwardly curved branchlets with a spiny apex. Reproductive

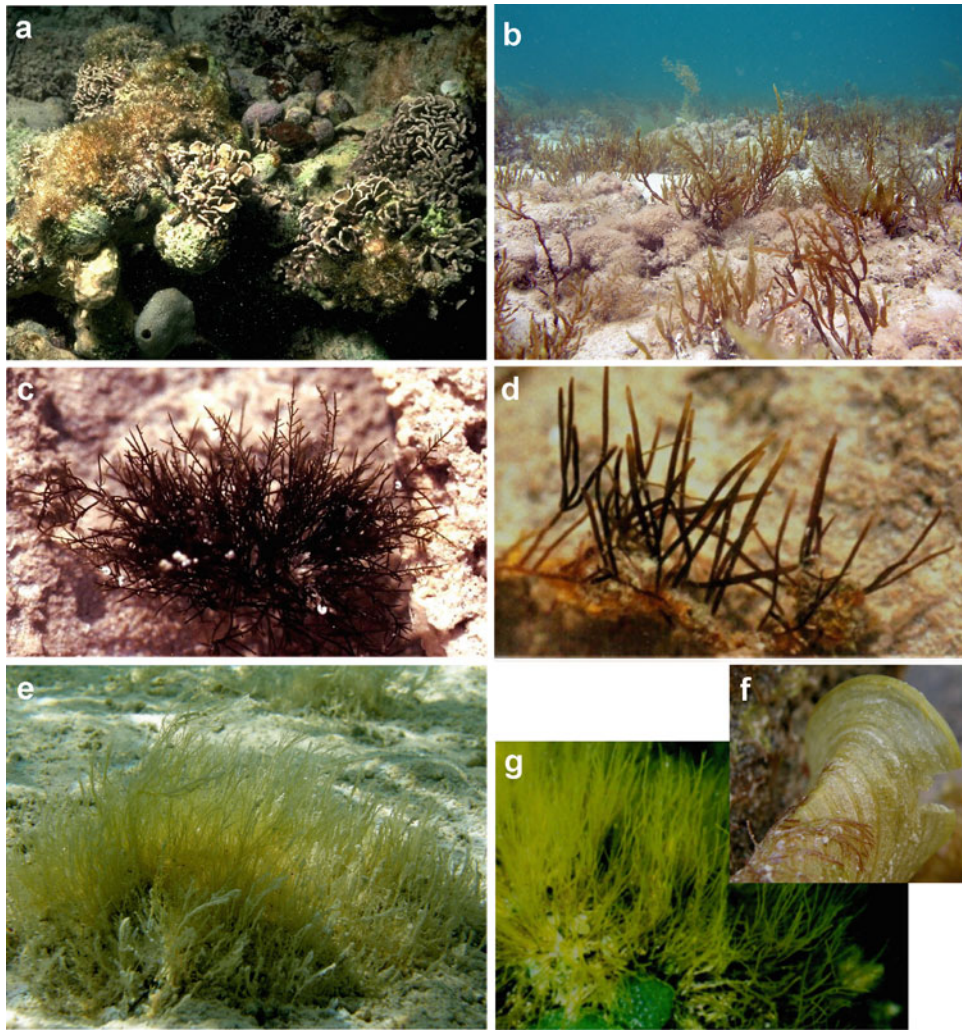


Fig. 14.10 (a) Edge of platform showing irregularly-surfaced clumps of the crustose coralline *Lithophyllum kotschyanum* and mats of red filamentous seaweeds; (b) Back area with hard surfaces colonized by pinkish clumps of the articulated coralline *Jania rubens* and the brown seaweed *Hormophysa cuneiformis*; (c) Habit of the 'red' seaweed *Geldium pusillum*; (d) Habit of *Gelidium pusillum* showing the erect

branches arising from a creeping basal portion; (e) Mat of the filamentous red seaweed *Polysiphonia kampsaxii* on a partially sand-buried hard surface in a back area; (f) The filamentous red seaweeds *Herposiphonia secunda* f. *tenella* on surface of the frond of *Padina boergesenii*; (g) Irregular branching patterns of *Gelidiella myriocladia* (Photos (a) D. George; (b, e) C. Teasdale, (c, d, f, g) D. John)

propagules often present, characteristically anvil-shaped. Occurs over the winter and in early summer where most common on small stones, shell fragments and partially sand-buried rocks behind shallow rocky platforms and seagrass beds; also in large shallow tide pools on the lower shore. Also known from Bahrain, Kuwait, Qatar and Saudi Arabia.

Family Peyssonneliaceae

Peyssonnelia simulans Weber-van Bosse (Fig. 14.9g)
Forming irregularly outlined crusts, easily removed from substratum, up to 4 cm in diam., leathery, only calcified on lower side, often deep red in colour. Frequently attached to coral fragments, rock ledges and more shaded basal parts of

living corals including the dead branches of *Acropora*. Also recorded from Kuwait and Saudi Arabia.

Family Solieriaceae

Wurdemannia miniata (Draparnaud) Feldmann & Hamel (Fig. 14.12a)

Wiry clumps or mats, often entangled, dark brownish red; prostrate branches attached at various points; erect branches up to 0.3 mm in diam. and reaching to 3 cm in height; branches round in section, irregularly to unilaterally divided, apically with a short point. Common along with other mat- or clump-forming seaweeds on rocks in shallow water, especially frequent on coral skeletons. Also known from Qatar and Saudi Arabia. Similar to *Gelidiella myriocladia* but dis-

tinguished from it by having several apical cells rather than a single cell.

Subclass Corallinophycidae

Order Corallinales

Commonly referred to as a 'coralline alga' since hard and rigid due to the cell walls being impregnated with calcium carbonate and therefore coral-like. Unfortunately external morphology is only a guide for identification of the crustose corallines since many taxa display a bewildering range of size and form. Few can be easily identified with confidence without using a microscope to examine anatomical and reproductive characters. An important group associated with coral reefs but still little researched in the Gulf.

Family Corallinaceae

Tetrasporangia zonately divided and borne within conceptacles. The family is divided into two groups: the articulated (geniculate) and the non-articulated (non-geniculate) corallines.

Crustose Corallines

Hydrolithon Foslie (Figs. 14.7g and 14.11a, b)

The three species known in the Gulf form thin 2-layered crusts. Identification to species usually requires microscopic examination. All grow epiphytically on brown seaweeds, mainly on *Padina boergesenii*, *Hormophysa cuneiformis* and species of *Sargassum* and *Cystoseira*.

Hydrolithon boreale (Foslie) Y.Chamberlain

Form mauve-pink crusts, flat or having overgrowing layers; filaments forming the basal layers sometimes terminating in a hair-bearing cell (trichocyte). Only reported in the Gulf from Abu Dhabi.

Hydrolithon farinosum (Lamouroux) Penrose & Y.Chamberlain (Fig. 14.12h)

Form pale pinkish crusts, never with overlapping layers; filaments of basal layers often terminating in hair-bearing cell. Also known in the Gulf from Bahrain, Dubai, Iran, Kuwait and Saudi Arabia.

Hydrolithon improcerum (Foslie & M.A.Howe) Foslie

Similar to *H. boreale* but frequently having conspicuous groups of hair-bearing cells. So far only known in the Gulf from Abu Dhabi.

Lithothamnion muelleri Lenormand ex Rosanoff (Fig. 14.11i)

Forms pale pinkish to brownish, encrusting to warty, up to 4 mm thick, frequently with numerous and short branch-like excrescences, usually 1–4 mm across, often somewhat raised multiporate conceptacles (usually sporangial) on the surface, often conceptacles depressed in centre. Fairly common on coral skeletons and on the base of *Lithophyllum kotschyianum* clumps. Only known in the Gulf from Abu Dhabi.

Another crustose coralline was discovered in Abu Dhabi by Dr. Chamberlain and has been provisionally identified as *Lithothamnion incrassatum* (Foslie) Foslie. The specimens form extensive, lumpy crusts (ca. 1 mm thick) whose margins are very thin, brownish-purple in shade and pale mauve-coloured when unshaded, with an outermost layer of relatively short and wide epithelial cells. The tetrasporangial conceptacles have similarly sized and shaped chambers as those in *Lithophyllum kotschyianum*, but differs in having papillate cells lining the pores and crusts that are somewhat detached, never thickened and do not bear branches.

Lithophyllum kotschyianum Unger (Figs. 14.2c–e, i, 14.4e, 14.10e, 14.11c–e)

Crustose base giving rise either to more or less hemispherical clumps of slender blunt protuberances or having simple or divided branches (round in cross section), with branches tips blunt or slightly tapering, or forming more brain-like clumps and of interweaving, flattened and fan-like branches, about 5–10 cm high, light pinkish-red; conceptacles low domed, inconspicuous, multiporate, mainly on upper parts of branches. Common in shallow water on the skeletons of *Acropora* and *Porites* as well as on hard surfaces down to a depth of at least 10 m. Known throughout the Gulf with Bahrain the type locality.

Neogoniolithon misakiense (Foslie) Setchell & L.R.Mason (Fig. 14.11c)

Form thin, distinct light to dark pink, smooth or somewhat rough surfaced crusts, with single-pored sporangial conceptacles. Growing on wave-exposed hard substrata on the fore reef and on the base of clumps of *Lithophyllum kotschyianum* and on hard surfaces between the dead branches of *Acropora*. Only known in the Gulf from Abu Dhabi.

Titanoderma pustulatum (Lamouroux) Nägeli

Synonym *Lithophyllum pustulatum* (Lamouroux) Foslie
Forms adherent, orbicular, smooth-surfaced crusts, often with thickened margins, mauve-pink, up to 30 mm in diam. Common on mollusc shells and frequently growing on the branches of *Lithophyllum kotschyianum*. Only known in the Gulf from Abu Dhabi.

Family Sporolithaceae

Tetrasporangia cruciately divided and loosely aggregated into superficial sori.

Sporolithon ptychoides Heydrich (Figs. 14.11f and 14.12j)

Commonly forming thickish crusts (up to 5 mm), very hard, flat to lumpy, sometimes bearing numerous protuberances, smooth-surfaced, pinkish brown where shaded and greyish-green where unshaded. Tetrasporangia forming slightly raised and indefinite patches (sori) on surface and associated with sterile filaments (sori). Very common on dead *Porites* and on shallow limestone ridges and platforms in relatively

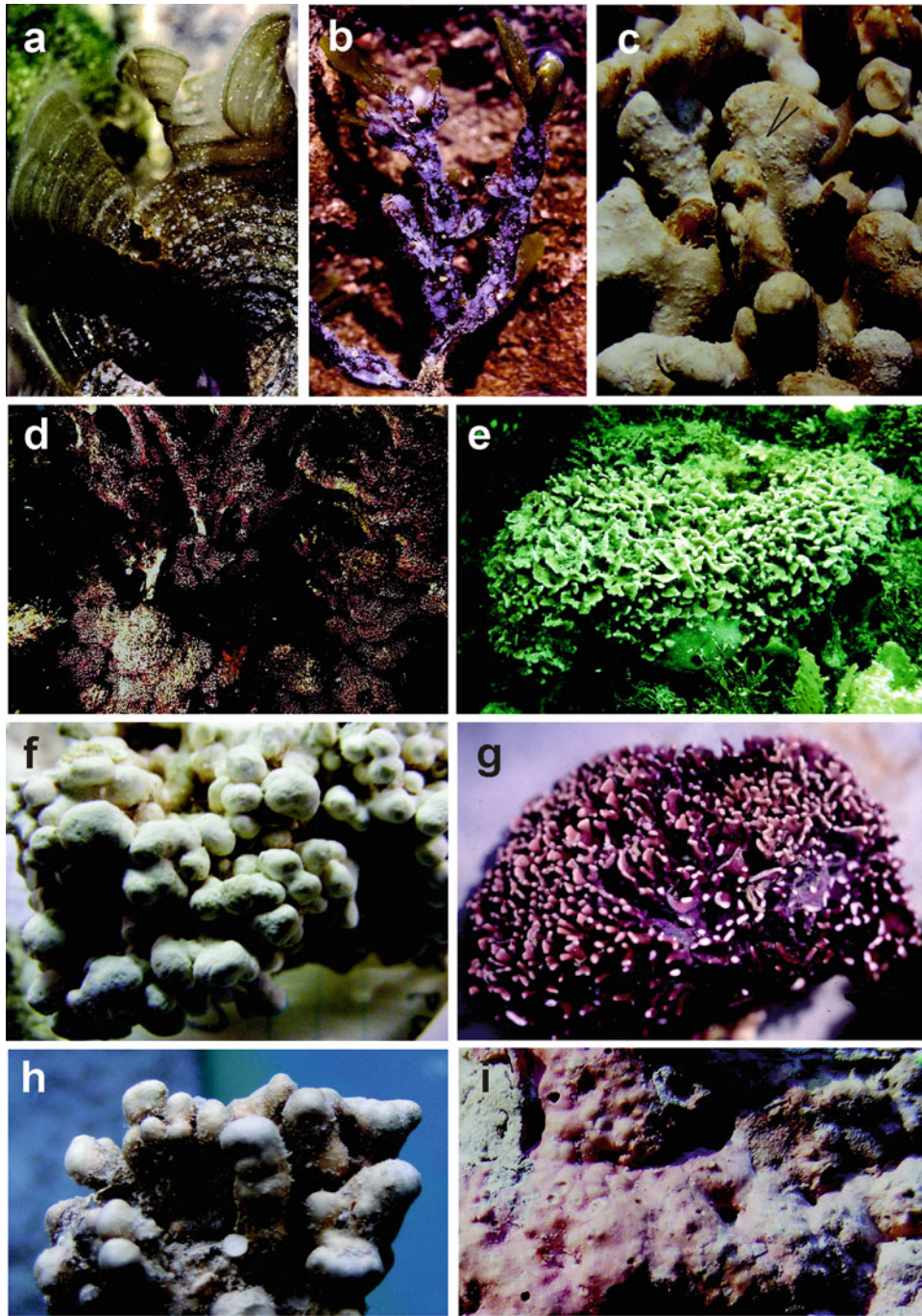


Fig. 14.11 (a, b) Pink crusts of the coralline *Hydrolithon* spp. on the brown seaweeds *Padina boergesenii* (a) and on old branches of *Hormophysa cuneiformis* (b); (c) Small crusts of *Neogoniolithon pustulatum* (see arrow) on the nodulose branches of the crustose coralline *Lithophyllum kotschyanum*; (d) Dead branches of *Acropora* covered by clumps of *Lithophyllum kotschyanum*; (e) Clump of a flattened-branched

form of *Lithophyllum kotschyanum* photographed *in situ* on a rocky ledge; (f) Nodular clumps of the crustose coralline *Sporolithon ptychoides*; (g) Dried out, dark pinkish-red clump of *Lithophyllum kotschyanum*; (h) Side view of the nodular or warty excrescences of *Sporolithon ptychoides*; (i) Irregularly surfaced pink crust of the coralline *Lithothamnion muelleri* (Photos (a–c, f–k) D. John; (d, e) D. George)

shallow water (0–5 m). Only known from Abu Dhabi in the Gulf. Another *Sporolithon*, *S. molle* (Heydrich) Heydrich (synonym *S. ptychoides* f. *molle* Heydrich), is reported by

DeClerk and Coppejans (1996: 280) who mention that it frequently covers the upper part of shallow patch reefs.

Articulated Corallines

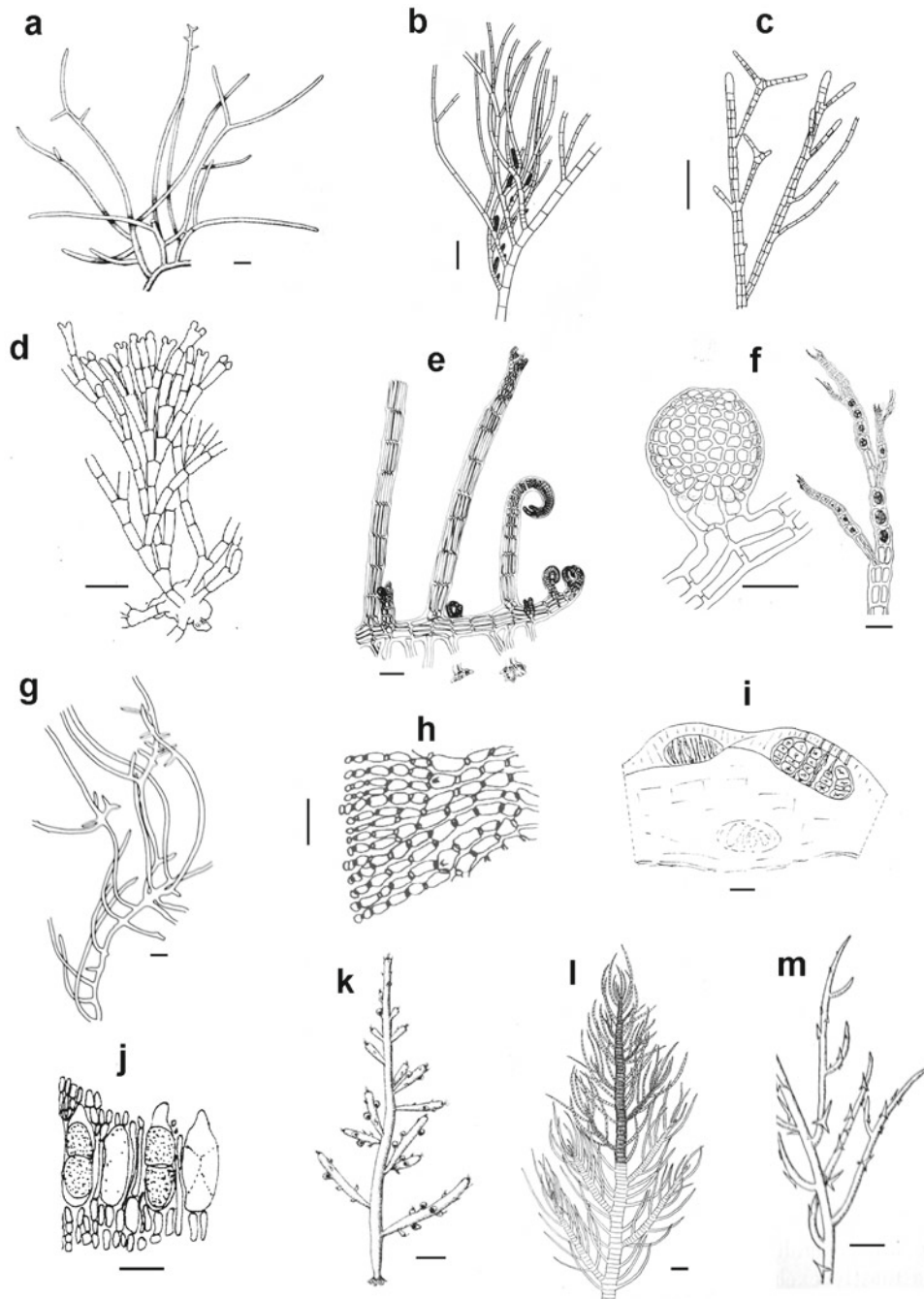


Fig. 14.12 (a) Branching pattern of *Wurdemannia miniata*; (b) Filaments of *Hincksia mitchelliae* showing the elongate multilocular sporangia; (c) Filament of *Sphacelaria rigidula* with the propagules having a stalk and two arms of almost equal length; (d) Habit of the articulated coralline *Jania puniula*; (e) Microscopic structure of *Herposiphonia secunda* f. *tenella* showing the prostrate and erect branches; (f) Portion of *Polysiphonia kampsaxii* showing a flask-shaped cystocarp and tetrasporangia in tapering filament tips; (g) Habit of *Gelidiella myriocladia*; (h) Surface view of the thin crust of *Hydrolithon farinosum* with the occasional larger cell (trichocytes) terminating a filament; (i) Microscopic section through the crust of *Lithothamnion muelleri* showing tetrasporangial conceptacles; (j) Section

through a sorus of *Sporoliton ptychoides* showing sterile filaments and zonately divided tetraspores; (k) Habit of *Chondria dasyphylla* showing a constriction at base of each irregularly arranged club-shaped branchlet; (l) Details of a branch of *Spyridia filamentosa* showing main branch and side branchlets; (m) Branches of *Hypnea cornuta* with each terminating in a point and bearing anvil-shaped propagules. Scale bars: 20 mm – h; 100 mm – b, c, e, i, j; 200 mm – f (left scale bar); 0.5 mm – a, d, g, m; 1.0 mm – i; 2 mm – k, f (right scale bar) (Photos (c, d, e, g) Jassund (1976); (h) D. John; (i, j) Y. Chamberlain; (a, k) Børgesen (1919); (b) Børgesen (1941); (f) Børgesen (1939); (l) Børgesen (1917); (m) Børgesen (1943))

Branches consist of calcified segments (intergenicula) connected by uncalcified flexible joints (genicula).

Jania rubens (Linnaeus) Lamouroux (Figs. 14.3d, f, 14.4a, b, 14.9a, c, 14.10b)

Forming spherical brittle clumps or tufts, 3–10 cm across; branches 150–225 mm in diam., regularly forked; segments heavily calcified, cylindrical, 3–6 times longer than broad, pinkish-red and sometimes bleached white (Fig. 14.9h). Commonly occurs as tassel-like growths on large brown seaweeds in shallow water along the Arabian Gulf coast, often also on rocky surfaces where forming very large population in back-reef areas, also forms free-living populations lying on the seabed in more wave-sheltered areas. Masses of bleached individuals are cast ashore in large numbers, especially during the early summer. Also reported from Bahrain, Iran, Qatar and Saudi Arabia.

Jania pumilla Lamouroux (Fig. 14.12d)

Forming low clumps, less than 2 cm high; branches about 100 mm in diam. below and tapering above, regularly forked; segments calcified segment, 3–5 times longer than broad. Commonly mixed with turf- or mat-forming seaweeds and occasionally epiphytic in mostly back-reef habitats and very evident in the early summer. Reported also from Bahrain, Kuwait, Iran, Qatar and Saudi Arabia.

14.8 Conclusion

The submarine seascape of the shallow inshore environment of the southern Gulf has undergone dramatic changes since summer 1996 due to a local shift from coral dominance to domination by seaweeds. The loss of living corals from shallow rocky platforms and offshore shoals has opened up extensive areas for colonization by seaweeds and sessile invertebrate animals. Episodes of coral death are reported from elsewhere in the southern Gulf although the impact of these episodes on seaweeds has been only comprehensively investigated in the Emirate of Abu Dhabi (UAE). Coral recovery is underway in parts of the southern Gulf (Burt et al. 2009), but it is difficult to predict just how long it will take for corals to re-establish to their former dominance (Riegl and Purkis 2009; see Chap. 5). Although the annual cycle of seawater temperature accounts for seaweed seasonality there is no evidence to suggest that exceptionally high summer values adversely impact upon them. Over the summer the dense beds of foliose brown seaweeds are much reduced and the few individuals that survive over the period are often heavily epiphytised. Very evident over the summer are crustose and articulated corallines and mats, turfs or clumps of filamentous seaweeds. The only larger brown seaweeds to sometimes survive over the summer as relatively healthy individuals include *Hormophysa*

cuneiformis and *Cystoseria trinodis*. Just a few coral reefs have remained relatively healthy over the past 15 years and these include *Porites*-dominated patch reefs lying to the east of Abu Dhabi City (George and John 2004). Regenerating and *Acropora*-dominated areas are reported in Qatar, Dubai, Sharjah (Sir Abu Nuair) and Abu Dhabi (see Burt et al. 2009; Riegl 2003; Riegl and Purkis 2009) as well as Iran. But in many formerly coral-dominated rocky areas the cover of corals remains low and seaweeds continue to dominate.

The most significant and important threats to shallow-water habitats in the Gulf come from massive coastal development involving dredging and creating new land for housing, leisure and industrial facilities. Some of these coastal developments have created artificial reefs in the form of breakwaters, causeways, jetties, seawalls and similar hard structures. Such man-made constructions have substantially increased the amount of hard-bottom habitat available for colonization by benthic organisms including seaweeds. For example, in Dubai (UAE) the amount of hard-bottom habitat has been very significantly increased by the construction of more than 65 km of protective rocky breakwater since natural-reef habitat is restricted to a series of discontinuous rocky caps along a 10 km nearshore band (Riegl 1999; Burt et al. 2008). The assemblages of seaweeds and invertebrate animals on the breakwaters surrounding the Jumeirah Palm, Jebel Ali Palm, World Islands and other Dubai waterfront developments are not necessarily comparable to those on natural hard-bottoms. For example, since 1998 coral assemblages have developed on the more wave-exposed sides of breakwaters off Abu Dhabi City and yet in winter the only seaweeds observed were corallines and turf- or mat-forming seaweeds rather than conspicuous foliose brown seaweeds (personal observation).

The inshore environment of the Gulf will continue to be subject to disturbances arising from human uses and activities as well as from longer term climate change (see Chap. 16). As long as there are hard surfaces in shallow water, seaweeds will continue to dominate the submarine environment in many areas until such time as reef-building corals are well-established. Coral recovery is expected to be hampered by competition with seaweeds as well as other factors including low numbers of surviving inshore corals that act as sources of inoculum and by any further episodes of elevated summer seawater temperature.

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Conservation of Marine Ecosystems with a Special View to Coral Reefs in the Gulf

15

Ashraf S. Al-Cibahy, Khalifa Al-Khalifa, Benno Böer, and
Kaveh Samimi-Namin

15.1 Introduction

The Gulf is one of the oldest water passages in the world. Historically it has been famous for its precious pearl oysters, and nearly a millennium ago, Arabian and Persian sailors and merchants in the Gulf area established a trade network linking the Gulf with areas as far east as China. The Gulf now has risen to prominence due to its vast oil (~66% of global reserves) and natural gas reserves (~45% of global reserves) and its contribution to the global demand on energy. This has resulted in a tremendous growth of regional wealth and concomitant economic development, with rapid population growth, urban development and intense development of the coastline. The Gulf coastline is ~3,700 km and the coastal population is projected at 15.55 million, with a higher concentration of cities on the Arabian than the Iranian shore. Thus, significant and steadily increasing pressure is exerted on the coastal and marine resources of the region with concomitant large-scale degradation of coastal ecosystems and, notably, coral reefs (Sheppard et al. 2010; Sale et al. 2011; Chap. 16).

The Gulf is considered the inner part of the ROPME (Regional Organization for the Protection of Marine Environment) Sea Area. ROPME mainly covers program

activities relating to marine pollution and conservation of marine resources and was created in 1979 to become the secretariat for the Kuwait Convention for Cooperation on the Protection of the Marine Environment from Pollution in 1982. The ROPME agreement was signed by Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates. Projects cover aspects of coastal area management, fisheries, public health, land-based activities, sea-based pollution, biodiversity, oceanography, marine emergencies, GIS and remote sensing, environmental awareness and capacity building. ROPME and its protocols have made positive contributions towards the protection of the marine environment and coastal areas from pollution, however, the region is still confronted with major environmental challenges. The ROPME Sea Area suffers from the impacts of haphazard coastal development, physical alteration, destruction of habitats, sedimentation, high salinity, extremes of temperature, a great number of land-based and sea-based pollution sources, and institutional weaknesses in addressing these issues. More than 40% of the Gulf coast is now developed (Hamza and Munawar 2009) and as a result of this and other environmental insults, the WWF considers the Gulf bioregion as critically endangered (Al Cibahy et al. 2008).

The Arabian region boasts remarkably high marine biodiversity, the crown jewels of which are the reefs. Environmental conditions are, however, difficult for corals (Chaps. 2, 5, 6, and 9). The Gulf is situated in a subtropical hyper-arid region with significant insolation differences between summer and winter that, combined with the *Shamal* – a unique local cold wind (Chap. 2) – results in seasonal temperature fluctuations of over 20°C, the highest that coral reefs can withstand (Chap. 6). In addition, high evaporation and limited circulation leads to significant salinity stress (>43 ppm) that causes a near- to total absence of corals in the most extreme environments (Chap. 2). Coral reefs occur (or occurred until recent local destruction) abundantly throughout the Gulf (Chaps. 2 and 11) and more effort should be exerted towards their protection (Hamza and Munawar 2009; Sale et al. 2011).

A.S. Al-Cibahy (✉)
Environment Agency-Abu Dhabi, Abu Dhabi, United Arab Emirates
e-mail: aalcibahy@ead.ae

K. Al-Khalifa
Public Commission for the Protection of Marine Resources,
Environment and Wildlife, Manama, Bahrain
e-mail: khalifa.a.khalifa@gmail.com

B. Böer
UNESCO, Doha, Qatar
e-mail: b.boer@unesco.org

K. Samimi-Namin
Netherlands Centre for Biodiversity Naturalis, P.O. Box 9517,
2300 RA Leiden, The Netherlands
e-mail: kaveh_s_n@yahoo.com

Table 15.1 Checklist of the status of each Gulf country with regards to the national and international legislations that govern the biodiversity conservation

Country	PAs in the national legislations	International conventions						Global network of biosphere reserves
		CBD	CITES	Ramsar	CMS	UNESCO world heritage	UNCLOS	
Bahrain	•	1996 (R)	x	1998 (A)	x	1991(R)	1985	
Iran	•	1996 (R)	1976 (R) (F)	1975 (A)	2008 (F)	1975 (A)	1998	
Kuwait	•	2002 (R)	2002 (R) (F)	x	x	2002 (R)	1986	
Oman	•	1995 (R)	2008 (A) (F)	x	x	1981 (A)	1989	
Qatar	•	1996 (R)	2001 (A) (F)	x	x	1984 (A)	2002	2007
Saudi Arabia	•	2001 (A)	1996 (A)	x	1991	1978 (A)	1996	
UAE	•	2000 (R)	1990 (A) (F)	2007 (A)	x	2001 (A)	x	2007

CBD Convention on Biological Diversity, *CITES* Convention on International Trade in Endangered Species of Wild Fauna and Flora, *Ramsar* The Convention on Wetlands of International Importance, *CMS* Convention on Migratory Species, *UNCLOS* The United Nations Convention on the Law of the Sea, (F) Entry into force, (A) Accession, (R) Ratification

Table 15.2 Some key anthropogenic threats to coral reef areas in Gulf countries

Country	Threats
Bahrain	Coastal development, anchor damage, over-fishing, spear fishing, solid wastes, oil pollution, trawling nets, sedimentation
Iran	Pollution from oil production, breakwater construction, sedimentation during land reclamation, dredging, depletion of corals by local people, fishing for aquarium trade, extensive anchor damage, discharge of nutrients and sewage
Kuwait	Fishing and recreational boating, solid litter that smothers reef organisms, oil pollution, discharge of ballast water, coastal development, eutrophication and harmful algal blooms
Oman	Coastal development, destructive fishing, hazardous and solid wastes, over-fishing, depletion of threatened species, oil pollution, trampling, eutrophication and siltation
Qatar	Coastal development, boat anchors, overfishing, oil pollution and siltation
Saudi Arabia	Sewage discharge, discharge of solid wastes from ships, and oil spills
United Arab Emirates	Coastal development, oil spills, sewage, anchoring, over-fishing, increasing coral diseases due to anthropogenic stressors, siltation from dredging and land reclamation projects, and harmful algal blooms

Measures have been adopted to promote the conservation and sustainable use of marine biodiversity in ROPME member states. The legislative framework for biodiversity is based on a wide range of national laws and multi-lateral agreements (Table 15.1). Of particular note, the ROPME member states signed and, subsequently, ratified the convention on biological diversity. Drafts of the protocol concerning the conservation of biological diversity and the establishment of protected areas and the concept paper on biodiversity have been prepared.

Rapid growth of ROPME and shared coastal and marine environmental issues among littoral states have resulted in numerous plans to reach sustainable coastal management and environmental pollution prevention. But such plans can only be implemented when littoral states prioritize the management schemes and incorporate them into their own national legislation, which has hardly happened. Similar to many regional seas programs, ROPME has faced many drawbacks since its inception. Military conflicts, poor enforcement of protocols, lack of adequate coordination, disharmony among littoral states and lack of sufficient managerial capacity have put many coastal management programs on hold (Table 15.2).

Despite all existing differences and difficulties, important tasks have been accomplished. Coastal management issues have been analyzed and well documented. ROPME can effectively coordinate and implement monitoring of water quality and coastal habitat, develop and implement a comprehensive pollution prevention scheme, educate the public in terms of coastal preservation, train technical staff, put in place an effective pollution prevention and waste management program, and establish the basis for an integrated regional coastal zone management plan. Numerous marine and coastal protected areas have been declared in the area.

15.2 Regional Need for Coral Reef Conservation and Management

Human pressures constitute the major threats to coral reefs in the Gulf region, especially from coastal development, the oil industry, unsustainable fishing and poor treatment of liquid and solid wastes. Climate change and its subsequent impacts are across the board issues that are more visible and tangible in the Gulf than many other coral reef areas.

The conservation of Gulf marine ecosystems is important since its marine biological diversity is of great value and an asset on both national and regional levels. If marine ecosystems are well managed, they can meet a broad range of economic, social and cultural aspirations. They can provide a range of essential environmental services that would be costly or impossible to restore or replace. Although conservation issues and management challenges have commonalities among ROPME countries, they differ in specifics and hence the management system should have the flexibility to be responsive to local context. Regional experts identified a number of significant needs and actions to improve coral reef conservation, including:

- Adoption of integrated coastal zone management approaches to harmonize all the uses in coastal and marine areas through integrated policies and guidelines, science, management, and land use planning;
- Development and implementation of comprehensive environmental assessments that include resource valuation, risk assessment, cumulative environmental and social impact assessments to ensure consistency with land use and resources management plans;
- Establishment of reception facilities for solid and liquid wastes at loading terminals and ports.
- Reduction and proper management of dredging and land-filling activities. The use of silt curtains should be mandatory in dredge-and-fill operations. Reef areas should be exempt completely from filling, dredging or borrowing, acknowledging their scarcity throughout the region;
- Reduction of diver and boat anchor damage. Mooring buoys should be installed at major reef sites in all countries to prevent further anchor damage to corals. Additionally, spear fishing should be banned to allow reef fish populations to recover;
- Implementation of solid waste cleanup projects in each country to remove accumulated debris from the reefs and coastal areas, including discarded fishing gear;
- Implementation of public education campaigns to increase understanding of the importance of coral reefs and their sensitivity to damage and pollution. These should highlight the use of moorings to prevent damage to corals, the need for fishing restrictions on reefs, the problems caused by littering, and the need for public and private participation in the management of coral reefs;
- Capacity-building to monitor and carry out coral reef research. This must also include the designation, where applicable, of competent authorities to manage and conserve coral reefs, and preparation of detailed management plans to promote sustainable and wise use of reef resources;
- Designation of additional marine and coastal protected areas (MPAs) as part of integrated management plans. MPAs considered as the most powerful tools and mechanism

that allow countries to protect their coral reef and other important ecosystems;

- Development of preparedness and emergency centers for marine and coastal hazards. The centers would work to improve the oil spill contingency plans and to enforce the use of navigational aids and radio communications in the waterways, especially on major shipping and transportation routes; and
- Encourage bilateral and multilateral collaboration and private sector involvement in the coral reef conservation initiatives throughout the region.

15.2.1 Role of the NGOs in Coral Conservation

Many local and international NGOs are active in the region and have been actively supporting coral reef conservation in the Gulf region. For example, the WWF has been active in the UAE through its local branch the EWS (Emirates Wildlife Society) and has, together with the management authorities of the UAE and Qatar facilitated major resource inventories, capacity building and the installation of monitoring programs. The Kuwait Environment Protection Society is also active in pursuing biological diversity conservation and management. Also UNESCO supports activities dealing with scientific research and conservation management of marine ecosystems in the Gulf from offices in Tehran and Doha which coordinates activities. Three platforms of UNESCO tackle Gulf marine conservation issues; the Global Network of Biosphere Reserves (BRs), the World Heritage Sites (WHS), and the Trans-Boundary Diagnostic Analysis of Coastal and Marine Environmental Issues in the ROPME Sea Area (TDA). BRs are sites for the reconciliation of nature conservation and sustainable development. UAE and Qatar have established the first two BR in the Arabian Peninsula in 2007, namely Marawah Marine Biosphere Reserve and Al-Reem. Significant work towards identification and establishment of BRs has been carried out in Sharjah, UAE in 2001 (Khor Kalba), Bahrain in 2002 (Hawar Islands), and there is an ongoing process in Oman since 2004 (Jebel Samhan mountain and coastline) and Iran has established ten BR's so far. The overall aim is to establish a network of sites that function as models for sustainable human living, demonstrating the reconciliation of sustainable development and nature conservation. WHS can either be cultural, or natural, or both and are of globally unique value for mankind and the Gulf has a variety of candidate natural sea and landscapes. Within TDA, the Regional Organization for the Protection of the Marine Environment (ROPME), the Regional Clean Sea Organisation (RECSO), the United Nations Environment Program (UNEP), and UNESCO aim at joint expert training workshops, National Action Plans, and Strategic Regional Action Plans for the management of cross-border issues, including the protection and utilization of coral reefs.

15.3 Marine Protected Areas

Protected areas in the Gulf countries are supported by development and implementation of scientific, legislative, and management frameworks. Their goal is to provide comprehensive inventories of potential protected areas and afford full assessment and monitoring of habitats and species, empower conservation by establishing proper legal mandates and enforcement systems, and build capacity to ensure management and the sustainable use and conservation of natural resources. Often, significant shortfalls are observed in either or all of these frameworks.

In the Gulf countries, several terms are used to describe the management status of the protected areas with little reference to the international categories identified by IUCN or UNESCO. Table 15.3 provides a brief description of the international categories that should be used in the Gulf countries to standardize their management initiatives of protected areas according to the objectives relevant to each category.

15.3.1 Bahrain

Bahrain is an archipelago of around 40 low-laying islands in addition to numerous islets, shoals and patches of reefs occupying a total land area of about 728 and 3,000 km² of territorial waters. Marine biotopes are diverse and include extensive sea grass beds and mudflats, patchy coral reefs as well as offshore islands. Sea grass beds are important foraging grounds for some threatened species such as dugongs and green turtles (Fig. 15.1). A considerable proportion of the coastline has been modified by coastal development involving dredging and infilling. Other major anthropogenic stresses on local biodiversity include industrial and oil pollution, over-fishing and invasive species. Bahrain has recently prepared a National Environment Strategy, which is currently under consideration for adoption by the competent national authorities. A number of initiatives attempt measures to minimize stresses imposed by over-fishing. All destructive fishing methods, such as explosions, poisons and

Table 15.3 Suitable protected areas regimes in the Gulf countries

Category description	IUCN category	UNESCO equivalent systems
Strict Protection: strictly protected areas set aside to protect biodiversity and also possibly geological/ geomorphological features, where human visitation, use and impacts are strictly controlled and limited to ensure protection of the conservation values. Such protected areas can serve as indispensable reference areas for scientific research and monitoring	Category Ia: strict nature reserve	Core areas of the biosphere reserve
Strict Protection: usually large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, which are protected and managed so as to preserve their natural condition	Category Ib: wilderness area	Core areas of the biosphere reserve
Large natural or near natural areas set aside to protect large-scale ecological processes, along with the complement of species and ecosystems characteristic of the area, which also provide a foundation for environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities	Category II: national park	Buffer areas of the biosphere reserve
Protected areas set aside to protect a specific natural monument, which can be a land form, sea mount, and submarine cavern, geological feature such as a cave or even a living feature such as an ancient grove. They are generally quite small protected areas and often have high visitor value	Category III: natural monument or feature	Cultural/natural heritage site Geopark
Protected areas to protect particular species or habitats and whose management reflects this priority through regular, active interventions to address the requirements of particular species or to maintain habitats	Category IV: habitat/species management area	Buffer areas of the biosphere reserve Rehabilitation sites
Protected area where the interaction of people and nature over time has produced an area of distinct character with significant ecological, biological, cultural and scenic value, and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated nature conservation and other values	Category V: protected landscape/seascape	Buffer areas and transition areas of the biosphere reserve
Protected areas which conserve ecosystems and habitats, together with associated cultural values and traditional natural resource management systems. They are generally large, with most of the area in a natural condition, where a proportion is under sustainable natural resource management and where low-level non-industrial use of natural resources compatible with nature conservation is seen as one of the main aims of the area	Category VI: protected area with sustainable use of natural resources	Buffer areas of the biosphere reserve Managed resources PA

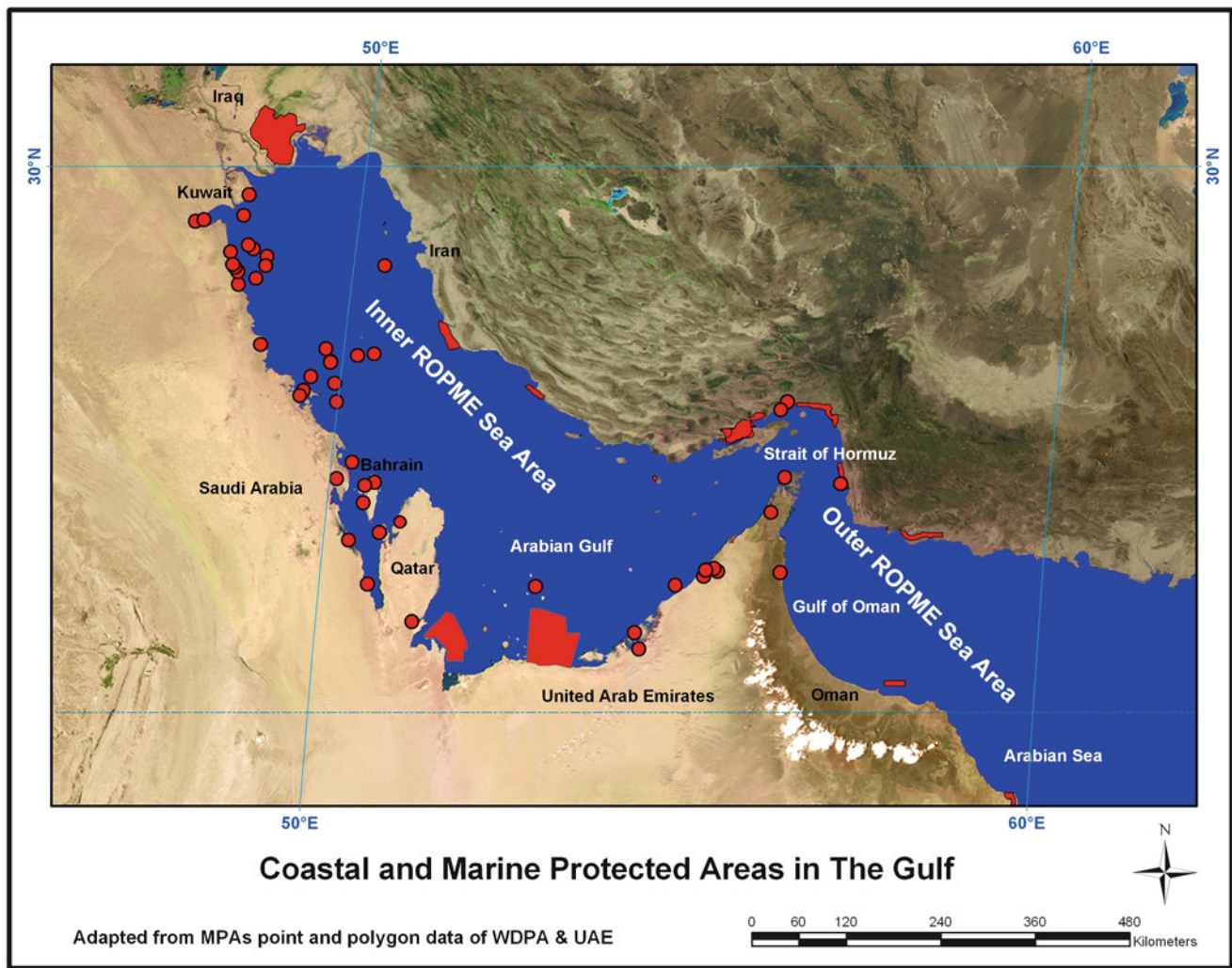


Fig. 15.1 Coastal and marine protected areas in the ROPME Sea Area

polythene nets, are prohibited. More sustainable traditional fishing methods, such as the wire and barrier traps are encouraged and maintained. Five marine areas in Bahrain were designated as Protected Areas (Table 15.4); Hawar Islands, Ras Sanad (Tubli Bay), Fasht Bulthama, Duwhat Arad, and Mashtan. The total area is about 580 km² which represent about 0.23% of the Gulf (Fig. 15.2).

The Hawar Islands are located 25 km southeast of the main island of Bahrain and form an archipelago of 16 small, limestone desert islands and islets that are surrounded by shallow sea and extensive seagrass and algae beds. These islands are important for breeding seabirds (world's largest colony of Socotra Cormorants, also Ospreys and Sooty Falcons). Also present around Hawar Islands are dugongs and sea turtles. Six of these islands have been designated as protected areas and access is limited. Some islands are hilly

with cliffs up to 20–30 m high, whereas others are flat and sandy with gently sloping shores. The largest of these islands is Hawar which covers an area of more than 40 km². Hawar Islands have been identified as one of two sites in Bahrain suitable for designation as a Ramsar Site and Important Bird Area. The shallow waters around the islands support a rich fishery and Arabian Oryx and the Reem Gazelle have been re-introduced.

Tubli Bay is an inshore coastal area situated in the north-east of Bahrain, characterized by mangroves, seagrass and corals. Around Tubli Bay, much of the coast is being reclaimed for urban development. Due to filling, the size of the Bay has decreased from 23.5 km² in 1956 to 16.1 km² in 1996. Tubli Water Pollution Control Centre discharges 160,000 m³ of treated effluent into the Bay every day. Sand washing plants which are the major source of siltation will

Table 15.4 List of Marine and Coastal Protected Areas in the Gulf Countries (The total area of the Gulf has been considered 251,000 km²)

Country	MPA site name	Location		Total area (km ²)	Management status	Legal status	Year	Total area of MPA (km ²)	% of Gulf area
		Latitude	Longitude						
Bahrain	Bulthama	26.53102	50.58307	NA	Protected area	Designated	2007	582.02	0.23
	Duwhat Arad	26.26666	50.61666	0.50	Protected Area	Designated	2003		
	Mashtan	25.80717	50.68183	0.02	Protected Area	Designated	2002		
	Hawar Islands	25.64305	50.76388	581.00	Protected Area	Designated	1995		
	Ras Sanad Mangrove	26.20000	50.50000	0.50	Strict reserve	Designated	1986		
Iran	Dayer-Nakhiloo	27.92162	51.67259	204.34	National parks	Designated	2008	7245.06	2.89
	Farur Islands	26.28356	54.51095	28.48	Protected Area	Designated	1987		
	Hara	26.84083	55.61611	865.81	Protected Area	Designated	1982		
	Hara, Gabrik and Jask	25.60861	58.26833	345.69	Protected Area	Designated	2001		
	Hara, Khoran	26.77777	55.39277	25.18	Protected Area	Designated	2001		
	Hara, Roud-e Gaz	26.32916	57.10861	169.14	Protected Area	Designated	2001		
	Hara, Tiab and Minab	27.09750	56.74303	412.58	Protected Area	Designated	2001		
	Hele	29.18573	50.80032	447.83	Protected Area	Designated	1976		
	Khark Island	29.32250	50.34944	20.82	Wildlife refuge	Designated	1975		
	Kharku Island	29.33459	50.35062	18.43	National natural monuments	Designated	2008		
	Mond	27.98027	51.42777	329.85	Protected Areas	Designated	2006		
	Nayband	27.31611	52.72777	476.87	National park	Designated	2008		
	Seraj	26.81304	53.69819	609.8	Protected Area	Designated	2000		
	Shadegan	30.50548	48.79840	3289.26	Wildlife Refuge	Designated	2001		
Shidvar	26.79388	53.41500	0.98	Wildlife Refugee	Designated	1975			
Kuwait	Doha	29.36666	47.81666	4.50	Protected Area	Designated	...	280	0.11
	Jal Az-Zor	29.66694	47.83305	250.00	National Park	Designated	1990		
	Khawr Mufattah	29.66694	48.40000	0.50	Protected Area	Designated	1990		
	Sulaybia Experimental Station SR	29.16694	47.66694	20.00	Scientific reserve	Designated	1979		
	Umm al-Maradim	28.66694	48.65000	5.00	National Park	Designated	1977		
Oman	Ad Dimaniyat Islands	23.83861	58.17111	203.00	Nature Reserve	Designated	1996	4,823.00	NA
	Jebel Samhan	17.51916	54.98222	4,500.00	Nature Reserve	Designated	1997		
	Ra's Al Hadd	22.37194	59.81722	120.00	Turtle reserve	Designated	1996		
Qatar	Khor Al Udeid	24.58333	51.33333	120.00	Fish sanctuary	Designated	1993	1,326.19	0.53
	Ras Ushairij	25.01111	51.14694	16.19	Gazelle Conservation Park	Designated	1991		
	Al-Dakheera				Protected Area	Proposed	2006		
	Umm Tais				Protected Area	Designated	2006		
	Al Reem			1,190.00	Biosphere reserve	Designated	2007		
Saudi Arabia	Jubail	25.50000	50.00000	2,300.00	Protected Area	Proposed	1994	2,300.00	0.92
United Arab Emirate	Jabal Ali Wildlife Sanctuary (D)	25.01666	54.93333	80.00	Wildlife sanctuary	Designated	1996	6,423.20	2.56
	Khor Kalba (Sh)	25.16666	56.36666	5.00	Nature reserve	Proposed	-		
	Marawah BR (AD)	24.31861	53.26972	4,255.00	Biosphere reserve (since 2007)	Designated	2001		
	Al Yasat (AD)	24.23339	52.01151	2,186.00	Managed resource PA	Designated	2005		
	Ras Al Khawr Wildlife Sanctuary (D)	25.19722	55.33333	6.20	Ramsar site	Designated	2007		
	Sir Bu Nuer (Sh)	54.21913	25.23316	13.20	Nature reserve	Designated	2000		
	Jazerat Al Hamra (RK)			5.00	Nature Reserve	Proposed	-		
	Khor Al Rams (RK)			4.00	Nature Reserve	Proposed	-		
	Khor Ras AL Khaima (RK)			6.00	Nature Reserve	Proposed	-		
	Dhadna (FJ)			0.10	Nature Reserve	Designated	1995		
	Al Aqa (FJ)			0.70	Nature Reserve	Designated	1995		
	Al Badia (FJ)			0.60	Nature Reserve	Designated	1995		
Al Faqeeq (FJ)			1.40	Nature Reserve	Designated	1995			
								22,979.47	7.23

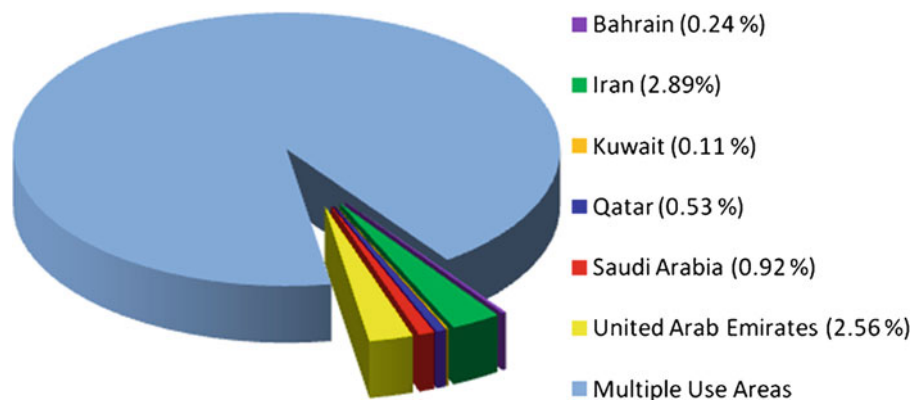


Fig. 15.2 Showing the marine protected areas of each Gulf country as a % of the total area of the Gulf

hopefully soon be banned from discharging in the bay. A stand of mangrove (*Avicennia marina*) is protected by the Public Commission for the Protection of Marine Resources, Environment and Wildlife (PCPMREW) at Ras Sanad in the SW of the Bay. This particular mangrove stand, estimated to be 430,000 m² in area, was designated as a nature reserve in 1986. The area is also a Ramsar listed site (Convention on the Conservation of Wetlands of International Importance especially as Waterfowl Habitat). The protected mangrove reserve at Ras Sanad has a vegetation cover of 100%. The average tree height recorded was approximately 4–5 m tall along the creek. The most common seagrass species in Tubli Bay is *Halodule uninervis*.

Fasht Bulthama is the most recent reef protected and is considered to be the healthiest coral reef of Bahrain. The reef falls within a broader protected area that also includes oyster beds, and is the furthest reef from the coast of Bahrain, thus reducing its vulnerability to coastal development. Protection is limited to a ban on trawling and the use of nets (Fig. 15.3).

15.3.2 Iran

The early efforts towards establishing MPA's in Iran dates back to 1950's. Later on in 1975, after standardization of the definition and criteria for selection and management of the MPA's by IUCN, the Department of the Environment (DOE) started to establish these areas in four separate categories. The latest information shows that Iran with its vast mainland so far has designated 150 Protected Areas, 35 National Natural Monuments, 42 Wild Life Refuge, and 26 National Parks; including 22 wetlands of international importance (Ramsar Sites), and 10 Biosphere Reserves, covering 166,767.34 km², or about 10% of the national land area (DOE 2011). In between the designated areas as MPAs, 15

are located along the Iranian coastline (Table 15.4). The total area of these coastal MPAs is 7,245.23 km² and accounts for the protection of 2.89% of the Gulf area (Fig. 15.2).

Coral reefs and Mangroves are the most important ecosystems along the Iranian coastline. Four of the designated regions (Nayband, Kharku Island, Khark Island, Farur Islands) are among the best coral areas in Iran and perhaps the Gulf with high coral coverage (Fig. 15.4) harboring hard coral assemblages and soft coral species.

The protected areas network (PAN) is the main tool for conserving and protecting biodiversity and nature in Iran. However, protected areas suffer from human pressure, especially the outlying parts. Iran recognizes the importance of the role played by protected areas, and aims, through its Ministry of Environment, at having at least 10% of its national land protected. Better integration between protected areas and surrounding zones is also under study and practical initiatives are being developed.

15.3.3 Kuwait

The State of Kuwait comprises the mainland and nine off-shore islands with a total area of 17,818 km², including the inhabited island of Failaka, the large low-lying muddy island of Bubyana near the mouth of the Shatt Al-Arab, and seven small coral islands mostly in the south. The terrain is flat or gently undulating, rising to a height of 271 m in the extreme southwest of the country. Kuwait's marine and littoral ecosystems contain the bulk of the nation's biodiversity heritage. Habitats of particular biodiversity importance and interest are the muddy intertidal shores, the sabkhas, oyster banks, sea grass and algal beds, the coral reefs and the open water habitats (Al-Rifaie 2007). Over 250 species of invertebrates, 105 species of marine plant and 240 species of fish are known, 95 of which are associated with coral reefs.



Fig. 15.3 Coral assemblages found in UAE. From *top to bottom*: *Top row*: dense table coral (*Acropora downingi*) thickets with interspersed massive corals like *Porites*. *Middle row*: dense thickets of the knob-coral *Porite sharrisoni* are among the most widespread and typical for

Western Abu Dhabi and Eastern Qatar. *Bottom row*: small massive corals, like these brain corals (*Platygyra*) occur widely on shallow hard grounds in varying density

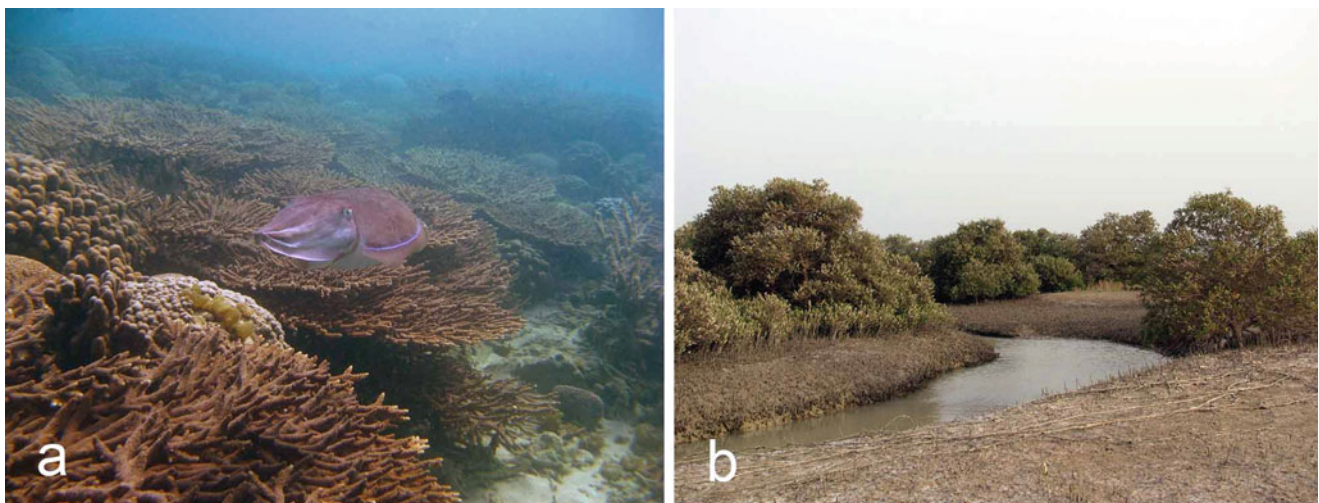


Fig. 15.4 Coral communities and Mangroves along the Iranian coastline; (a) *Acropora* dominant assemblages at Kharku Island (Photo: K. Samimi-Namin), (b) Mangrove vegetation of *Avicennia marina*, Mele Gonze, Bushehr province (Photo: A. Mobaraki)

Many marine species such as shrimps and grouper are of major importance for commercial and sport fishing. Many governmental and non-governmental organizations in Kuwait have mandates to use natural resources: Environment Public Authority (EPA); Public Authority for Agriculture and Fish Resources (PAAFR); Kuwait University (KU) and Kuwait Institute for Scientific Research (KISR) are responsible by Amiri Decrees for management, conservation and research on biodiversity in the State of Kuwait. Conservation of nature has been prominent in the environmental policy adopted by the Council of Ministers. The main law governing the conservation of natural habitats is Decree Law No.62 of 1980, which indicates a general policy for the protection of the environment and provides for designation of two categories of protected area, National Parks and Nature Reserves. Continuous human activities along the coastline have resulted in considerable disturbance to marine ecosystems. The extensive inter-tidal mudflats in Kuwait Bay have come under pressure from dredging and landfill for urban and industrial developments. Large quantities of sand have been removed from beaches for construction purposes. Some parts of the coastline are being destroyed by the disposal of untreated sewage, while other areas are being polluted by industrial effluents with high concentrations of ammonia, mercury and chlorine. Oil pollution as a result of accident oils pillage is a continuous threat, while pollution from the disposal of ballast water in inshore waters continues, regardless of the legislation which prohibits this. The last of Kuwait's coastal fringing reefs, which probably used to extend as far north as Ra's al-Ardh, is currently under threat from large-scale urban and industrial development. Nesting seabirds on the offshore islands are vulnerable to human disturbance, and there is a certain amount of shooting. Littering has also become a problem on some of the offshore islands because of their popularity for outdoor recreation.

Seven protected areas have been established out of 14 proposed sites. Five of these are marine and coastal of an area of 280 km² (Table 15.4) and account for a protection of 0.11 of the Gulf (Fig. 15.2). The Doha Nature Reserve, established in 1988, is located on the south side of Kuwait Bay. Its area of 4.5 km² has inter-tidal mud flats and sabkha with some reed-beds, important for migratory waterfowl during the migration seasons and in winter.

15.3.4 Oman

Oman's land consists of sand and gravel desert plains, mountain ranges and coastal lines. Despite its arid climate, it is an area of relatively high biodiversity, especially in the regions with a higher level of precipitations. Terrestrial biodiversity is an important component of Oman's biodiversity as rangelands and woodlands are found to harbor a diverse array of

plants (~1,208 species). The Sultanate is striving for the enhancement of protection of the environment and conservation of its natural resources and 6 nature reserves were proclaimed accounting for 9.6% of the total land area. Oman has also set up three marine and coastal protected areas on the Arabian Sea. These are Ras Al Hadd Turtle Reserve, Jebel Samhan and Ad-Dimaniyat Islands. On the Gulf side, Oman has not established protected areas, yet. The Musandam Peninsula just on the narrow entry of the Strait of Hormuz is considered as an important diving destination for its spectacular coral reef areas. The upwelling current mixes the deep cool water with the surface water and provides an abundance of plankton making this a rich feeding ground for a huge variety of marine life. The marine sites of Musandam have great potential to be included in the protected area network for conservation of coral reefs in the Gulf.

15.3.5 Qatar

The State of Qatar comprises the entire Qatar peninsula with an area of 11,586 km². The country has very little variations in its geography, most of the surface being plain with small, scattered carbonate mountains in the north (Dukhan area) and sand dunes in the south East (Umm saieed, Khor Al Odaid). The remaining areas have either stony (Hazm) or soft soil areas (Rowadh). Habitats found in Qatar include mangroves, sabkha, sand dunes, Hammada desert (rocks and gravel), rocky ecosystems, wadis and runnels, and depressions that collect fine sand. The marine and coastal habitats include sea grass beds, coral reefs, and mangrove swamps. Most coral reefs have been severely impacted by heat since the late 1990s (Chaps. 2, 5, and 6) and many have been degraded by coastal construction. Urban development, especially along the coastline, has emerged as a significant threat to the biodiversity of the country. Qatar has established 5 coastal and marine protected areas accounting for 1,326 km² (Table 15.4) which represents about 18% of the total area of Qatar and 0.53 of the Gulf (Fig. 15.2). Nearly all habitat types being represented in these protected areas, in addition to two new proposed sites for designation. Al Reem is designated as a Biosphere Reserve under the UNESCO Man and Biosphere Program (MAB) and includes mudflats and sea-grass beds. Limestone cliffs, mesas, wadis, sabkhas and gravel plains constitute the terrestrial site. Khor Al Odaid in the SE region has been assessed for its suitability as a World Heritage Site but has not yet been proposed. The site is a globally unique tidal lagoon inside an area of mobile sand dune, with parabolic dunes, rowdats, wadis, mesas and sabkhas and a seascape with coral reefs, seagrass beds, and algal mats. Al Dakheera in the NE is the largest mangrove forests in Qatar and a preliminary management plan has been developed to manage the coastal wetland system, khawrs

(embayments), mudflats, salt marsh, sabkha, coral reefs, seagrass beds, etc. of this area. The fauna includes over 130 species of birds, Hawksbill Turtle, Hooded Muttonbird, Spiny-tailed Lizard and 44 species of terrestrial insects. The mangrove *Avicennia marina* is a key plant species.

Qatar enacted the law concerning the protection of wildlife and their natural habitats in 2004 which provides a sound legal basis for the rehabilitation and management of wildlife habitats and empowers the wildlife department of the competent authority to propose suitable wildlife sites for designation as protected areas. However, an explicit provision for the designation of protected areas needs to be introduced in the legal domain. The law empowers the competent authority to prohibit or control activities that can cause damage to the habitat or the biodiversity therein, and requires it to protect the endangered species. Law enforcement in the PAs is done by the rangers of the Ministry of Environment who are employed for protection in ecologically important areas. Like coral reefs, mangrove coverage along the eastern shores of Qatar have significantly declined due to increased human activities.

15.3.6 Saudi Arabia

The Kingdom of Saudi Arabia is about 1,969,000 km² in area with territorial seas along the Gulf and the Red Sea. Fifteen protected areas cover almost 4% of the country's surface. The national system plan for protected areas has identified 13 marine and coastal sites for the development of protected areas but only Al Jubail on the Gulf side is proposed as a marine and coastal protected area since 1994. The proposed coastal area and Jubail group of islands are 2,300 km² (Table 15.4) and represent about 0.92% of the total area of the Gulf (Fig. 15.2).

A National Biodiversity Strategy for the Kingdom of Saudi Arabia was prepared for the Ministerial Council for consideration and approval. Its scope includes the protection, restoration, sustainable use, equitable sharing, and systematic monitoring of Saudi Arabia's biodiversity. It also looks at the Islamic visions and basic principles guiding the conservation of biological resources and sheds light on the fact that the conservation of the natural environment is an imperative command of Allah. The protection of the natural environment from abuse by man leads to the welfare of man himself together with that of all other beings. The strategic goals for the conservation and sustainable use of biodiversity in Saudi Arabia include in-situ and ex-situ conservation; both inside and outside protected areas to conserve and develop forest and woodlands, desert rangelands, living marine resources, and agricultural biodiversity. The protected area system plan regulates access to genetic resource and introduces national bio-safety standards; supports scientific research;

enhances environmental education; encourage collaborative management; promote cooperation for biodiversity; and generate income from wildlife resources and develop nature based tourism. The plan for implementation of the biodiversity strategy considers the necessity for involvement of the government agencies, non-governmental organizations, scientific institutions and local stakeholders in Saudi Arabia. Extensive national efforts are being exerted in the field of enhancing environmental education and public awareness, building capacity of personnel working in the conservation field, expanding establishment of new protected areas in accordance with the National System Plan, properly managing existing protected areas while recalling traditional practices of land use and encouraging sustainable use of natural resources in the country.

A national system plan for protected areas was developed in 1990 to cover at least 10% of the total Kingdom's area through a process that involved extensive field surveys and a wide range of consultations over a period of 2 years. The system Plan has identified 104 sites, terrestrial and marine, representing the key biotopes and landscape features and covering the habitats of critical species in the Kingdom. The individual nominated protected areas were all selected in accordance with a sound set of guidelines and criteria. Although, all declared protected areas are planned to conserve their biological diversity, only some of these protected areas are regulated and enforced. In formulating the management regime for protected areas, it has adopted several of the principles of the Hima system, the traditional system for sustainable management of natural resources.

15.3.7 United Arab Emirates

The United Arab Emirates (UAE) borders both the Gulf and the Arabian Sea, with coral reefs along both shores. Coral reefs abundantly occurred in the emirates of Abu Dhabi, Dubai, and the offshore parts of Sharjah. Rampant coastal development, driven by a strong aspiration to diversify the economic sources and decrease the dependence on oil as the major source of gross national product (GNP) is now posing a major threat to the very existence of coral ecosystems. The UAE has established 13 marine and coastal protected areas that cover 6,563 km² (Table 15.4). Their biggest, Marawah Marine Biosphere Reserve, covers 4,225 km². The first four marine protected areas in the UAE were established in 1995 on the east coast of Fujairah Emirate at Dibba, Al Faqueet, Dadna and Al Aqa. Abu Dhabi Emirate designated officially the Marawah Marine Protected Area in 2001, Al Yasat Marine Protected Area in 2005 and proposed Bul Syayef MPA in 2007. Marawah was included as the first Marine Biosphere Reserve in the country and the region.

Dubai had originally declared its Jebel Ali coral reef protected area in 1996, but this stretch of coast and reef has subsequently largely been lost due to coastal construction of artificial islands.

The guardian of Abu Dhabi's coral reef environment is the Environment Agency – Abu Dhabi (EAD) since its establishment in 1996. EAD has been proclaimed as the competent authority for the environment in Abu Dhabi Emirate and thus its mandates include adapting applied research, ascertaining procedures and processes for environmental management, quality control, and development. Magistrate power of juridical confiscation has been assigned to specific EAD staff for surveillance and control of Abu Dhabi's environment. Many coral reef areas are situated in private areas belonging to the ruling family and other dignitaries. These areas are managed by the relevant private offices. In the other Emirates, the guardians of the coral reef resources are usually situated within the municipalities and there is a need for strengthening the management capabilities for coral reefs. Of all Emirates, only Abu Dhabi and Dubai had mapped their coral reefs in their entirety and are therefore fully aware of the extent of the resource. In Dubai, management of the reefs is made complicated by the fact that they have been excised from the control of the municipality's environment department and responsibility was transferred to the major developers. Thus the state's influence on management decisions was greatly diminished. The two major Federal Laws 23 and 24 issued in 1999 constitute the basis of the legal framework for the protection of coral reefs. All trawling was banned, first in Abu Dhabi Emirate and in 2005 in the entire UAE. Although more than 10 federal laws and 20 Amiri decrees have been produced by the UAE since its creation in 1971, none of these laws and decrees provides a comprehensive framework for integrated planning and management of the coastal zone. As a milestone for the UAE, the first comprehensive Coastal Zone Management Law has recently been proposed for the Emirate of Abu Dhabi. Also, in 2008, a national coral reef conservation plan was developed for Abu Dhabi. In addition to the existing national legislation and conventions, the UAE have ratified a number of environmental strategies and action plans in the region, such as the "Regional Action Plan for the Conservation of Coral Reefs in the Arabian Seas Region" developed and the "Kuwait Action Plan". With their national legislation and regional agreements, the UAE disposes of the entire legal framework for an effective protection of their coral reefs. However, there is an urgent need to implement the integration of the environment and its preservation in the decision making at high local and/or federal levels in the development planning. To facilitate coral reef protection, a detailed mapping effort within EAD's Coral Reef Mapping and Assessment program has provided a synoptic overview and a map where exactly coral reefs occur in Abu Dhabi Emirate.

Commercial fishing is a significant challenge for conservation of coral reefs in the Gulf. A lively fishing industry locally owned but with expatriate fishermen, has increased in UAE waters over the last decades. Few of the fishing methods are sustainable and declines of some fish stocks around 80% were recorded (Chap. 8). Also significant depletion of pelagic fish stocks, with near-extinction of a locally endemic subspecies of sailfish as just one example, was caused largely due to fisheries activities in the nursery grounds of some species outside Gulf waters. These stock depletions may have knock-on effects on other Gulf ecosystems. While significant challenges to the conservation of the UAE's coral reef resources exist, progress has also been made. The quality of governance of coral reef resources, as well as public and official awareness of their value, has increased over the recent years. Industry has become actively involved in conservation efforts and the public is increasingly demanding conservation and responsible management of the natural resources. Despite the fast pace of its economic expansion and spectacular urban growth with concomitant development of infrastructure in the terrestrial and marine realms, the UAE is indeed making efforts to improve its record on coral reef conservation.

15.4 Future Prospect of Marine Conservation in the Gulf

For the past several years, the main efforts in the Gulf to maintain coral reefs have been through the allocation of MPAs which despite some successes has fallen short of their full potential. The management tools employed to protect Gulf coral reefs barely achieve conservation objectives and many coral reefs continue to degrade. Protection of corals must be more proactive (Rinkevich 2008) and it is important to stress the need for training and empowerment of more Gulf experts with a good professional background in ecosystem research, monitoring, and management, supported by understanding of environmental law and national socio-economic requirements. The universities have been established, the environmental awareness has been generated, but the participation of the local Gulf experts in the marine and coastal management, as well as cross-border research, is still weak. Efforts should concentrate both on how to conserve what is left (Young 2000) as well as on active efforts how to restore reef resources. Presently 'management' and 'conservation' is considered by many authorities in the region as synonymous. Rather than implementing active rehabilitation or conservation instruments, management concentrates on the act of managing from behind a desk. This has caused numerous setbacks to the adequate protection of corals. Ways forward have been discussed (Khan 2007; Nadim et al. 2008).

Corals of the Gulf thrive in extreme climatic conditions relative to other coral communities around the world and

have high resilience to natural and some man-made disturbances. The resilience of Gulf corals can probably best be sustained though retaining biodiversity in coral reefs and adequately incorporating corals from different reefs under a network of protected areas, or managed reserves (Levin and Lubchenco 2008). Many coral reefs of the Gulf are suffering impacts and stressors from 'avoidable' sources, mostly destructive fishing methods and sedimentation. To better tackle resilience building in an ecosystem that shares the interests of many societal sectors, marine spatial planning (MSP, Gilliland and Laffoley 2008) can contribute positively by addressing social, economic and environmental aspects within long term policy prospects. MSP can be applied over extensive periods of time and is responsive to changes in both the ecological and technological context. Many of the Gulf States have adopted economic strategies that span over the timeframe of decades (e.g. Bahrain Vision 2030 and Plan Abu Dhabi 2030). These economic strategies are based on the objective of strengthening economic resilience and reforms in several sectors of the economy. Though these plans are based on economics, they encompass other aspects such as urban planning and environmental conservation. Placing coral reef conservation in the broader context of strategic economic development on the national level will certainly empower authorities and non-governmental organization to engage more actively in shaping a better foundation for marine conservation. Early stages of a MSP have been drafted in Bahrain and Abu Dhabi as part of the economic vision, which is a testament of the opportunities strategic master planning can offer to coral reef management and conservation. Another strength that such protocols add to marine conservation is the ability to monitor and evaluate progress of interventions undertaken under the umbrella of the economic strategy, which has been overlooked in many coral conservation initiatives in Gulf.

The ecological services provided by the coral reef ecosystems in the Gulf have been ignored in the past development plans. However, the recent economic changes forced the strategic plans of the Gulf States to look into diversification

of the sources of national incomes and to consider different sources of income related to the environmental services. Coral reef conservation can indeed play an important role in economic diversification by supporting extractive and non-extractive uses, such as sustainable tourism activities. Gulf states have barely lived up to their responsibilities of conserving their marine environment and coral reefs and are therefore at threat of destroying a resource that could very much be used to their own benefit.

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Charles Sheppard, Mohsen Al-Husiani, F. Al-Jamali,
Faiza Al-Yamani, Rob Baldwin, James Bishop,
Francesca Benzoni, Eric Dutrieux, Nicholas K. Dulvy,
Subba Rao V. Durvasula, David A. Jones, Ron Loughland,
David Medio, M. Nithyanandan, Graham M. Pilling,
Igor Polikarpov, Andrew R.G. Price, Sam J. Purkis,
Bernhard M. Riegl, Maria Saburova, Kaveh Samimi-Namin,
Oliver Taylor, Simon Wilson, and Khadija Zainal

16.1 Introduction

The Gulf is located in a subtropical, hyper-arid region. It is shallow, and bordered by several wealthy states (Fig. 16.1) undergoing rapid economic growth involving substantial construction along shores and offshore regions, underpinned by its oil and gas industry, and by wealth derived from financial centres. Thriving economic activity has, over the

past few decades, begun to exert significant pressure on the Gulf's marine environment. It is changing rapidly, by developments which include construction, substantial coastline alterations, habitat loss, creation of beds of shifting or suspended sediments, and temperature and salinity changes in restricted water flows along the coast, as well as by climate warming. The Gulf suffers from a "shifting baseline syndrome" (Pauly 1995; Sheppard 1995) and it is difficult to find

C. Sheppard (✉)

University of Warwick, Coventry, CV4 7AL, UK
e-mail: charles.sheppard@warwick.ac.uk

M. Al-Husiani • F. Al-Yamani • J. Bishop • I. Polikarpov
Kuwait Institute for Scientific Research, Salmiyah, Kuwait

F. Al-Jamali
University of Qatar, Doha, Qatar

R. Baldwin
Five Oceans Environmental Services, P.O. Box 131, Muscat, Oman

F. Benzoni
University of Milano-Bicocca, Piazza della Scienza,
I-20126 Milano, Italy

Institut de Recherche pour le Développement (IRD),
101 Promenade Roger Laroque, BP A5, 98848, Noumea Cedex,
New Caledonia, France
e-mail: francesca.benzoni@unimib.it

E. Dutrieux
Creocean, Montpellier, France

N.K. Dulvy
Simon Fraser University, Burnaby, British Columbia, Canada

S.R.V. Durvasula
Dartmouth, Nova Scotia, Canada

D.A. Jones
P.O. Box 443, Ctra. Cabo La Nao (Pla) 124-6,
03730 Javea, Alicante, Spain

R. Loughland
AES International Consultants, Manama, Bahrain

D. Medio
Halcrow Group Ltd., Leeds, UK

M. Nithyanandan
Al Khiran Pearl City Project, La' Ala Al-Kuwait,
Souk Al-Kuwait Building, P.O. Box 22964,
Safat 13090, Kuwait

G.M. Pilling
CEFAS, Lowestoft, Suffolk, UK

A.R.G. Price
University of Warwick, Coventry, CV4 7AL, UK
e-mail: andrew.price@warwick.ac.uk

S.J. Purkis • B.M. Riegl
National Coral Reef Institute, Nova Southeastern University,
Dania Beach, FL, USA

M. Saburova
Institute of Biology of the Southern Seas, National Academy
of Science of Ukraine, Sevastopol, Ukraine

K. Samimi-Namin
Netherlands Centre for Biodiversity Naturalis, 2300 RA
Leiden, The Netherlands
e-mail: Kaveh_s_n@yahoo.com

O. Taylor • S. Wilson
Five Oceans Environmental Services, P.O. Box 131,
Muscat, Oman

K. Zainal
The University of Bahrain, P.O. Box 32038,
Sakhir, Bahrain

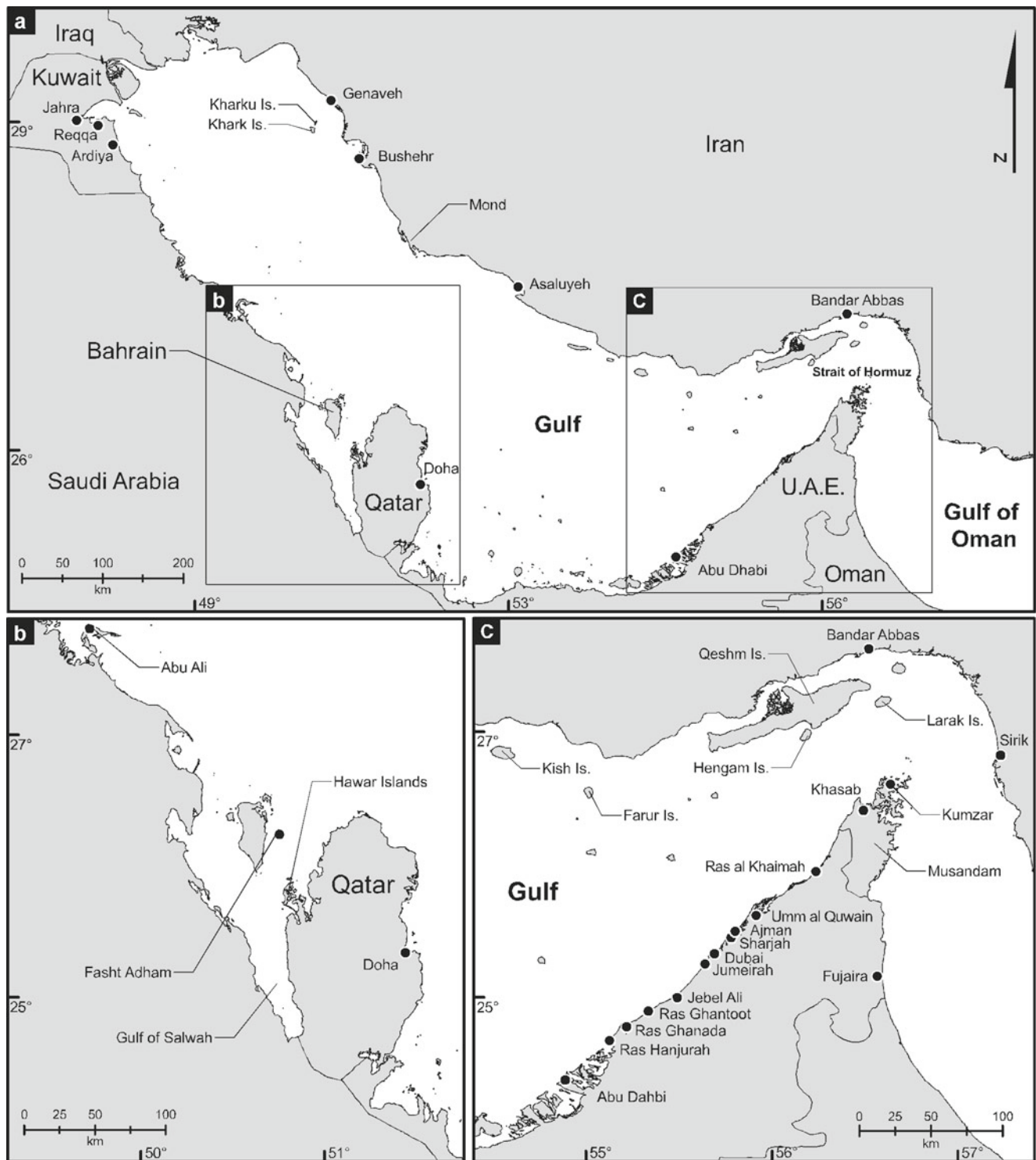


Fig. 16.1 Map of the Gulf showing place names and political boundaries

any meaningful baselines, not only because of ongoing, intensive constructions that cause large-scale alterations of the environment, but also because of several recent episodes of marine mortality from seawater warming.

Even without the enormous construction projects that have become common-place in most Gulf states, the accumulation of many smaller projects would still add up to

major changes. Many projects include 'baseline' surveys using a range of tools such as Environmental Impact Assessments (EIA), in which, typically, the existing habitat is examined and a judgement made on the extent of potential impacts, and proposals on how to reduce these and monitor them. But commonly, the science has the ability to advise only slight changes to a project, and what is often missed

also is that the ‘baseline’ chosen is little more than an already severely degraded marine ecosystem.

Many studies remain confidential for alleged commercial or security reasons, and there is too little sharing of environmental information in this sea area. This is, perhaps, one reason why Gulf marine ecosystems are so poorly contextualised, why synergies are poorly understood, and why cumulative and trans-boundary impacts are rarely considered. Because of this, some studies preceding developments today may provide deceptively little useful information on how much more stress a benthic habitat might tolerate, and confusion in terminology adds to ambiguity (Foden et al. 2008). Some planned constructions near or on Gulf coral reefs provide a good example, because their present condition is now so distorted that the study can provide no meaningful, scientific reference value. This article attempts to add context to such developments.

An overarching problem in assessing development impacts is the difficulty of adopting a synergistic or strategic approach. Of all the world’s multi-national bodies of water, the Gulf is both of a uniquely small scale and is almost enclosed. Despite efforts of the Regional Organization for Protection of the Marine Environment (ROPME), there is limited exchange of information among government agencies, projects or neighbouring countries. There remains a general resistance towards a holistic approach that looks not only at immediate impacts but also synergies with other projects close by, despite calls for greater integration such as advocated by Krupp (2006, 2008) for ‘Transboundary Diagnostic Analyses’, and a start made towards this essential aim.

Many new developments have very robust and well designed mitigation measures with, in some cases, state of the art monitoring programmes, but these might achieve little in terms of ecological sustainability because they are not encouraged or allowed to look at coastal development in a holistic or cumulative manner. This is recognised by Zainal et al. (2009) who has considered accumulated impacts over the last 40 years in Bahrain, and by Al-Yamani et al. (2001, 2004) who similarly assessed past, current and future integrated impacts on Kuwait’s marine environment. Some projects may eventually fail economically precisely because of their ecological shortcomings.

16.2 Topography and Oceanography Limitations

The Gulf is little more than 60 m deep and most of its area is less than half that. Its photic zone mostly extends to only 6–15 m. Only the Iranian shore has steeply sloping sections. The Arabian shore is more arid and has no permanent river input, consists mainly of carbonate sediments and has a very gradual slope (Seibold 1973). Limestone domes and some reefs give relief to the otherwise flat, mostly sandy sea bed that supports seagrasses, coral reefs, non-accreting coral communities, and algal beds, most of which intergrade with each other in many places.

High temperature and salinity of Gulf waters, combined with vigorous aeration of sediments by long-shore currents, causes much unconsolidated sediment to cement into hard-grounds by fibrous aragonite growth. Cementation may be rapid, requiring only months to a few years to develop. The resulting solid limestone provides habitat for hard substratum species, though sometimes the constant shifting of unconsolidated sand sheets can make new settlement difficult.

16.2.1 Natural Stresses: Temperatures and Salinity

The water temperature regime and elevated salinity of the Gulf are important environmental stressors, and warming enhances effects of pollution (Schiedek et al. 2007). Air and water temperature track each other strongly (Sheppard and Loughland 2002). The Gulf’s subtropical location means that it is warm enough to harbour a wealth of tropical biota both subtidally and intertidally, but its high-latitude location results in significant seasonal insolation fluctuations (Kleypas et al. 1999). Combined with atmospheric dynamics driven by cold winds (the Shamal) from the nearby Anatolian and Iranian highlands, this results in a marked amplitude of summer/winter temperature differences (Fig. 16.2 and Table 16.1).

High temperatures in summer and dry winds in winter create 1–2 m equivalent of evaporation per year, added to which is the general lack of precipitation. Salinity of >39 psu occurs in most Gulf waters. Much of the evaporation takes place along the shallow Arabian shorelines, causing increasing salinity and density currents which sink towards the northeast, eventually exiting the Strait of Hormuz in its deepest part (Hunter 1986). Replacement water flows in through the Strait of Hormuz in surface levels, passing inwards along the Iranian coast before reaching the Arabian coasts in a broadly anti-clockwise flow (Fig. 16.3). The mass water balance is given in Table 16.2. Several complications to this pattern are caused by, for example, the projection of Qatar into the central part, but the general pattern appears to be clear. Low flushing rates in major embayments such as the Gulf of Salwah south of Bahrain lead to salinities of over 70 psu (see also Chap. 2). It has been proposed that propagules of corals, fishes etc. from outside the Gulf reach the Iranian shoreline first, and then circulate towards the Arabian States (Sheppard et al. 1992).

16.2.2 Historical Ecological Constraints

At the start of the Holocene, the basin was almost completely dry, so its marine history is only ~15,000 years (see also Chap. 3). Seabed presently at depths of 4–6 m has only been submerged for 3,000–4,000 years, so modern benthic habitat development is comparatively young. The most extensive high-diversity marine environments in the Gulf are coral

Fig. 16.2 Sea surface temperature from central Gulf (Hadisst1 data). 1 × 1 degree lat/long block whose top left corner is 57 N, 52 E. *Central line* is 12 month running mean

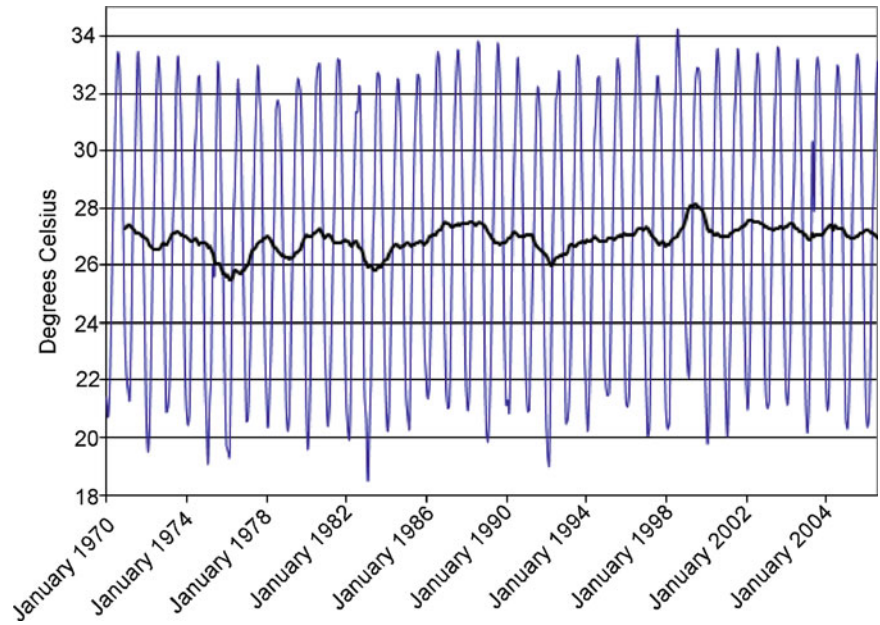


Table 16.1 Temperature extremes recorded from Arabian coral reefs or from limestone platforms supporting coral communities (From Sheppard et al. (2010). By permission of Elsevier)

Location	Latitude (N)	Min °C	Max °C	Range	Source
Saudi Arabia	27	11.4	36.2	24.8	Coles and Fadlallah (1991)
Qatar	24	14.1	36	21.9	Shinn (1976)
Abu Dhabi	25	16.0	36.0	20.0	Kinsman (1964)
Kuwait	29	13.2	31.5	18.3	Downing (1985)

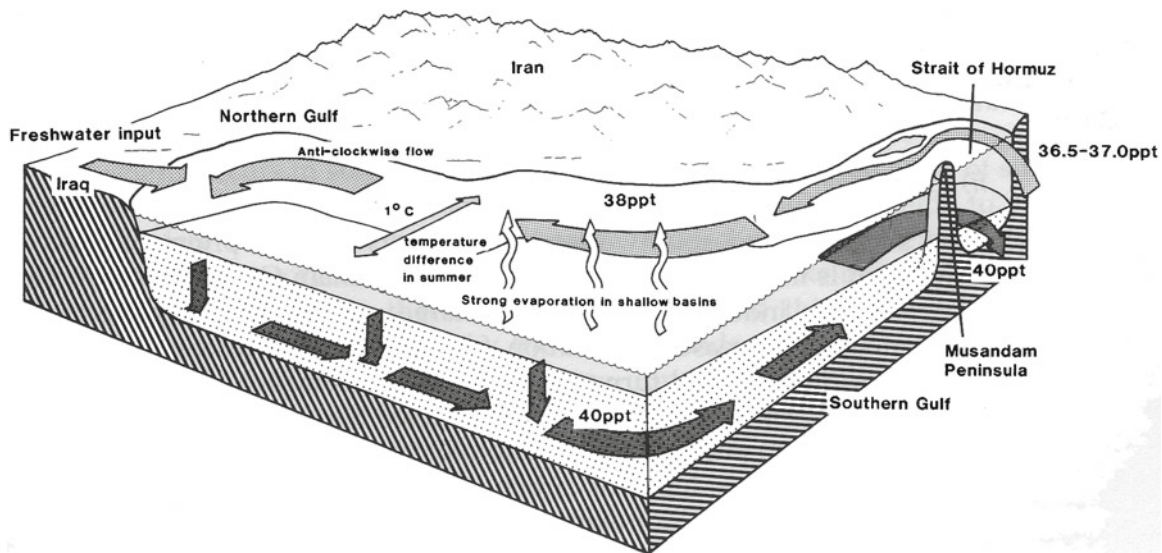


Fig. 16.3 Major current flows in the Gulf (From Sheppard et al. 1992). Mechanisms causing the density gradient in the Gulf and the flow through the Straits of Hormuz. *Light arrows* are incoming surface

water from the Gulf of Oman. *Dark arrows* are a denser, deeper water flow. *Light shading* in Gulf shows “wedge” of water of increasing density

Table 16.2 Estimates of the water, dust and sediment budgets for the Gulf. All aquatic discharge values are in $\text{km}^3 \text{ year}^{-1}$ (From Wright (1974), Saad (1985), Reynolds (1993), Akmansoy (1996), ROPME (1999), Johns et al. (2003), Hashim and Hajjaj (2005), Al-Yamani et al. (2008a, b); From Sheppard et al. (2010). By permission of Elsevier)

	Volumes	Depth equivalent
Water flows		
Total volume	~8,600 km^3	
River discharge	35–133 $\text{km}^3 \text{ year}^{-1}$	0.2 m year^{-1} depth
Surface inflow at Hormuz	7,250 $\text{km}^3 \text{ year}^{-1}$	
Deep outflow	6,620 $\text{km}^3 \text{ year}^{-1}$	
Net evaporation	~350–800 $\text{km}^3 \text{ year}^{-1}$	1.67 ± 0.39 m year^{-1}
Industrial discharges cooling water etc ^a	>7.3 $\text{km}^3 \text{ year}^{-1}$	0.02 m year^{-1}
Sediments		
Dust storms input	60–200 × 10 ⁶ t year^{-1}	
River sediment input	62.4 × 10 ⁶ t year^{-1}	

^aThis waste water is mostly not new input, but is recycled from intakes. Note that although this overall value of 2 cm appears relatively small, it is not evenly spread but is concentrated in near-shore, shallow localities

reefs and coral dominated substrata of hardgrounds, seagrass meadows and algal beds. At species level, the Gulf, on many counts, is biologically impoverished (see also Chaps. 11, 12, 13, and 14), partly because of its short age, but mostly, because of harsh environmental conditions. Low species richness was reported in early studies (Basson et al. 1977), and was confirmed by most later research, for most major benthic groups such as corals and echinoderms (Sheppard et al. 1992; Price 1982). Recent assessments of fish have raised earlier estimates to 542 species (Krupp et al. 2000) though the total number may be well over 600 (Price et al. 2002), while groups such as ocyrodid crabs may be surprisingly species rich (Al-Khayat and Jones 1996). For reef building corals, the Gulf is an impoverished subset of the Indian Ocean (Sheppard 1998), ranking 24th out of 26 Indian Ocean sites in terms of species richness (see also Chaps. 11 and 12). In contrast, population *densities* of several groups are comparable to those of other tropical areas.

16.3 The Main Reefal Habitats and Species Groups

16.3.1 Corals, Coral Reefs and Diagenetic Hardgrounds

Many of the ‘coral reefs’ described for the Gulf are areas of hard substratum which are not actively accreting but are modern veneers of living coral on much older limestone domes or recently formed diagenetic hardgrounds, many of which are visually indistinguishable from true reefs (Shinn 1969) (Figs. 16.4 and 16.5). These together with the relatively few true reefs provide the most diverse habitats, though not necessarily the most productive. They have been subject to the most research (Table 16.3). Most of the 55–60 coral species are found widely in the Indo-west Pacific, but the closest faunistic proximity to other coral areas unsurprisingly is the Arabian Sea and Red Sea (Sheppard and Sheppard 1991; Wallace 1999; Veron 2000) due to a shared

paleoceanographic history of restriction during the last sea-level low stand and simultaneous flooding during the Holocene transgression (Sheppard et al. 1992). There are few or no endemic corals in the Gulf; some previously thought to be endemic also occur in the Gulf of Oman (Claereboudt 2006), a situation which also probably applies to fish (Krupp, personal communication).

The total reef extent and coral diversity may be highest along the Iranian shore, but throughout, many corals have been killed by warming episodes, which are predicted to increase in severity and frequency (Sheppard 2003). Scleractinian corals off Kish and Larak Islands have been used for investigating the predominance of clade D (heat tolerant) *Symbiodinium* and its possible relation to high or extreme temperatures (Ghavam Mostafavi et al. 2007). Some Iranian coral communities are unique: Samimi-Namin et al. (2009) describe one at Larak Island which is partly intertidal with a particularly high tolerance to exposure. In the last 15 years there has been a general sharp decrease in living coral cover over most of this region (Rezai et al. 2004), with an accompanying modification of coral species distribution.

Along the Arabian peninsula, coral assemblages show best development offshore, but there are important fringing systems too (in particular Abu Dhabi, Qatar, Saudi Arabia). Reef development is patchy, but is of ecological interest given the stresses they encounter and competition from other benthic groups. At Umm al Quwain for example, coral patches are limited (less than 10 species and 0.01% cover) and hardgrounds are mainly occupied by very extensive algal reefs, mangrove and seagrass habitats surrounded by a 30 km long sand spit. Similarly most sites visited in the Emirate of Ras Al-Khaimah have shown only occasional (<10 species and <0.01% cover) corals, being dominated instead by tidal lagoons, with high cover by muddy and sandy substrata with mangrove and seagrass habitats.

Many older ‘reef’ descriptions, however, are increasingly invalid following recent mortalities from massive developments and from warming water during the past 15 years. Mass mortality events, especially in 1996 and 1998, affected

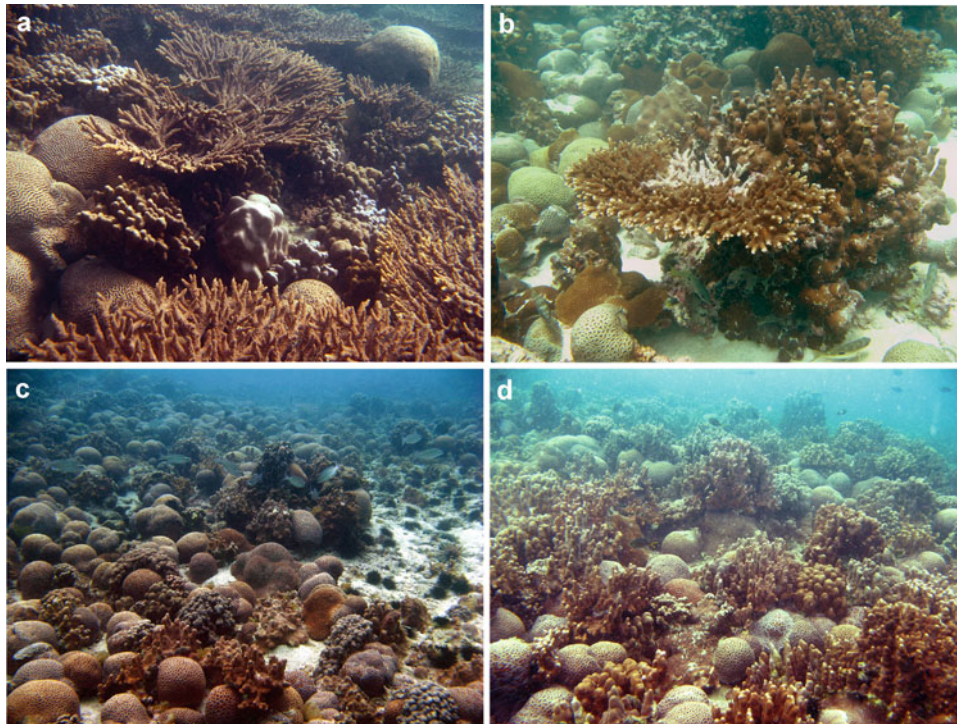


Fig. 16.4 (a) Healthy fringing coral assemblages, east side of Kharku Island, near the most western boundary of developed coral communities in the northern part of the Gulf, 7–9 m depth (Photo: K. Samimi-Namin) (b) fringing reef regenerating its *Acropora* cover after the bleaching disturbances between 1996 and 2002 near Ras Ghanada, Abu Dhabi (Photo: B. Riegl) (c) Juvenile faviids showing healthy recruitment. Healthy fringing coral assemblages, faviidae

dominant, western side of Kharku Island, the most western boundary of developed coral communities in the northern part of the Gulf, 9 m depth (Photo: K. Samimi-Namin). (d) Healthy fringing coral assemblages, faviidae and *Porites* equally dominant, western side of Kharku Island, the most western boundary of developed coral communities in the northern part of the Gulf, 9 m depth (Photo: K. Samimi-Namin)

species differentially (Shinn 1976; George and John 2006; George and John 2006; Riegl 1999, 2003; Purkis and Riegl 2005; Wilkinson 2008). Detailed studies in Dubai showed six species of *Acropora* temporarily disappeared after the 1996 temperature anomaly, but these regained a foothold 10 years later. The two main warming events in 1996 and 1998 (Fig. 16.2) removed mainly the shallow *Acropora* species, but while they have shown some recovery, especially in offshore locations, faviid corals and *Porites* are now achieving spatial dominance in perhaps most mid depth areas (Figs. 16.6 and 16.7), changing the nature and overall rugosity of the reef.

Qatar has seen striking coral decline, a condition typical of the Gulf generally (Fig. 16.5). Recent (2007–2008) surveys found only 20 species of hermatypic coral, and only five species (three genera) at the offshore island of Halul (SCENR 2007, Qatar Ministry of Environment in press). Twenty five years ago, *Acropora* was “very common” in the west and north coasts of Qatar (Emara et al. 1985), and it was even recorded in the Gulf of Salwah (Sheppard 1988). In 2007 and 2008, however, extensive surveys found living *Acropora* only at Halul Island, and the previous presence of staghorn corals along the mainland coast could only be inferred by

dead colony fragments in the rubble. Genera like *Montipora* and *Pavona*, once abundant around Qatar (Emara et al. 1985), no longer appear to exist (*Montipora*) or are very rare (*Pavona*). Further south on the east coast of Qatar hard corals are now largely absent from inshore areas; surveys in 2005 and 2007 recorded much long dead *Porites* with *Acropora* rubble, and only occasional *Siderastrea* and faviids. In deeper water (10–12 m) on flat hardgrounds in non-reef settings, reef dwelling genera (*Anomastrea*, *Turbinaria*) are found in several areas.

Most shallow coral reefs around Qatar are now covered in thick algal turf. The remnants of the previous high coral cover are found as rubble or lie beneath a thick layer of crustose coralline algae (CCA). These secondary carbonate producers (Perry et al. 2008) dominate over corals.

At the extreme eastern entrance to the Gulf, in Musandam, coral communities survive in much better condition. Around Khasab and Kumzar, they are still dominated either by high cover of Acroporids including *Acropora pharaonis*, *A. valida* and *A. arabensis*, interspersed by assorted faviids or, where rock shelves are narrow and shaded, by extensive overlapping *Platygyra daedalea* interspersed with occasional *Stylophora*, *Porites* and small branching *Acropora*. In many

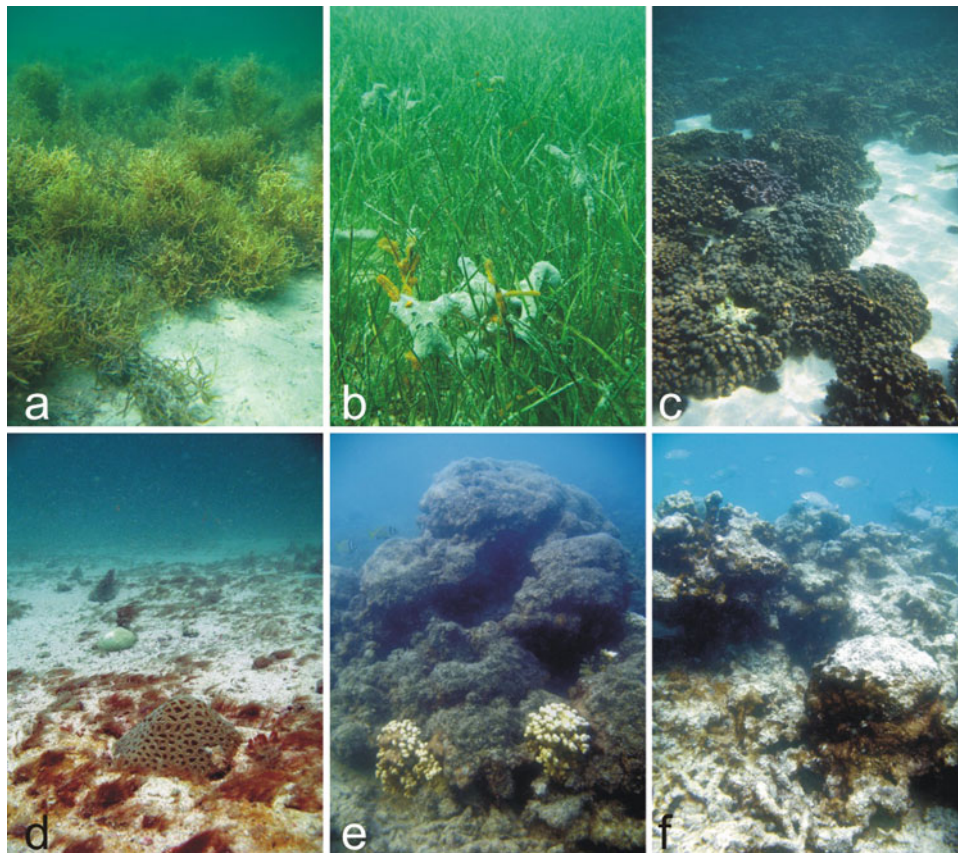


Fig. 16.5 The main subtidal benthic assemblages found in Qatar: (a) bed of brown alga *Hormophysa* in the northern Gulf of Salwah (4 m); (b) seagrass (*Halodule*) with sponges (light blue) and colonial tunicates (orange) growing on the leaves of the marine plants (6 m); (c) high cover monospecific patch of *Porites cf. harrisoni* in Halul Island (2 m); (d) scattered coral colonies growing on flat hardgrounds off the northern tip of the Qatari peninsula (12 m); (e) two living and partially bleached *Porites harrisoni* colonies growing on a dead coral community covered in algal turf (4 m); (f) dead massive and branching corals covered in sediment and algal turf devoid of any living coral colonies for tens of square metres (2 m) (Photo: Francesca Benzoni)

Table 16.3 Some recent atlases, sketches and descriptions of Gulf reefs, and publications with lists of species. Includes some older but key works (From Sheppard et al. (2010). By permission of Elsevier)

Location	Reports of reef distributions and component corals
General	Sheppard and Wells (1988), Sheppard and Sheppard (1991), Sheppard et al. (1992, 2000), Pilcher et al. (2000), Spalding et al. (2001), Wilkinson (2008), Fadlallah et al. (1993), Carpenter et al. (1997a), Fatemi and Shokri (2001), Wilson et al. (2002), Coles (2003), Rezai et al. (2004), and Reefbase http://www.reefbase.org
Iran	Harrington (1976), Harger (1984), Rezai (1995), Shokri et al. (2000), Samimi-Namin et al. (2009), and Samimi-Namin and van Ofwegen (2009a, b)
Kuwait	Downing (1985, 1992), Fadlallah et al. (1993, 1995), Hodgson and Carpenter (1995), and Carpenter et al. (1997b)
Saudi Arabia	MEPA/IUCN (1987), Krupp et al. (1996), Basson et al. (1977), Vogt (1996), Fadlallah et al. (1993, 1995), and Loughland and Abdulkader (in press a, b)
Bahrain	Alkuzai et al. (2009), Fadlallah et al. (1993, 1995), and Loughland and Zainal (2009)
Qatar	Fadlallah et al. (1993), Shinn (1976), SCENR (2007), and Qatar Ministry of Environment (in press)
Abu Dhabi	Hellyer and Aspinall (2006) (incl. several chapters by D. George and D. John) and Emirates Heritage Club (2004)
Dubai	Riegl (1999, 2003), Riegl et al. (2001), Purkis and Riegl (2005), and Purkis et al. (2005)

instances coral cover can exceed 50–80% over small areas, providing a basis for relatively diverse fish and invertebrate assemblages.

Once thought to be largely absent, octocorallia are now being discovered in greater abundance than previously

expected, and so far 35 species of octocorals in 24 genera have been identified from the Gulf (Samimi-Namin and van Ofwegen 2009a; Chap. 12). While several authors reported occasional soft coral species, most provide little information (Thomson and Simpson 1909; Stiasny 1940; Burchard 1979;

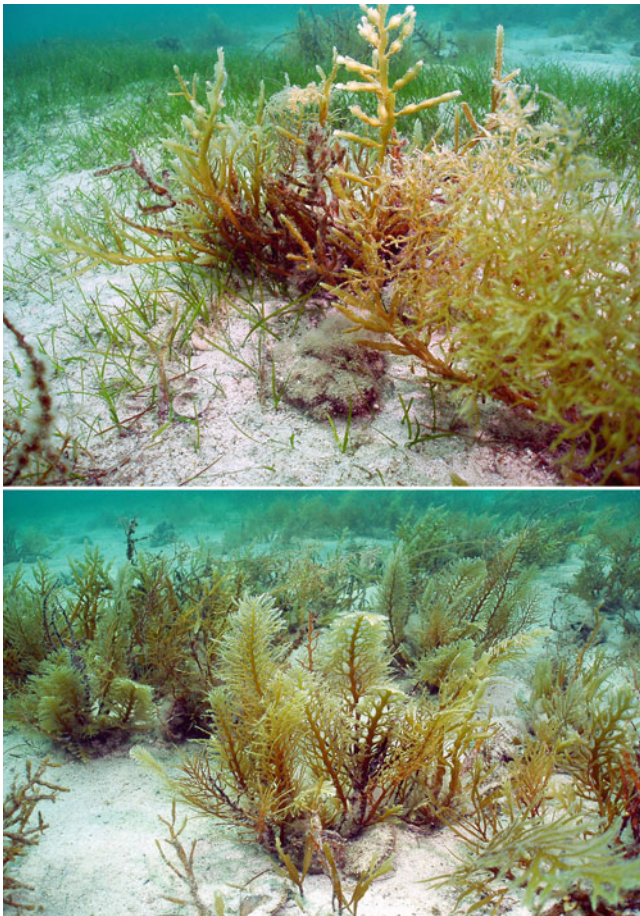


Fig. 16.6 Typical algal beds of the Gulf (Fasht Jaradah, between Qatar and Bahrain) 3–5 m depth. *Top*: The phaeophytes *Sargassum* sp and *Hormophysa*. Note intermixed seagrasses. *Bottom*: *Sargassopsis decurrens* and *Hormophysa cuneiformis* on hard substratum concealed by a thin layer of sand (Photos Charles Sheppard)



Fig. 16.7 *Ulva* on Kuwait Bay shore, April 2008. During winter and spring time, seaweeds cover the shallows and sandy and mud shores after storms in Kuwait Bay, giving rise to detrital food chain at supralittoral and sublittoral zones (Photo by Igor Polikarpov)

Rezai 1995), though George (2006) is a useful exception. The striking *Dendronephthya* occurs in the east, as does the precious black coral *Antipathes* in Musandam (Sheppard et al. 1992). Several species occur around Iranian islands (Rezai 1995, Rezai et al. 2004; Samimi-Namin and van Ofwegen 2009a, b) including the alcyonaceans *Sinularia* and *Sarcophyton*, sometimes in high abundance. Their distribution is mainly limited to the eastern Gulf and they have not reached further west than Farur Island on the Iranian side, suggesting an ecological barrier to their distribution. They may be the dominant components in some coral communities, and some live in the low inter-tidal zone (Samimi-Namin et al. 2009). Being zooxanthellate species, they are found only shallower than 10 m depth where there is sufficient light. Azooxanthellate pennatulacea and gorgonians can be found in deeper waters (<10 m depth) where suitable substrata exist. No reef building hydrozoa are known to occur but the gorgonid *Menella* is fairly conspicuous at least to the mid-Gulf deeper reefs.

16.3.2 Macroalgae

More widely distributed, but in the same zone as coral reefs, macroalgal meadows (Fig. 16.6) are a major sublittoral habitat on limestone mounds and hardgrounds. These usually have patches of sand which commonly support seagrasses in intermixed assemblages (Fig. 16.6 top). Where seagrasses are sparse, macroalgal beds are the primary habitat for all organisms requiring plants for shelter. Algae meadows also co-occur with seagrasses and corals, and all these habitats are not mutually exclusive in the Gulf (Fig. 16.6 bottom). Large *Sargassum* beds commonly dominate offshore domes of limestone which otherwise appear relatively depauperate, developing to maximum extent in winter (John and George 2003). Dense *Hormophysa* beds occur around the SE Gulf, along with the coral *Siderastrea savignyana*. These large phaeophytes are rarely consumed directly by herbivorous animals, but their substantial volume and subsequent decay provides considerable input into the microbial loop. During winter and spring, especially after a storm, *Ulva* are washed upon sandy and muddy shores in many areas such as Kuwait Bay (Fig. 16.7), giving rise to further input to the detrital food chain in both supralittoral and sublittoral zones.

16.4 Pressures on Fisheries

Fishing makes an important contribution to food security in Gulf countries and has historical and traditional significance as well as being a source of recreation (see also Chap. 8). Commercial vessels tend to target shrimps and pelagics, while artisanal fishers tend to focus upon predatory demersal

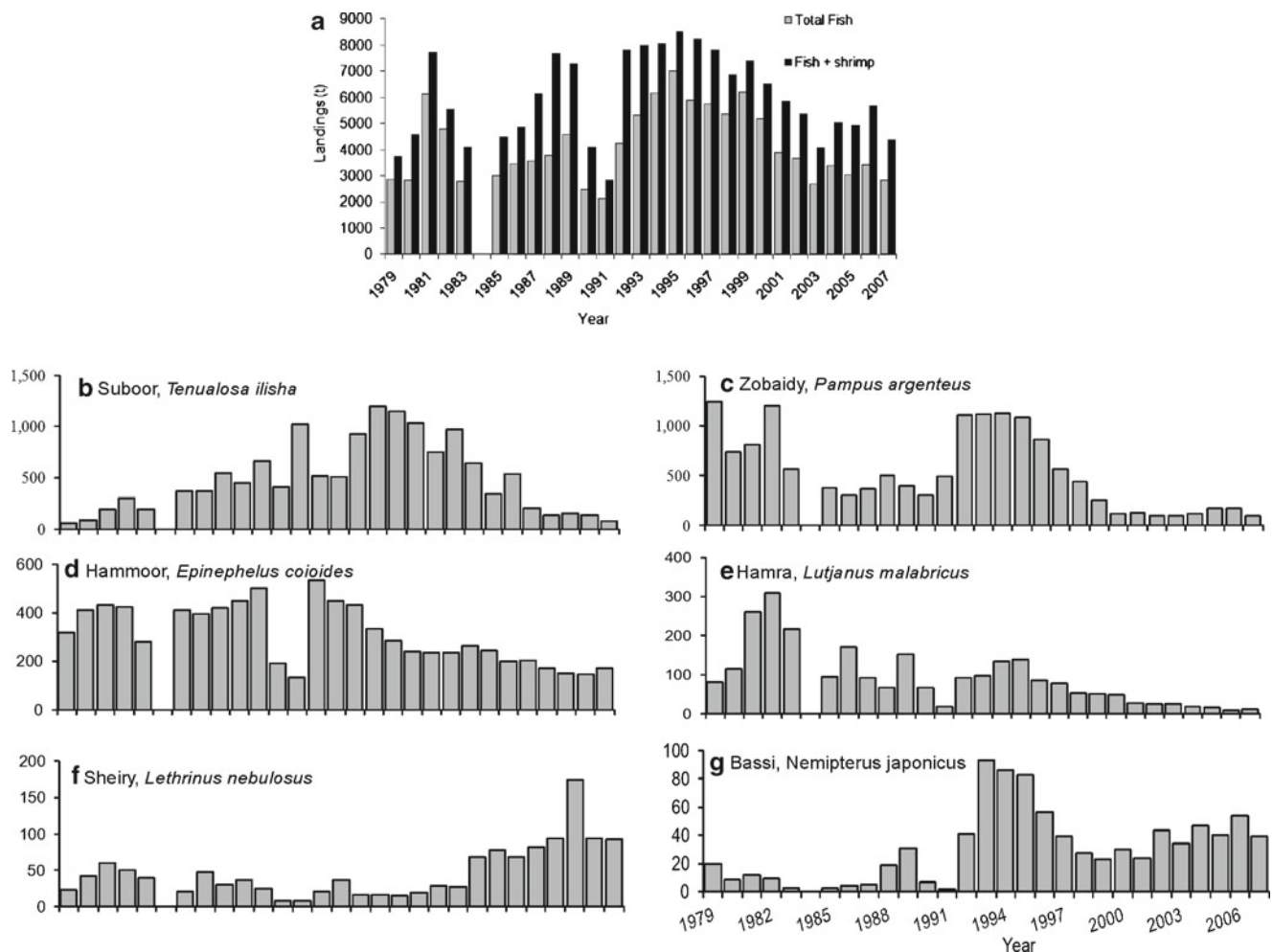


Fig. 16.8 (a) Kuwait's landings of fish and fish and shrimp (total) from 1979 through 2007 (Data from CSO 1979–2007). (b–g) Kuwait's landings of selected species from 1979 through 2006 (Data from CSO 1979–2007)

species (groupers, emperors) using gillnets, traps ('gargoor'), staked nets (hadra) and handlines (De Young 2006).

Saenger (1993) and Bishop (2002) have shown a link between the permanent loss of intertidal and shallow subtidal nursery grounds with declining fish and shellfish catches. Data from two areas clearly show very substantial declines in commercial fish over the past 10–20 years, following growth of this industry in the period 1970s–1990s.

Kuwait's total fisheries landings initially fluctuated to about the mid 1990s during its expansion phase, but have steadily declined thereafter, such that landings in 2007 were less than half their peak 1995 level (Fig. 16.8). The large fluctuations in 1990 and 1991 were affected by the Iraqi destruction of many fishing vessels. Since 1979, finfish have accounted for 49–87% of the total landings, with the remainder being primarily penaeid shrimp (CSO 1979–2007).

Probable reasons include overfishing, nursery ground destruction, and reduced discharge of the Shatt Al-Arab (discussed later). Particularly hard hit are species directly affected

by the Shatt Al-Arab discharge, such as the anadromous *Tenualosa ilisha* and estuarine-dependent *Pampus argenteus* (Fig. 16.8b, c). From 1995 to 2007, landings of the former decreased 93% from 1,197 t to just 78, while the latter decreased 91%, from 1,128 to 101 t. These two species accounted for 32% of Kuwait's total finfish landings in 1995, but in 2007, they accounted for 6%. Other important species in decline are *Epinephelus coioides* and *Lutjanus malabaricus*, whose landings decreased 68% and 92% respectively (Fig. 16.8d, e).

Circumstantial evidence shows a relationship between the decreased landings of these species and the decreased river discharge, although overfishing is undoubtedly important. The changed salinity conditions have been favourable for other species: sport fishermen report catching *Lethrinus nebulosus* in Kuwait Bay, a species formerly confined to Kuwait's southern waters. Commercial landings of this species from 1994 to 2007 increased from 17 to 92 t, an increase of 441% (Fig. 16.8f). Another species whose landings have increased since the mid 1990s include *Nemipterus japonicus*

Table 16.4 Biomass density estimates (t. km⁻²) of demersal species (based on trawl surveys) from the current survey and the demersal fisheries survey of 1978 (FAO 1981) (Taken from Shallard and Associates (2003a, b); From Sheppard et al. (2010). By permission of Elsevier)

Fish group	1978 biomass (t km ²)	2002 biomass (t km ²)
Non-commercial	2.0 – 3.0	0.44 – 0.53
Commercial	2.0 – 3.0	0.26 – 0.65
Total fish	4.0 – 6.0	0.70 – 1.18
% of 1978 biomass present in 2002		
Non-commercial fish	19.4% (18 – 22%)	
Commercial fish	15.2% (13 – 22%)	
Total fish	18.8% (17 – 20%)	

(Fig. 16.8g). However, these total amounts are low and do not offset losses of the others, including some of Kuwait's most esteemed fishes.

In the UAE, fish stock assessment surveys conducted in 2002–2003 showed significant differences relative to comparable surveys conducted in 1978 (see also Chap. 8). In this location there are no estuarine effects to complicate the patterns seen. Table 16.4 compares biomass data for several groups in 1978 and 2002 (Shallard and Associates 2003a, b; EAD 2008), in which data are broken down into at least eight genera or Family groups. In summary, using the total measured commercial and non commercial species, biomass in 2002 was only 18.8% of that in 1978 (range 17–20%).

In both areas, overfishing because of increased demand, as well as changes to essential habitats including, in the Kuwait case, reduced river water input, appear to be the causes of the large declines.

16.5 Consequences of Climate Change

16.5.1 Temperature Anomalies and Reef Associated Invertebrates

The effects of the anomalously high sea surface temperatures in 1996 and 1998 especially (see Fig. 16.2) and the massive coral mortality that arose from them, is increasingly well documented (Riegl 1999, 2002; George and John 1999; Sheppard and Loughland 2002; Purkis and Riegl 2005; Riegl and Purkis 2009). Other events occurred in 2002 and 2010, but caused less coral mortality (see Chaps. 5, 6, and 7). These events affected all species groups associated with corals; previously thriving *Acropora* reefs disappeared at least locally and temporarily at <4 m depth as did many associated live sponges or other large invertebrates. In many cases, almost no reef fish remained at all over many hectares. Deeper than about 4 m, many reef areas still supported numerous small coral patches and colonies unaffected by bleaching. Several years after these disturbances, some areas remained unchanged

while others showed significant recovery of coral cover (>50% at times). But significantly, many recovered shallow reefs became dominated by faviids and poritids instead of the previous *Acropora* (see Fig. 16.4; Riegl 2002, 2003; Chap. 5). This does not apply to all locations, however; in locations from Musandam to Kuwait, *Acropora* sp. and Pocilloporidae now thrive in many locations (Benzoni et al. 2006), and in several offshore areas *Acropora* have also recovered their former abundance. Marine life mortality from these warm episodes thus showed some regional differences, probably related to patches of persistent cooler water.

16.5.2 Harmful Algal Blooms (HABs), Degraded Water Quality, and Marine Mortality

Where conditions of high surface water temperatures, low wind speeds, light and nutrient levels combine, harmful algal blooms can result (Al-Aarajy 2001; Heil et al. 2001; Glibert et al. 2002). On their decay, the algae reduce dissolved oxygen, resulting in significant fish kills (Al-Ansi et al. 2002). Toxins produced by the algae may also kill fish and can accumulate in shellfish (e.g. paralytic shellfish toxins; Glibert et al. 2002) with the potential to poison consumers. Warming water temperatures may lead to increases in the frequency and severity of fish kills associated with plankton blooms.

The frequency and severity of HABs is increasing and examples being reported from almost all areas of the Gulf. Increased nutrient levels around fish cages used in mariculture may contribute. In Kuwait Bay for example, mariculture led to a HAB incident in 1999 (*Karenia selliformis* and *Prorocentrum rathymum*) that affected both caged and wild fish resulting in a major fish kill (Al-Yamani et al. 2000). Again in 2001 another fish kill was caused by discharge of ~30,000 m³ untreated sewage water during an abnormally hot and humid summer with very low wind speed and low mixing of the water column. Most probable cause of the mortality was bad water quality that affected the immune system of the marine biota, resulting in infection by the pathogenic bacterium *Streptococcus agalactiae* (Jafar et al. 2009). Elsewhere in the Gulf, HAB incidences accompanied by massive fish kills are known from Abu Dhabi, Dubai, Ajman, Fujairah, Iran and Oman during August 2008-May 2009. The main HAB species causing the marine mortality has been identified as *Cochlodinium polykrikoides* (see also Chap. 7).

16.5.3 Potential Impacts of Climate Change on Fisheries

Many Gulf fishery species are in severe decline (Chap. 8). Projected temperature increases as well as habitat changes can affect distributions, migrations and abundance of fish

stocks, and coastal and inland fisheries (Allison et al. 2009). For exploited species, the impacts of climate change include effects on individuals (Wood and McDonald 1997), populations (Cushing 1982; Edwards and Richardson 2004, Chap. 9), and ecosystems (Feeley et al. 2004; Harvell et al. 2002). Such effects likely coincide with more general warming-related changes in habitat quality and productivity which affect fished species and fisheries, e.g. in the event of coral reef loss (Hoegh-Gulberg 2005; Graham et al. 2006). Gulf fish species are notably hardy, but tend to show high fidelity to specific sets of environmental conditions.

In the Gulf, average projected air temperature rises by the end of the century are around 2–4°C (Meehl et al. 2007). Precipitation is expected to increase slightly overall (Meehl et al. 2007), but outputs from rivers entering from the Shatt Al-Arab are expected to decrease (Milly et al. 2005, and see later). Mud flats, many of which are being ‘reclaimed’ are important nursery ground for some species (Wright 1988; Bishop and Khan 1991; Al-Yamani et al. 2008a), and their biology and recruitment, at least in the northern Gulf, is affected by the level of discharge from the Shatt Al-Arab (Wright 1988; Morgan 1989; Ye and Almatar 2003).

Climate change impacts on primary production will also affect fish and fisheries production (Cushing 1982; Jennings et al. 2008). Decreased primary production in some regions (Sarmiento et al. 2004; Behrenfeld et al. 2006), and altered timing can be critical to fish recruitment success. Peak fish spawning events may be coincident with periods of high zooplankton abundance (Houde et al. 1986), while recruitment success may also be related to temperature and salinity conditions at the time of spawning (Wright 1988). Changes in timing of annual recurring life cycle events such as spawning could lead to a decoupling or mismatch between predatory fish and their prey resource, affecting population dynamics and abundance.

Because fishing increases the sensitivity of fish populations to climate change (Rindorf and Lewy 2006), reduction of current overfishing will improve resilience, at least in the short term. However, the reduction in the diversity and abundance of smaller reef fishes (Graham et al. 2006, 2007) and the increase in human population which causes an increasing demand for fish, further increases the unsustainability of coral reef fisheries of the Gulf.

16.6 Diversity and Robustness in the Gulf

Given the rates of change and levels of stress encountered in the Gulf, the extent to which different measures of biodiversity are related to resilience or robustness of the system, or other indicators of ecosystem functioning is unclear and requires urgent attention (Pimm et al. 2001; Price 2002). Conceptually, high b-diversity areas might be envisaged as

having several distinctive ‘compartments’, each containing a particular and perhaps semi-autonomous suite of species or assemblages; this might be either taxonomic, or have a functional standpoint (e.g. variety of feeding types or ability to absorb shock). Systems characterized thus, particularly with limited connectedness between compartments, have high modularity: this is one hallmark of resilient or robust systems (Walker and Salt 2006). This may certainly be the case in corals where two distinctive guilds have very different dynamics in reaction to stress (Riegl and Purkis 2009; Chap. 5).

Diversity in the Gulf is naturally influenced by spatial scale which will inevitably be reduced in smaller areas compared to that in oceanic basins (Warwick and Clarke 1995). This can create difficulties when comparing the Gulf’s diversity with other areas. For example, echinoderms, a group that has been comprehensively studied (Price and Izsak 2005), show a species richness which is lower than that in the Red Sea at four different spatial scales, though species richness correlated positively with spatial scale in both regions (Table 16.5). Further, when size of water body was compensated for in a recent study of 2,894 species of marine algae from 66 sites in the Indian Ocean region, the Gulf overall ranked 62nd out of 66 (Price et al. 2006). Thus it is relatively species poor for this group too. However, the diversity of macrozoobenthos (270 species) is relatively high while the level of dominance is low (Al-Yamani et al. *in press*).

β -diversity, or change in species composition along a spatial gradient may, in contrast to other measures, may be relatively high in the Gulf (Table 16.6). In this respect, the Gulf shares certain ecological features with other ‘stressful’ environments which are characterized by harsh conditions and low species richness, yet which tend to have high levels of β -diversity (Price 2002).

On the basis of species richness alone, which is the measure favoured by global conservation programmes and most ecologists, the Gulf has sometimes been perceived as unimportant. Yet with an expanded view of biodiversity, incorporating for example β -diversity and taxonomic distinctness (a relatedness measure), the Gulf’s status improves. Like rarity, taxonomic distinctness is relatively uninfluenced by spatial scale and sampling thoroughness (Izsak and Price 2001). Values of taxonomic distinctness in echinoderms are very similar for the Gulf and the Red Sea over all spatial scales (see Table 16.5), for example. Similarly, taxonomic distinctness of algae is exceptionally high, at least for certain sub-regions of the Gulf (Saudi Arabia, Bahrain and Kuwait), in contrast to patterns of species richness.

Whether marine environments exhibiting high β -diversity, like the Gulf, are more resistant to specific or multiple disturbances is considered to be a priority research objective.

Table 16.5 Comparison of biodiversity of echinoderms in the Gulf and Red Sea according to one or more values of species richness (SR), endemism and taxonomic distinctness (Δ^*) at different spatial scales (From Price and Izsak (2005); From Sheppard et al. (2010). By permission of Elsevier)

Scale	Arabian Gulf			Red Sea		
	SR	Endemism (%)	Δ^*	SR	Endemism (%)	Δ^*
P	2–10 ^a	0	3.83–4.90 ^a	17 ^b	0	4.610 ^b
	1–8 ^a	0	3.00–5.00 ^a	26 ^b	0	4.400 ^b
S	16 ^c	0	4.508 ^c	53 ^c	<1	4.546 ^c
	16 ^c	0	4.475 ^c			
	22 ^d	?	4.546 ^d			
L	55 ^f	2 ^h	4.546 ^f	176 ⁱ	5.3	4.529 ⁱ
	c. 66 ^g	7.5		139 ⁱ	5.1	4.588 ⁱ
B				114 ⁱ	7.3	4.450 ⁱ
	101 ^j	12	4.572 ^k	235 ^l	10.4	4.528 ^l

P Point, S Sample, L Large area, B Biogeographical province

^aRange of values from separate (qualitative) sampling units from 8 intertidal sites in Tarut Bay, Gulf coast of Saudi Arabia, during 1945–1947 and 1977 (Computed from Price (1981))

^bValues for 2 transects ~ 500 m, one in the Gulf of Suez and the other in the northern Red Sea (Data from James and Pearse (1969))

^cValues for pooled (qualitative) sampling units from eight sites in Tarut Bay during 1945–1947 and 1977 (Izsak et al. 2002)

^dValues for pooled triplicate 0.1 m² coastal benthic samples using box scoops at eight subtidal sand/seagrass stations in Safaniya/Manifa area of Gulf coast of Saudi Arabia (From McCain (1984))

^eValues from collections in Sharm Obhur creek, Red Sea coast of Saudi Arabia (From Tortonese (1979))

^fValues for Gulf coast of Saudi Arabia (Price 1981)

^gValue for the Gulf coast of Iran (From Hedging (1940), Mortensen (1940), Price and Rezai (1996))

^hAssuming the *Amphiura* ?sp. nov. reported from Manifa on the Gulf coast of Saudi Arabia was actually a new species (Price 1981)

ⁱValues for the Red Sea, Gulf of Aqaba and Gulf of Suez respectively (From Price (1982))

^jValue for whole Gulf (From Price and Rezai (1996))

^kValue for whole Gulf (From Izsak et al. (2002))

^lValues for whole Red Sea (Including Gulfs of Aqaba and Suez; from or computed from Price (1982))

Table 16.6 Biodiversity in the Gulf and other stressful marine environments, showing various measures of biodiversity on ordinal scale (From Price (2002); From Sheppard et al. (2010). By permission of Elsevier)

Environment/ ecosystem	Element of biodiversity			
	SR	Endemism	Δ^*	B-diversity
Gulf	+	++	–	+++
Estuaries	+	+	–	+++
Hydrothermal vents	+	+++	+++	+++

+ low, ++ moderate, +++ high, – insufficiently known, SR species richness at small and large spatial scales up to biogeographical province for the Gulf, and at smaller scales (sample species richness) for estuaries and hydrothermal vents, Δ^* taxonomic distinctness

16.7 Stresses from Developments and Discharges

Massive coastal habitat modification by dredging and converting shallow, productive marine areas into land for homes, recreation and industrial facilities causes significant and important threats to the sustainability of all Gulf ecosystems (Bishop 2002; Khan et al. 2002; Khan 2007; Jones et al. 2007; Munawar et al. 2002; Zainal et al. 2009). By the early 1990s, over 40% of the coast of most Gulf States had been subjected to modification resulting in significant loss of

biodiversity and productivity (Al-Ghadban and Price 2002). This loss of habitat is now expanding even more rapidly with increasingly ambitious projects including causeways and artificial islands (Erdelen 2007). Many projects involve massive deposition of material into shallow waters, resulting in replacement of several square km of productive tidal flat by inert fill material. Creation of offshore islands and structures has involved destructive dredging of seagrass and algal and coral beds whose ‘reclaimed’ material, taken from ‘borrow pits’ then further destroys other areas onto which it is dumped. Areas with constricted water flow, such as Dubai Creek, have become polluted, with grossly changed fauna (Saunders et al. 2007). In addition, there is some unpublished evidence that some of these developments (e.g. the Palm developments in Dubai Emirate) may have caused significant increases in coastal erosion in neighbouring Sharjah as well as localised changes to sea surface temperatures as a result of significant discharges of hot water associated with their infrastructure. Solid fill causeways and barriers greatly interrupt longshore water and sediment movements, leading in many cases to further armouring to counter undesirable and sometimes unexpected consequences of earlier work. Furthermore, there is reason to believe that a system of causeways currently planned in parts of the Gulf may potentially lead to habitat fragmentation of very sensitive and

endangered species such as the Dugong. Al-Jamali et al. (2005) cite other examples of poor construction design leading to coastal habitat degradation. Probably no other sea area of this size in the world is affected by such a high intensity of coastal manipulations. Numerous authors have remarked on the damage being caused, and most also caution that coastal resources must be accorded much more recognition and attention if their remaining areas are to survive and provide beneficial goods and services.

Diversity and productivity of fisheries also are particularly threatened by these activities. Permanent loss of intertidal and shallow subtidal nursery grounds due to converting shallow sea to land contributes to declining fish and shellfish catches (Saenger 1993; Bishop 2002). Primary productivity in intertidal and unimpacted shallow subtidal habitats is six times higher than that in offshore waters (Jones et al. 2002). For most Gulf States, coastal habitats are less than 20% of the total sea area, yet their ecological value, especially seagrass and tidal flats, is 40–75 times greater than open ocean (Costanza et al. 1997; Balmford et al. 2002). There is little ecological value to saline desert or urban development, yet developers prefer the coast and shallow seas rather than sites further inland because of the increased value of water-front property.

16.7.1 Coastal Developments

High-profile and large-scale developments have occurred all along the Arabian coastline (see also Chap. 10). From having low and largely rural populations 50 years ago, high indigenous birth rates and a shift to urban areas have greatly increased total and localised populations, added to which is immigration of labour which in some countries has increased populations several-fold. Sometimes developments have been spectacular and dramatic, such as in Dubai, but ports, airports and coastal industry (e.g. Khalifa Port in Abu Dhabi and New Doha International Airport in Qatar) may have consequences to coastal and offshore ecology equally important.

In Dubai, much of the coastline was originally fringed by relatively dense coral growth. In the 1990s, dense coral existed between Ras Ghantoot and Jebel Ali, off the Deira corniche, and wide rubble fields today indicate previously dense coral off the Dubai aluminium smelter. In Jebel Ali these were verified to be in good health in 2005 (Purkis and Riegl 2005; Purkis et al. 2005) but likely met their demise sometime shortly prior to 2007 when construction gathered pace. During the 1980s and early 1990s, heavy industry, shipping and increasing effluents from desalination and electricity generation exerted a smaller toll on the coral reefs than natural temperature variability. In the late 1990s, construction was begun on the Jumeirah Palm, in an area that

harboured dense pearl-oyster beds, some seagrass and algae, but no coral reefs. In 2004, work began on the Jebel Ali Palm which is now situated over what was previously the Gulf's second most biodiverse and documented ecosystem. Although the extent of the coral reefs was known from 1995 onward, adjustments in construction layout were only introduced at a late stage, cause severe losses in the core coral reef area.

From detailed previous research in Dubai during the 1990s and early 2000s (Riegl 1999, 2003; Riegl et al. 2001; Purkis and Riegl 2005), it is known that 34 hard coral species occurred between Jebel Ali and Ras Ghantoot. The largest impacts on coral diversity, until the construction of the Jebel Ali Palm, came from sea surface temperature anomalies of 1996 and 1998. Selective mortality removed all *Acropora* from the system for several years. Subsequent strong regeneration has led to reestablishment of much of the fauna along this substantial stretch of coast, including outside the footprint of the Jebel Ali Palm. This suggests that the coral communities here are very robust, with a resilience that evolved in step with repeated heat stress events.

A further major dredge and fill project, the Deira Palm, will cover a coral area that was, until the late 1980s, the location of some good *Acropora* growth, but which was already impacted by construction of the Deira corniche. With the enormous expansion of Dubai, development has moved into Sharjah, Umm al Quwein and Ras Al-Khaimah, where major coastal developments are planned or are in early phases of construction.

The Emirates of Umm Al-Quwain and Ras Al-Khaimah have limited coral growth. However, they do have several examples remaining of unique, pristine and highly complex systems of inter-tidal, sub-tidal and terrestrial habitats: two of their main sites (Khor Qurm and Ras Al-Beidah) are undergoing or have been proposed for large scale coastal developments. Important ecological features include a wide range of marine and inter-tidal assemblages; extensive mangroves; high numbers of marine turtles and birds; and widespread sea grasses with a good water quality and rich and varied benthic life. As a result the Umm Al-Quwain site in particular is considered one of the most important bird areas of the Middle East and was classified as a Globally Important Bird Area by Evans (1994) and an Important Bird Area of Middle Eastern importance.

These Emirates presently contain extremely rich and unusually unimpacted marine and nearshore environments which, aside from presenting a high level of biodiversity, clearly play a crucial role in many marine processes within their borders and beyond. This should be borne in mind when considering developments beyond their borders as well as within, given the extent of coastal modifications already undertaken and planned. This kind of holistic approach has largely been lacking.

Table 16.7 Original size of Bahrain and its expansion since 1963 (From Zainal et al. (2009); From Sheppard et al. (2010). By permission of Elsevier)

Period	Area km ²
Original land mass (1963)	668
Additions:	
1963–1977	13
1977–1982	1.5
1982–1989	20
1989–1997	9
1977–2004	16
2004–2006	10
2006–2008	22

One of the largest and hitherto least impacted high-diversity habitats in the UAE is situated at Ras Ghanada. Around this headland, mangrove-lined creeks, dense seagrass beds and an extensive coral area are found, and the area is important for foraging green and hawksbill turtles and coastal and marine birds. It is the only area in the southwest Gulf that has as many high-diversity habitats in such close proximity. This area is threatened by a major port development between Ras Ghanada and Ras Hanjurah.

Nowhere has coastal alteration been more marked than in Bahrain. The Kingdom itself has expanded its land area into shallow water by 91 km² from 668 km² in 1963 to 759 km² in 2007, an increase of 11% (Table 16.7) (Zainal et al. 2009). Further, the area dredged for material has severely damaged or destroyed an additional several hundred square km in the sea to the north of the Kingdom. From ten of the projects where data exists 153 km² shallow marine habitat has been lost from the dredging and fill combined (Zainal et al. 2009). In both excavation and filled areas, sediment plumes of unmeasured size have covered equally significant additional areas for extended durations.

The dredging, from areas sometimes euphemistically named ‘borrow pits’, and its deposition on shallow habitat to form land land, doubtless combined with temperature stress, has also caused the complete demise of the largest single reef in the area, and possibly once the largest in the Gulf. Fasht Adham with other smaller detached sections (with different names) extended from eastern Bahrain into Qatari waters. In the 1980s it was a rich reef with high coral cover of 50–75% in most measured locations (Alkuzai et al. 2009), while today it supports almost no living coral at all (Fig. 16.9). The limestone substratum is composed of dead coral skeletons covered with sediment and fine filamentous algae. Its demise was attributed to a combination of the warm water events of 1996 and 1998, together with coastal engineering works which added significant levels of stress through sedimentation. To seal the demise of this once rich reef, the Qatar-Bahrain Causeway is in its final stages of design. The 40 km long mixed road and rail causeway-

bridge will link Bahrain to western Qatar using Fasht Adham. About half of this length will be solid fill, leaving only the remainder as bridge (Zainal et al. 2009). This causeway east of Bahrain would be the second linking Bahrain to a neighbouring state, the other being the existing one on its western side connecting it to Saudi Arabia.

Many key issues are being investigated regarding the causeway, including potential modifications to currents, sediment transport and effects on seagrass beds, algal reef habitats and dugong populations. But while these issues are being investigated by the developer, regulators and other relevant government departments in both Bahrain and Qatar, what is missing in this and other major developments may be the ability to deflect such high-prestige developments completely if or when it is found that their environmental costs are too high. For the total Gulf system, cumulative effects may be greater than the effects of any one development alone.

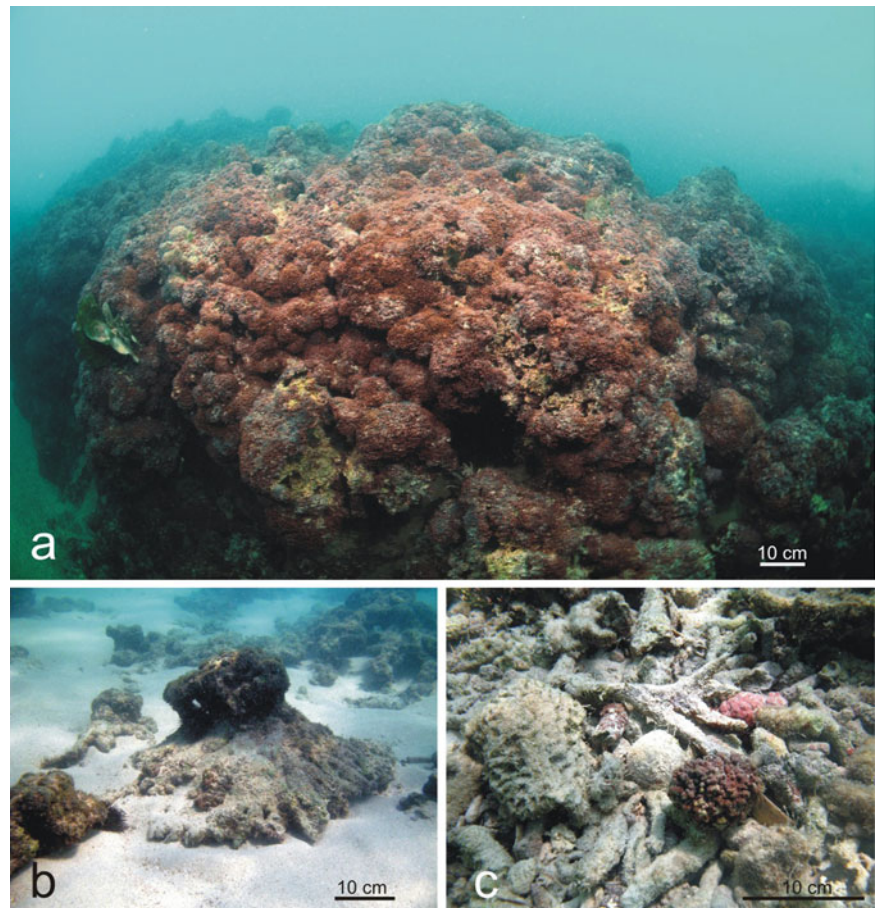
It is self evident that Gulf coral and seagrass species have a relatively higher thermal tolerance compared to other Indo-Pacific species (Hughes et al. 2003): only the ‘toughest’ few have ever occurred in the Gulf in any case. Coral species killed in 1998 in the central Indian Ocean, for example, include about 20–30 species found in the Gulf which survive temperatures 2–3°C higher every year without being killed. However, the combined stresses of increasing temperatures and anthropogenic impacts mean that even these ‘toughest’ of habitats are proving to be decreasingly productive and resilient. The resulting declining trajectory is already clear and well advanced. Despite their relative thermal resilience, predictions of climate change suggest that the maximum thermal tolerance thresholds for these species will be chronically exceeded in future (Hoegh-Gulburg 1999). Additionally, climate change-induced ocean acidification is likely to reduce the calcification rates of all calcifying organisms too (Caldeira and Wickett 2003; Hughes et al. 2003; Veron et al. 2009) and in the Gulf these include several important algal species as well as corals.

In many instances, if there had been better site selection (i.e. if ecologically poor sites which abound were selected rather than rich ones), and if there was better, long term synergy/strategy in development, the Gulf could probably achieve the desired development without so many local examples of important loss.

16.7.2 Oil Pollution

The Gulf has about 800 offshore oil and gas platforms and 25 major oil terminals. About 25,000 tanker movements sail in and out of the Strait of Hormuz annually and transport about 60% of all the oil carried by ships. These resources are so valuable to consumer countries as well as producers that, in a recent series of reports analysing the full social cost of car

Fig. 16.9 Shift from coral to crustose coralline algae dominated benthic assemblages: (a) a crustose coralline algae dominated reef south of Fasht al Dibal (5 m); (b) dead and toppled *Acropora* colony in a shallow lagoon off the north coast of Qatar (2 m); (c) living crustose coralline algae rhodoliths (pink) and dead coral rubble and, a large *Platygyra* fragment is recognisable on the left hand side, and a large branching *Acropora* fragment in the top-centre of the image (Photo: Francesca Benzoni)



use in USA, Delucci and Murphy (2008) showed that the economic cost to the United States of defending the Gulf's oil reserves and supply infrastructure is US\$3–30 billion per year.

Activities associated with oil traffic include shores heavily contaminated with oil residues, tar balls and trace metals. About 2 million barrels of oil are spilled annually from the routine discharge of dirty ballast waters and tank washing, partly due to the lack of shore reception facilities. Toxicity and physical damage from clean-up operations, remains a problem, though responsible and appropriate use of dispersants and sorbents can result in substantial benefits (Kirby and Law 2008). An additional source of oil pollution is the estimated 6–8 million barrels spilled into the Gulf during the Iran/Iraq war (Price and Robinson 1993); some habitats of Kuwait and the northern half of Saudi Arabia were extensively affected.

Oil pollution accounts for 0.5–1.51% total organic carbon (TOC) compared to the 0.5 natural background level. Data by Al-Ghadban et al. (1994) showed an increase in TOC to 2.8%, which results in shifts in planktonic populations from diatoms to flagellates, dinoflagellates and benthic algae. Besides increasing primary production, benthic algae may

out-compete corals and other reef-building organisms (Pastorok and Bilyard 1985). Spilled fractions of deposits may persist for many decades (Owens et al. 2008).

The enormous volume of ballast water from tankers may have introduced exotic biota; for example there has been an increase in recorded dinoflagellate species from <40 in 1931 to ~200 species in 1996 (Subba Rao and Al-Yamani 2000). A programme is underway to investigate this subject in more detail (Clarke et al. 2003)

16.7.3 Discharges from Desalination and Other Industry

Desalination has an environmental cost (Purnama et al. 2005). The combined seawater desalination capacity in the Gulf countries exceeds 11 million m³ per day which is 45% of the total world capacity (Lattemann and Höpner 2008), equivalent to 15% of the former flow of the Euphrates. Saudi Arabia, Kuwait and the UAE have the largest installed desalination capacity in the Gulf with a production of about 1.8 km³ year⁻¹ (Hashim and Hajjaj 2005). This industry returns to the Gulf over 7 km³ year⁻¹, using 2005 figures

(Table 16.3). This water may be brine (from desalination plants), is commonly hot, and often also contains pollutants including biocides introduced to prevent pipe and conduit biofouling. Extreme aridity and unfavourable geology result in these countries not having suitable alternative sources of potable water for domestic and industrial use. For example 90% of Kuwait's potable water is derived from desalinating seawater (Darwish et al. 2008), and this level of dependence is seen throughout the region.

Sewage is discharged to such an extent in the north of the Gulf to have been implicated in the shift in the dominant forms of plankton. For example about $23 \times 10^9 \text{ m}^{-3} \text{ day}^{-1}$ wastewater and $0.003 \times 10^6 \text{ km}^{-3} \text{ day}^{-1}$ sanitary wastewater are dumped into the Gulf (Al-Muzaini and Hamoda 1998). Three Kuwait coastal suburbs Ardiya, Jahra and Reqqa discharge $0.282 \times 10^6 \text{ m}^{-3} \text{ day}^{-1}$ (Al-Muzaini et al. 1991). The organic content of the sewage dumped into Kuwait waters also has a relatively high organic content.

Discharges of heated water into the Gulf are massive, from discharges from >55 desalination plants as well as power stations and heavy industrial facilities. In Kuwait alone $33.6 \times 10^6 \text{ m}^{-3} \text{ day}^{-1}$ chlorinated cooling water and 17 metric tonnes of residual oxidants are discharged (Al-Mutaz 1991). These can cause elevations of 5°C and 3 psu above ambient into waters which are already warm and highly saline (Linden et al. 1988). These values can be compared with the volumes naturally exchanged, input and evaporated in the Gulf (Table 16.3). Their effects are sometimes assessed in a local sense, but not on a Gulf-wide basis.

16.8 Positive Examples and Limitations

Some developments limit impact and in some cases coastal development can provide new opportunities for reefal biota. Recolonisation of hard corals onto breakwaters has occurred at some of the Dubai Palms, where rocky reef ecosystems are developing with sometimes good cover but with a lower diversity than is found on natural reefs nearby (Burt et al. 2009, Chap. 10). In Qatar, translocation of coral colonies from sites near the New Doha International Airport and from gas facilities at Ras Laffan to existing reef habitats offshore in Qatar has been successful, which has led to increased interest in coral transplantation.

There remains the dilemma of whether new habitats can equal those destroyed by developments in terms of size, diversity, resilience and 3D complexity, or whether they simply aim to meet certain simplistic criteria recommended by present, non-holistic (i.e. project by project) EIA processes (Chap. 10). In the case of coral colonies transplanted in Qatar, the venture is apparently a success. In the case of more complex and extensive reef habitats such as Taeweelah (Abu Dhabi) and other well studied reef areas mentioned

above, there is no possibility that whole integrated reef systems could be moved *in toto* to offset developments. In many cases, artificial substitutes are vastly smaller than the damaged areas they are supposed to replace. The approach in some cases has been to negotiate the best possible location for the proposed development and to develop and implement robust, science based monitoring programmes, but the drawback to the latter is that monitoring can do nothing useful if the results are not acted upon, as has too often been the case once a project has started.

As noted earlier, better site selection, coupled with appropriate design, can achieve both economic and ecological goals. While some developments have demonstrated that it is possible to create new marine productivity in desert areas of low ecological value, the question must also be asked if these man-made habitats are more or less resilient to environmental stress than those they have replaced.

16.9 Ongoing and Proposed 'Mega Projects'

Two major projects or proposals are in one case well underway and, in another case, speculative and futuristic, but with much about it already written. Both could result in enormous increases to Gulf salinity, above the already high existing level.

16.9.1 Damming of the Tigris and Euphrates: Turkey's Southeastern Anatolia Project (GAP)

The Tigris and Euphrates join in southern Iraq and, along with the Karun River, drain through the Shatt Al-Arab into the Gulf. This, together with other smaller rivers, adds the equivalent of 0.2 m year^{-1} into the Gulf (Table 16.2). However, the Gulf's evaporation equivalent of $1\text{--}2 \text{ m year}^{-1}$ greatly exceeds both precipitation and the input of river water (Ahmad and Sultan 1991) Table 16.8 shows details of the river inputs and their sediment loads. Peak flow from melting snow is usually during April–May. In 1970 the Southeastern Anatolia Project (GAP: Turkish acronym) was planned to utilize the rivers (Tomanbay 2000). This project will comprise 56 dams (Lawler 2005) which, once completed, will generate annually 27,300 GWh and irrigate $1.7 \times 10^6 \text{ ha}$ (Yüksel 2006). It aims to increase production of agricultural crops and, by 1999, it was 40% completed at a cost of \$32 billion. Its completion requires \$900 million by 2010 and financial problems have extended its deadline until 2047 (Cumhuriyet 1999). Many groups campaigned against the Ilisu Dam on the Tigris as it would dislodge 50,000 people and would destroy Hasankeyf, renowned for its first settlement built in 10,000–8000 B.C. This has survived nine civilizations

Table 16.8 Distribution of Euphrates and Tigris River waters (From Sheppard et al. (2010). By permission of Elsevier)

River	Total	Turkey	Syria	Iraq	Iran
Length (km), and % of river in each country					
Euphrates	3,000 km	41	24	35	0
Tigris	1,862 km	22	2	76	0
Euphrates-Tigris basin area (km ²) and % of distribution in each country					
Euphrates	444,000 km ²	28	17	40	0
Tigris	387,000 km ²	12	0.2	54	34
Total	765,000 km ²	22	10	51	17

to date, but it may not survive the tenth, because in 2007 a consortium of companies, Turkey's Water Management Authority as well as financiers signed a loan agreement for \$1.63 billion to build the Ilisu Dam. Some fear it could be Turkey's white elephant (Braun 1994).

Several concerns exist. The effects on Kuwait's fisheries are already described. There are also concerns over water sharing in the riparian down-stream nations (Çarkoğlu and Eder 2001) as GAP will greatly diminish and degrade their water supply in future (Gruen 2000). Once GAP is completed, the flow of the Euphrates will decrease from the 30 billion cubic meters (BCM) at the Syrian border to 16 BCM, and to 5–9 BCM at the Iraqi boarder (FAO 1997). Water regulation, fragmentation, sediment imbalance, partial or complete drying, salinisation, chemical contamination, acidification, eutrophication and microbial contamination are some of the syndromes commonly associated with damming rivers (Maybeck 1990), and in the GAP area itself insect transmitted diseases have greatly increased (Gratz 1999; Ozdogan 2005) as the hydroclimate changed (Fig. 16.10).

The marshlands themselves need to be flushed with fresh water for removal of salt and hydrogen sulphide. Reduced flushing decreased the Mesopotamian marshland from 8,500 km² in 1984 to 745 km² in 2002. Flooding the marshlands with river waters after the 2003 war partially restored them to 4,000 km² (Jones et al. 2006; Richardson et al. 2005). Iraq completed a "Third River" with 565 km outfall drainage. This river was designed to remedy the chronic salinity problem in the farmland between the rivers; it collects wastewater and drainage from 1.5×10^6 km² salt-encrusted fields and discharges into the Gulf via Khor Al-Zubair and Khor Al-Sabbiya. An extensive study was conducted on the impact of the man-made Third River on the northern Gulf's salinity, water quality and biota (Al-Yamani et al. 2008a, b; Al-Yamani 2008).

Undammed, these rivers supply over 11% of the water which replaces that lost by evaporation. Effects of river damming on final Gulf salinity appear not to have been computed, and nor have there been studies on the effects on Gulf biota, with the exception of the fisheries impacts already described. As GAP dams are completed, river discharges will greatly



The three largest reef cover categories on Fasht Adhm, 1985 and 2007

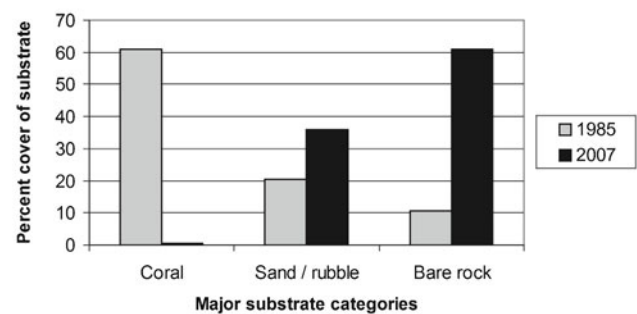


Fig. 16.10 Top: Fasht Adham in 2006. Coral cover was almost zero; figure shows remnants of rapidly eroding massive corals and barely recognizable *Acropora* colonies. Bottom: Change in Fasht Adham 1985–2006. Cover by coral, sand and bare, sedimented rock

diminish. Fluvial outflow is rich in nutrients (Talling 1980) and contains 1.82–7.07 mmol l⁻¹ PO₄-P, and 365.9–733.8 mmol l⁻¹ NO₃-N. High levels of nutrients exist in Shatt Al-Arab waters: 1.55–6.01 mmol l⁻¹ PO₄-P 135.6–306.9 l⁻¹ SiO₂-Si and 21.5–52.7 mmol l⁻¹ NO₃-N (Saad 1985), which can be attributed to the river run-off. These nutrients, silicates in particular, sustain a qualitatively and quantitatively rich diatom crop (116 species), ~94 mg chl *a* l⁻¹ in the northern Gulf waters (Subba Rao and Al-Yamani 1998, 2000).

An increase in planktonic diversity with distance from the river mouth (Fig. 16.11) may be caused by the decrease in river discharges and depletion of silicates; a replacement of diatoms by dinoflagellates that do not require silica has been observed in other areas such as the Baltic (Suikkanen et al. 2007; Wasmund and Uhlig 2003) and in a Swedish fjord (Filipsson et al. 2005). Diversion of water increased pollution, and negatively impacted the biota in the Azov Sea Basin also, reducing catches of commercially important fish (Volovik 1994), as was the case also with the Nile's Aswan dam in 1965 which reduced freshwater flow by 90%, resulting in a collapse of the fishery in the next 15 years (Nixon 2003). Changes in nutrient load caused by damming the

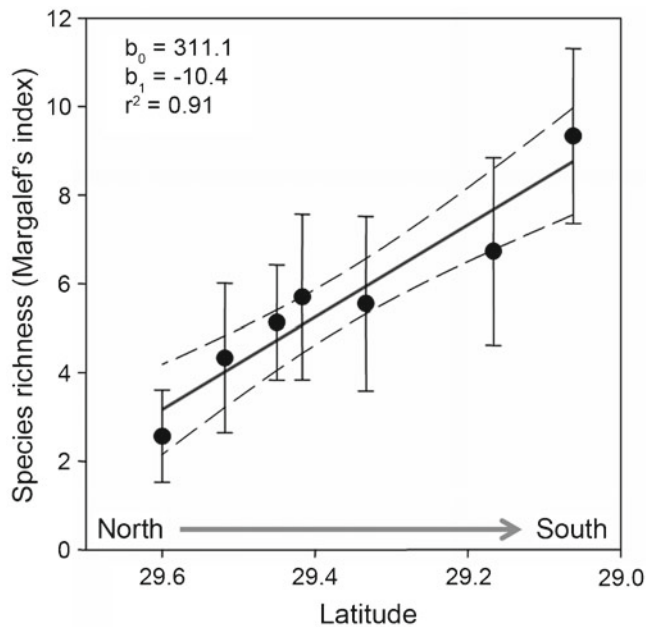


Fig. 16.11 Margalef's index for phytoplankton community in Kuwait's waters (β -diversity) showing an increase in diversity from waters nearest to Shatt Al-Arab northern area towards the south

Danube River similarly affected the food web in Black Sea surface waters (Humborg et al. 1997). It is possible that in the Gulf, trophodynamics of sardines and larvae of fish and shrimps, which are pelagic feeders, may be also affected due to shifts in pelagic biota.

The socio-economic impact of reducing the flow of fresh water to the northern Gulf may also be significant. Rising salinity will increase the costs associated with desalination and may result in ambient seawater salinities exceeding design specifications of facilities. This has potentially serious implications for the security of water supplies in Gulf States as desalination remains the only realistic supply source. While the GAP will benefit Turkey, it leaves a trail of environmental impacts on the riparian areas, marshlands and the Gulf. There is great merit in the suggestion (Freeman and Angin 1999) of applying organizational theory and practical experience with management of this large-scale common property resources problem. Downstream (literally in this case) problems for the Gulf as a whole have not been addressed to anything like the necessary degree.

16.9.2 Hormuz Strait Dam Futuristic Megaproject

Imaginative plans have been provisionally developed to create a dam across the Strait of Hormuz, leading to evaporative loss of water in the Gulf, creating a water level difference of about 20 m which would then be used to generate hydro-electric power (Schuiling et al. 2005). It would replace

hydrocarbons as a source of revenue and energy, when hydrocarbons run out. The principle is straightforward, and has been proposed for the Red Sea also (Schuiling et al. 2007). From the total water volume of about 8,600 km³, about 326 km³ year⁻¹ of water evaporates from the Gulf. Replacement is mostly from the Indian Ocean, with about 37–133 km³ year⁻¹ entering from rivers. The sill in the Strait is about 100 m deep. If there were a dam, evaporation would drop the level of water in the Gulf by 1–2 m year⁻¹ and a permanent inflow through an array of turbines could be maintained. Construction could be by cement, the volume needed being about 30% of 1 year's global cement production. But since much of the substrate in the Strait is limestone, injection of sulphuric acid (sulphur being a waste product of the present oil industry) could convert the limestone to gypsum. Gypsum has double the molar volume of limestone, and the expansion thus caused can only be accommodated by upward lift of the sea bed, thus reducing the amount of concrete needed for the dam.

The claim has been made that this development could accommodate both wildlife and humans simultaneously. At present it is difficult to see how. Salinities would not only be raised to levels well beyond that seen in present constricted embayments (like the southern Gulf of Salwah) but would continually rise for the duration of the dam as seawater continued to evaporate. After several years the Gulf would simply become a salt basin. This could, however, be partly avoided by outlet pipes which would permit highly saline water to exit into the Arabian Sea; suitable depths for the discharge are over 200 m which would require pipes to extend for about 100 km.

The proponents point out that the electricity produced would save 23.8 megatons of CO₂ annually if produced by coal, an increasingly important point. But the terrain left by the receding water in the Gulf as evaporation takes place would be highly inconducive to life, with no biota larger than nematodes able to survive in the highly saline soils, a point which appears to be overlooked in those parts of the proposals which talk of using the newly exposed land for agriculture (though the authors point out that genetic engineering might help species, even crops, to survive). If the Turkish damming of the major rivers proceeds according to plan too, then the reduced fresh water input would accelerate sea level fall so that the efficiency of the generating system would increase proportionally. It would also remove the only reliable and plentiful source of water on which the region depends for desalination.

Whether or not this is science-fiction (many present developments here would have seemed equally futuristic a century or two ago), ecological aspects are treated with the same cavalier lack of attention that ecology often receives (although in this case this obviously is a preliminary outline, focussing on engineering aspects only). The documents of Schuiling et al. (2005, 2007) are clearly interesting, and the

carbonate-to-gypsum technique has already been proven on limited scale. If it happens, then any other environmental impact in the Gulf would be relatively insignificant.

16.10 Problems from Recent Gulf Wars

The deliberate 1991 oil spill at the end of the First Gulf War occurred in an environment that was both far from pristine and highly naturally stressed (Price 1993, 1998). Published figures put the spill at around 6–8 million barrels, although some estimates (Tawfiq and Olsen 1993; Linden and Husain 2002) consider the volume higher. In addition to the oil spill, extensive pollution, a drop in temperature and reduction in photosynthetically active radiation (PAR) came about from the conflagration of more than 700 oil wells, which burned for several months (Literathy 1993; Munawar et al. 2002). The 1990–1991 Gulf conflict, one of several in the region in recent decades (Literathy et al. 2002), generated much research. Books (Sadiq and McCain 1993; Krupp et al. 1996; Otsuki et al. 1998), special issues of journals (Price and Robinson 1993; Al-Muzaini et al. 1998) and numerous research papers (Readman et al. 1992, 1996a, b; Fayad and Overton 1995; Jones et al. 1998) and reviews have been devoted to both immediate and wider environmental consequences. These studies and ongoing assessments, including those linked to environmental damage claims, have helped to make this part of the Gulf well studied.

Despite numerous assessments, issues surrounding environmental damage have not been fully resolved, although damage to intertidal regions, including their cyanobacterial mats, was severe (Al-Thukair et al. 2007). Coral reefs, however, mostly escaped damage, largely due to location (Vogt 1996). In all habitats, overall impact was greatly influenced by geographical location; Abu Ali island half way down the Saudi Arabian coast acted as an oil trap. Subtidal damage was relatively limited, and intertidal systems that were impacted showed considerable variability. Intertidal recovery in many oiled areas was well underway by the mid- to late-1990s (Jones et al. 1998). These authors tentatively suggested a period of 3–5 years for return to normal diversity (species richness), and a period of 3–6 years for restored abundances on rocky shores and intertidal soft substrata. Later assessments for environmental damage compensation by claimant countries, believed recovery times to be substantially longer than half a decade, particularly for marsh areas and low-energy tidal flats.

16.11 Prognosis for Gulf Coral Reefs

To avoid further degradation of marine habitats, in particular coral reefs, any single project should consider existing, planned and ongoing projects together. Reefs and mangroves

in particular are more threatened here than in any other sea. According to a recent compilation by Wilkinson (2008) only 3% of all reef habitats in the Gulf are under low threat levels, which compares very poorly with most other warm seas. A summary of the main pressures facing the Gulf is given in Table 16.9. But although the region contains the world's largest oil fields and second largest gas reserves, and despite the deliberate input of at least 8–10 million barrels in 1991, oil is not the most harmful ecological disturbance. Coastal dredging, infilling and conversion of shallow waters into land currently represent a much more serious threat (Al-Ghadban and Price 2002). A once-productive tidal flat or shallow nursery area, replaced by say a corniche road, buildings or other invasive coastal infrastructures, is unlikely ever to become biologically productive again. Insufficient attention is being given to the costs of loosing habitats (Costanza et al. 1997; Beaumont et al. 2008).

Lost or degraded coastal systems can be offset to some degree by the creation of artificial marine waters in saline sabkha and hypersaline khors of low ecological value, as has been shown above. But while engineering solutions such as this might help offset some damage, it is not, by itself, sufficient to reverse the last 15 years of unsustainable and damaging coastal development that is now so prevalent throughout much of the Gulf. Moreover, the prevailing approach envisaging the translocation of existing habitats or the creation of new artificial ones cannot remain unchecked forever as, in principle, suitable areas may soon be exhausted.

Besides pressures originating within the Gulf, its environment is subject to severe outside disturbances. Particularly significant is episodic seawater warming and consequent coral mortality, sea level rise, and the diversion of rivers entering the Shatt Al-Arab. Changes in salinity, nitrate, chlorophyll-*a* in Kuwaiti Gulf waters, for example, have already come about and permanent removal of seasonal flooding will also impact the northern Gulf's marine environment, with serious implications for fisheries.

Despite the many marine studies undertaken in the Gulf, collateral environmental damage from coastal development continues at an unprecedented and alarming scale. Effects of scores of individual environment impacts are clearly by far the greatest threat to the region. Extensive research, environmental assessments and alleged 'baseline surveys' have brought no guarantee of natural resource or coastal protection. Short-term and often ill-conceived investments continue to be big drivers of coastal use and allocation of beach frontage in the region.

Critical over the coming decade will be the degree to which the Gulf can absorb additional shocks and disturbances, yet continue to provide valuable ecosystem and economic services. Resource damage is progressing on such a scale that it possibly will overwhelm the resilience of the system. Resilience or robustness is a useful framework for

Table 16.9 Major environmental disturbances in the Gulf arising from human uses and activities within the region (From Price (1993), added to which are the major impacts from climate change; From Sheppard et al. (2010). By permission of Elsevier)

Coastal and marine use	Actual or potential environmental pressures
Shipping and transport shipping ports	Oil spills; anchor damage Coastal 'reclamation' and habitat loss; dredging, sedimentation; oil and other pollution
Residential and commercial	Coastal 'reclamation' and habitat loss; dredging, sedimentation; sewage, fertilizer and other effluents; eutrophication; solid waste disposal
Industrial development oil and petrochemical industry	Oil, refinery and other effluents containing heavy metals; drilling muds and tailings; air pollution
Desalination and seawater treatment plants	Effluents with elevated temperatures, salinities and sometimes heavy metals and other chemicals
Power plants	Various effluents; air pollution, increasing greenhouse gases and global warming; acid deposition
Fishing and collecting	Population decline of target and non-target species and changed species composition of fish, shrimp and other biota; habitat degradation (including anchor damage)
Recreation	Some reef degradation from anchor damage and collecting
Agriculture	Local eutrophication (e.g. from fertilizers); only low levels of insecticides such as DDT, aldrin, dieldrin and lindane recorded in marine sediments and biota, saline intrusion and possible effects on coastal ecosystems

understanding and assessing this (Jen 2005; Wagner 2005; Walker and Salt 2006) but, with few exceptions (Izsak et al. 2002), empirical and synergistic studies incorporating long-term or historical data have not been done in the Gulf.

Increasing the Gulf's network of coastal protected areas (Krupp et al. 1996) may be one practical means of retaining or re-instilling functionality and robustness. These will help against the many uncertainties now facing the Gulf's productive habitats. To that end a number of proposals are being considered in many countries, and some marine protected areas have in fact been declared in the past two decades. But to be effective, given the small scale of the Gulf and the obvious cumulative and transboundary impacts, only a large network of closely monitored and protected sites could effectively offset many of the on-going and planned threats. In other words, stronger environmental considerations, greater interaction amongst projects, increased information sharing between government departments, a longer-term viewpoint and agreed Gulf-wide strategic approaches are required to ensure both the ecological and economic sustainability of the Gulf.

The alternative is that one of the world's youngest seas will become one with the least value and greatest problems. If current trends continue, we will also lose a unique marine environment whose coral reefs could crucially function as a living laboratory to explore how reefs may adapt elsewhere on the planet, given the forecast rise in sea surface temperatures.

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Charles Sheppard, Mohsen Al-Husiani, F. Al-Jamali,
Faiza Al-Yamani, Rob Baldwin, James Bishop,
Francesca Benzoni, Eric Dutrieux, Nicholas K. Dulvy,
Subba Rao V. Durvasula, David A. Jones, Ron Loughland,
David Medio, M. Nithyanandan, Graham M. Pilling,
Igor Polikarpov, Andrew R.G. Price, Sam J. Purkis,
Bernhard M. Riegl, Maria Saburova, Kaveh Samimi-Namin,
Oliver Taylor, Simon Wilson, and Khadija Zainal

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