



The Khaled bin Sultan Living Oceans Foundation  
Habitat Mapping and  
Characterization of Coral Reefs  
of the Saudia Arabian Red Sea:  
2006-2009

Final Report

Andrew Bruckner  
Chief Scientist, KSLOF  
[Bruckner@livingoceansfoundation.org](mailto:Bruckner@livingoceansfoundation.org)  
December, 2011



Front cover: Shallow coral reef in the Farasan Banks. Photo by Andrew Bruckner

Back cover: Juvenile Napoleon wrasse (*Cheilinus undulatus*) above a field of *Porites lutea* and *Millepora* colonies, Al Wajh Bank. Photo by Andrew Bruckner.

Khaled bin Sultan Living Oceans Foundation  
8181 Professional Place  
Landover, MD, 20785 USA  
Philip G. Renaud, Executive Director

<http://www.livingoceansfoundation.org/>

Published by Panoramic Press, Phoenix Arizona, USA

First published 2011

The information in this Final Report is believed to be true and accurate at the time of printing but the authors and the Living Oceans Foundation cannot accept any legal responsibility or liability for any errors.

Photographs contained within this document are courtesy of Andrew Bruckner, Annelise Hagan, Gwilym Rowlands, and David Obura

Compiled by Andrew Bruckner and typeset by Art Webb

Citation: Bruckner, A. (2011) Khaled bin Sultan Living Oceans Foundation Habitat Mapping and Characterization of Coral Reefs of the Saudi Arabian Red Sea: 2006-2009. Panoramic Press, Arizona, 140 pp.

## EXECUTIVE SUMMARY

The Khaled bin Sultan Living Oceans Foundation implemented four research missions in the Saudi Arabian Red Sea from 2006-2009 using the M/Y Golden Shadow as a research platform. The research was undertaken to improve the understanding of the spatial distribution, size and condition of shallow marine habitats, and to identify options to enhance the conservation and management of Saudi Arabian coral reef ecosystems. The research focused on three priorities: 1) characterization and mapping of shallow marine habitats off the Saudi Arabian Red Sea coastline; 2) assessment of the composition, population structure, cover and health of key reef species, including stony corals and soft corals, algae, and fishes; and 3) characterization of past impacts, patterns of recovery, ongoing stressors and resilience indicators. Outputs included a Geographic Information System (GIS) database, detailed high resolution habitat maps compiled in an HTML format CD, the *Khaled bin Sultan Living Oceans Foundation Atlas of Shallow Marine Habitat in the Saudi Arabian Red Sea*, a coral reef symposium held in Jeddah in 2012, a movie on the Farasan Islands, and numerous scientific presentations and publications. Additional products in development include a Red Sea coral reef book entitled “*Conservation of Coral Reef Ecosystems of the Saudi Arabian Red Sea*”.

Quickbird multispectral satellite imagery (DigitalGlobe Inc.) was acquired for 25,000 km<sup>2</sup> of coastal and offshore marine habitats in the Saudi Arabian Red Sea, from the shoreline to depths of 20-30 m, extending up to 100 km offshore. Satellite imagery was supplemented with hyperspectral imagery in the Farasan Islands (3200 km<sup>2</sup>) and Al Wajh lagoon (approximately 2000 km<sup>2</sup>). Detailed groundtruthing focused on acquisition of data needed to identify, characterize and validate habitats, derive depth, determine reflectance of various objects and habitats, validate the position on the ground with the imagery, remove artifacts associated with atmosphere and water conditions, and improve accuracy of the resulting maps.

All of the habitat maps, imagery, data, photographs and video were compiled into a GIS database. The GIS database and associated habitat maps provide a spatially-based platform for management. These maps identify at least seven different geomorphologic reef structures in the Red Sea, including barrier reef systems, lagoonal patch reefs, reticulate reefs, submerged limestone platforms, coral pinnacles, atoll-like structures, and island and mainland fringing reefs. Shallow marine areas are subdivided into 12-15 distinct marine habitat types in each region, including specific reef environments, grassbeds, mangroves, algal flats, and sand-bottom communities. The habitats are discriminated to depths of about 20-30 m. Assessments of wave and tide height, sediment characteristics, turbidity, reflectance of corals, algae and non-living substrates, and sediment and hard bottom profiling, along with historic datasets (e.g. temperature) were used to determine linkages between the coral reef ecosystems and the environmental drivers, geological features and biological attributes that shape these ecosystems.

SCUBA assessments were completed in representative reef environments to determine 1) what organisms were present; 2) the status and health of these organisms and threats affecting them; 3) the potential for recovery from past disturbances; 4) factors and processes that control the health and resilience of these communities, and enhance their persistence into the future and ensure they rebound following acute disturbances; and 5) management and conservation actions needed to enhance ecosystem health and resilience. Major results of this project include the identification of Red Sea indicators of resilience, ecological areas that exhibit high resilience, as well as the major causes of degradation of these ecosystems. The research missions provide key information on resilience principles and tools to facilitate place-based management actions. Habitat maps provide information on the locations and spatial extent of different habitat types, including the potential area of critical habitat for reef building corals. An analysis of the spatial distribution of corals in the landscape, and the sizes and abundance of corals within various habitat types provides an indication of the spatio-temporal functioning of the coral reef community. From the maps, it is possible to quantify the overall size (spatial coverage) of coral reefs along the Red Sea coastline, and the amount of suitable habitat for corals. Transect data provides information on the density of corals per defined spatial unit, colony size structure, patterns of coral recruitment, and health status of reef building corals, reported by genera. Together, these two data sources can be used to estimate the total number of corals expected to occur in the system, and the total carrying capacity of the system if every available and useable spatial unit was occupied.

Ras Qisbah reef structure was diverse, with reefs exhibiting a reticulated or honeycomb structure built on a *Porites* framework, and surrounding seagrass beds, algal flats, soft coral areas and sandy lagoons. Living coral cover was highest at 3-4m (approx. 30%), with much lower cover (<5-20%) in deeper reef environments (5-17m depth). Reefs showed evidence of a past mortality event in 1998 or 1999, affecting 50-75% of the corals. Most of the *Porites* colonies in deeper areas had died prior to this event, with replacement by foliose and plating corals, most of which subsequently died in the last 3-9 years. Living corals were typically small in size (<1m diameter), dominated by highly fragmented remnants of large *Porites* colonies, with dead skeletal surfaces colonized by small massive faviid corals and branching corals, especially in the genus, *Acropora*, *Montipora*, *Stylophora*, *Seriatopora* and *Millepora*, and the soft coral *Xenia*. The only exception were isolated colonies on the exposed outer slopes at Al Farshah that reached sizes of 4-5m diameter. Most sites were conducive to future colonization and growth of corals, with low amounts of fleshy algae and moderately high levels of herbivory, although coralline algal cover was also low.



The scientific data collected during these missions was used to formulate recommendations on conservation and management actions that, if implemented, will help protect precious coral reef resources and habitats in the Saudi Arabia Red Sea. The most urgent actions include:

1. The establishment of networks of MPAs addressing the following criteria:
  - a. Inclusion of representative habitats that are physically and ecologically connected, including seagrass beds, mangroves and corals reefs.
  - b. Inclusion of sites with unique species, exceptional health, and low current threat levels from human impacts.
  - c. Inclusion of sites that possess ecological, environmental and physical resilience attributes.
  - d. Implementation of marine zoning to minimize environmental damage to reef ecosystems and prevent social conflicts from different user groups with a minimum of 20% of the shallow water habitats (0-20 m depth) that are designated as no-take sites.
  - e. The implementation of no-take MPAs within certain key locations including Al Wajh Bank, Farasan Banks and Farasan Islands.
    - i. Key reefs and associated habitats in Al Wajh Bank, including shallow lagoonal *Acropora*-dominated habitats; islands, reefs and associated habitats located along the barrier reef; the reticulated reef system located to the south of the bank; and offshore pinnacle reefs.
    - ii. Midshelf and offshore reefs, islands, and lagoons in the Farasan Banks
    - iii. Offshore submerged *Acropora* coral habitats in the Farasan Islands that are located seaward of the existing MPA.
    - iv. Offshore barrier reef communities in Yanbu.
2. Revision of existing fishery management plans to protect and enhance coral reef fisheries
  - a. Reduce the use of fish traps and gill nets in coral reef environments.
  - b. Restrict the harvest of herbivores, including parrotfish, surgeonfish, rabbitfish and other herbivores.
  - c. Ban on the harvest of sharks, endangered groupers, humphead wrasse and other species on the IUCN Red list.
  - d. Protection of certain keystone species including sea cucumbers, giant clams, octopus and lobsters.
3. Implement new coastal zone management practices to reduce anthropogenic stressors and improve water quality near coral reefs
4. Establish a coral reef monitoring program for the Red Sea
  - a. Implement monitoring methods that can detect changes to these habitats and effects of management measures.
  - b. Include random monitoring of representative habitats in each region.
  - c. Establish and fully characterize permanent Legacy sites that encompass each region, different depths and different management scenarios, and reevaluate these periodically to assess changes and responses to management.
5. Conduct novel restoration projects,
  - a. Establish a coral nursery program and coral transplantation efforts for degraded sites.
  - b. Remove coral eating snails and crown of thorns sea stars during population outbreaks.
  - c. Conduct pilot studies to remove encrusting sponges that are overgrowing corals.
  - d. Evaluate impacts of other pest species such as damselfish, and collect these species in areas where they are causing significant impacts.

## **Five Summary Recommendations**

### **1. Establish Marine Protected Areas (MPA).**

The Saudi Arabian Red Sea coastline contains many coral reefs with a high conservation value that could benefit from inclusion in a Red Sea MPA Network. These should include sites with 1) a unique geomorphology; 2) high quality habitats with high cover and diversity of reef-building corals; 3) rare and endemic species and organisms with a restricted distribution; 4) low current threat levels from human impacts; 5) reservoirs of biodiversity and sources of seed stock; 6) different reef types and associated habitats such as grassbeds and mangroves; 7) habitats not present in other areas in the Red Sea; and 7) a high degree of connectivity with other sites inside and outside of MPA networks.

**Sites with high resilience should be included in MPA networks.** Physical and environmental parameters, such as the distance from shore, reef slope, facing direction, wave exposure, proximity to deep water, flushing, tidal change and other environmental parameters are important factors affecting coral population dynamics, health, survival and resiliences, and connectivity between sites. While these factors can't be easily manipulated, sites are worthy of protection due to 1) their role as refuge and sources of seed stock and 2) presence of favorable environmental and physical attributes that are likely to minimize or counter impacts from global stressors such as climate change. By identifying and including these areas in networks of MPAs, their survival and recovery will also help ensure the survival and recovery of sites outside these networks.

**Areas established as MPAs should be zoned for specific uses, including areas set aside as no-take MPAs, sites open only to research and monitoring, and sites with multiple uses including recreational (SCUBA) use, fishing, and educational use.** Representative sites exhibiting these features should be protected through the establishment of networks of Marine Protected Areas (MPAs) that include areas open to multiple uses as well as areas closed to all extractive uses. A minimum of 20% of all shallow marine habitats within the Saudi Arabian Red Sea should be considered for no-take designation. The place-based management and spatial zoning could be achieved through use of the high resolution habitat maps and GIS database developed by the Khaled bin Sultan Living Oceans Foundation as framework to identify habitats and boundaries between different zones.



**One of the critical areas that should be considered for MPA designation is Al Wajh Bank.** Al Wajh is a unique marine and coastal ecosystem that is of a large size and contains a high diversity of reef habitats and other marine and coastal habitats that are not found elsewhere in the Red Sea. The area contains all types of marine habitats, including extensive mangrove forests and sea grass beds that serve as critical nursery areas for fisheries species and a barrier reef system bordering its seaward edge. The reefs of Al Wajh support Red Sea endemic corals, undescribed coral species, and species with restricted distributions. The reefs show a high level of ecological connectivity, both within the bank and between Al Wajh and other reefs outside of the Al Wajh Bank area. This ecosystem serves as a critical breeding ground for fishes, corals and other keystone species, and also provides critical sources of larvae needed to replenish and repopulate other sites in the Red Sea. A management program for marine areas around Al Wajh should include establishment of effective measures to control collection of fish and invertebrates on reef flats and shallow reef communities, spearfishing, and use of fish traps. The bank is currently experiencing high levels of fishing pressure; development is minimal but has the potential to expand as tourism grows. The area also exhibits a high potential for disturbances from climate change, due to the presence of nearly 3000km<sup>2</sup> of shallow, calm lagoonal habitats that heat up during periods of unusual thermal anomalies. Elimination of human stressors and protection through designation as a network of no-take MPAs can help promote the survival of the reef communities by enhancing recovery rates from past bleaching events and ensuring that communities are able to resist degradation during future sea water warming events. If fishing pressure continues at current levels, key indicator species will be eradicated with cascading negative impacts on the rest of the ecosystem. This includes loss of many of the key reef-building corals that shape the environment and create habitat utilized by fishes and motile invertebrates. Industrial development, dredging, land filling and reclamation and discharge of from desalinization plants and sewage sources could also cause large-scale degradation due to increased input of pollutants and sediments, loss of critical coastal and island nursery mangrove and grassbeds habitats, and physical impacts associated with increased human pressure.

**A second critical area in need of immediate protection as an MPA includes coral reefs in the midshelf and outer Farasan Banks.** The Farasan Banks includes the largest number of reef types found in Saudi Arabia, and is home to atoll-like structures (tower reefs) found nowhere else on the planet. Because of the remote nature of the Farasan Banks, the extensive shallow habitat, and treacherous navigation hazards, the sites currently have very low human pressure. In addition, the Farasan Banks appears to be a bridge between the more northern Red Sea coral reefs and the southern Red Sea and Indian Ocean, sharing species from both regions and also containing endemic species. The area contains unique coral assemblages and undescribed species of corals that are new to science, such as the largest living stand of bubble coral (*Plerogyra sinuosa*) known to occur in the world, huge stands of precious black corals (antipatharians), the largest remaining populations of sharks in the Red Sea, whale shark feeding grounds, extensive habitats for nesting turtles, habitats occupied by endangered dolphins, whales, and dugong, several large bird rookeries, and the most extensive deep water (mesophotic) coral communities found in Saudi Arabia. The Farasan Banks also exhibits the highest potential for recreational SCUBA diving-based tourism. While relatively healthy fish populations still occur here, fishing pressure is rapidly increasing and the use of new destructive gear types (fish traps) is expanding in the region. Given the close proximity to the Farasan Islands and Jizan, and the occurrence of the largest shrimp farm in Saudi Arabia at the northern end of the Farasan Banks, the potential for human impacts is great, while establishment of this region as a no-take MPA would have minimal economic implications at this time and much greater economic benefits for non consumptive uses (tourism) in the future.

**The existing MPA in the Farasan Islands should be expanded to encompass offshore submerged coral habitats.** Saudi Arabia took promising steps to enhance conservation by establishing the Farasan Islands MPA. This MPA encompasses one of the most productive marine areas in all of Saudi Arabia. The conservation area currently includes critical nursery and breeding grounds for turtles, marine mammals and marine birds, as well as key shallow marine habitats including grassbeds, fringing coral reefs and mangroves. However, due to the shallow nature of the platform, significant seasonal upwelling, and high turbidity of the nearshore areas, much of the underwater habitats are formed primarily from coralline algae

with high seasonal cover of fleshy seaweeds (macroalgae) like *Sargassum* that are known to smother corals. In contrast, extensive offshore submerged coral reef habitats exist to the west and northwest, outside of the current MPA boundaries. These include extensive stands of the fragile branching coral in the Genus *Acropora*. These corals are among the fastest growing reef-building corals that produce important high relief habitat used by reef fishes for nursery areas and protection. The *Acropora* habitat was in excellent condition during the 2006 surveys, with live coverage of 70-100%. Because of the importance of these corals in producing and maintaining healthy reef systems, and the fragility of these corals to physical impacts (anchoring and ship strikes), bleaching, and predation by crown of thorns (COTs; *Acanthaster planci*) sea stars, as well as the relative rarity of these types of habitats in Saudi Arabia, it is imperative that these are offered protection from human activities, including impacts from fishing gear and boats and sediment and pollution associated with coastal development. The corals found in these offshore submerged habitats, due to their proximity to deep water and strong currents and wave action, are likely to be an important source of coral larvae that seeds other reef environments in the Farasan Islands as well as reefs in the Farasan Banks. If these habitats are destroyed or degraded, commercially important reef fishes will lose critical habitat essential for their survival, reproduction and growth.

## **2. Implement new fishery management plans.**

Fishery management measures should be adopted that emphasize maintenance of biodiversity, functional diversity, and high biomass of certain keystone species, such as herbivorous fishes that control macroalgae and top predators that regulate population structure of lower trophic groups. Unsustainable coral reef fisheries and use of destructive fisheries gear types should be eliminated, with emphasis on measures that 1) reduce or eliminate the use of fish traps, gill nets and other gear types that do not discriminate among species, life stages (e.g. juvenile vs. adult) or sizes of species caught; 2) ban anchoring in sensitive areas; and 3) limit the capture and take of coral reef associated fishes that help maintain proper functioning of the reef community. For instance, species in the family Scaridae should be protected due to their feeding on algae that would otherwise outcompete corals; predatory fishes in the family's Lethrinidae, Balistidae, Labridae, Serranidae and Lutjanidae should be protected because of their importance in controlling *Acanthaster* sea



stars (COTs) and muricid gastropods in the genus *Drupella*, both of which are important corallivores that can destroy entire reef tracts. Large populations of these reef fish species will help prevent explosions of these corallivores, prevent overgrowth of reefs by macroalgae, and help ensure high levels of ecological reef resilience.

### **3. Improve Coastal Zone Management.**

Efforts should target reduction of anthropogenic stressors in areas close to high value coral reefs, especially Yanbu (shipping impacts, potential oil pollution, highly saline, hot water from desalination plants, and introduction of invasive species), Al Wajh (unsustainable fishing and coastal development) and the Farasan Banks/Islands (reef fisheries, habitat impacts, land-based input of pollutants). Measures should address proposed and existing coastal and industrial development, with emphasis on the reduction of 1) run-off, sewage and other pollutants; and 2) discharge of water from desalinization plants. Implementation of these measures will improve water quality, promote healthy coral communities, and reduce the proliferation of nuisance species. Outcomes of environmentally friendly development practices and reductions in discharge of pollutants will enhance coral survival, prevent recruitment failure of corals, reduce proliferation of macroalgae and encrusting and bioeroding sponges, and promote adaptation of coral reefs to climate change. These efforts can be achieved through strengthened legislation, better coordination among sectoral ministries, and enforcement of laws, as well as the replanting of coastal vegetation (especially mangroves).

### **4. Establish a Coral Reef Monitoring Program.**

A long term monitoring program should be established that incorporates representative sites within each region, sites under different management regimes, and sites across gradients of human population. This would allow determination of the status and trends of reef associated communities, impacts of future disturbances, and outcomes of new management measures. Targets of monitoring should emphasize tightly linked organisms (corals, fish and algae), and include programs that 1) quantify biological attributes of these species, including population dynamics (diversity, abundance, cover, size structure and recruitment), condition and threats; 2) assess populations of commercially important fishes and invertebrates and

organisms that regulate the health and resilience of these ecosystems; 3) characterize environmental parameters, especially temperature (using data loggers), turbidity, and measures of water quality; 4) measure human uses and ecosystem services provided by reefs, especially fisheries; and 5) assess the effectiveness of management measures.

## **5. Conduct Novel Ecological Restoration Projects.**

In sites of high value that are being impacted by natural stressors and/or have declined due to an acute disturbance such as a large scale bleaching event, efforts should be directed at repopulating stony corals that once occurred in the site and the control and removal of pest species. This could include a) the establishment of coral nursery sites to propagate key reef-building corals; b) transplantation of corals into degraded sites; c) removal of *Acanthaster* sea stars (crown of thorns) and *Drupella* snails (corallivores) during population explosions; d) removal of benthic invertebrates that are carpeting the reef and overgrowing/bioeroding corals such as certain soft corals, colonial anemones and bioeroding sponges; and e) population control of nuisance species and pest species including certain damselfishes that establish algal lawns on living corals.

## Table of Contents

|                                                                     |           |
|---------------------------------------------------------------------|-----------|
| <b>Executive Summary .....</b>                                      | <b>i</b>  |
| <b>Five Summary Recommendations.....</b>                            | <b>iv</b> |
| <b>Acknowledgements .....</b>                                       | <b>1</b>  |
| <b>Preface.....</b>                                                 | <b>2</b>  |
| <b>1. Introduction.....</b>                                         | <b>4</b>  |
| <b>3. Outcomes .....</b>                                            | <b>11</b> |
| <b>4. Relationship with existing plans and recommendations.....</b> | <b>13</b> |
| <b>5. Methods.....</b>                                              | <b>16</b> |
| <b>5.1 Vessel support and equipment.....</b>                        | <b>16</b> |
| <b>5.2 Image Acquisition .....</b>                                  | <b>17</b> |
| 5.2.1 Multispectral imagery .....                                   | 18        |
| 5.2.2 Hyperspectral imagery .....                                   | 18        |
| <b>5.3 Groundtruthing.....</b>                                      | <b>20</b> |
| 5.3.1 Single beam sonar .....                                       | 20        |
| 5.3.2 Sub-bottom profiler.....                                      | 20        |
| 5.3.3 Spectral reflectance measurements .....                       | 21        |
| 5.3.4 Photography and videography .....                             | 21        |
| <b>5.4 Initial processing of imagery .....</b>                      | <b>23</b> |
| 5.4.1 Optically derived water depth .....                           | 23        |
| 5.4.2 Water column correction.....                                  | 24        |
| 5.4.3 Image masking .....                                           | 24        |
| <b>5.5 Production of thematic habitat maps .....</b>                | <b>25</b> |
| 5.5.1 Edge-detection .....                                          | 25        |
| 5.5.2 Spectral Classification.....                                  | 25        |
| 5.5.3 Textural analysis .....                                       | 26        |
| 5.5.4 Contextual editing.....                                       | 26        |
| 5.5.5 Filtering.....                                                | 27        |
| 5.5.6 Quality control .....                                         | 27        |
| 5.5.7 Accuracy assessment.....                                      | 28        |
| <b>5.6 SCUBA Surveys .....</b>                                      | <b>28</b> |
| 5.6.1 Benthic cover and population distributional patterns.....     | 29        |

|                                                               |           |
|---------------------------------------------------------------|-----------|
| 5.6.2 Coral community structure and population dynamics ..... | 34        |
| 5.6.3 Resilience assessments.....                             | 35        |
| 5.6.4 Fish Surveys.....                                       | 40        |
| <b>5.7 Coastal and Marine Surveys.....</b>                    | <b>41</b> |
| 5.7.1 Marine mammals and turtles.....                         | 41        |
| 5.7.2 Coastal vegetation.....                                 | 41        |
| <b>5.8 GIS Database.....</b>                                  | <b>41</b> |
| <b>6. Results.....</b>                                        | <b>42</b> |
| <b>A. Habitats of the Saudi Arabian Red Sea.....</b>          | <b>42</b> |
| <b>6.1 Reef Types.....</b>                                    | <b>42</b> |
| <b>6.2 Habitat types.....</b>                                 | <b>43</b> |
| 6.2.1 Windward coral crests.....                              | 44        |
| 6.2.4 Columnar frameworks.....                                | 46        |
| 6.2.5 Reef walls/drop-offs.....                               | 47        |
| 6.2.6 Sparse corals, rubble, and sand .....                   | 48        |
| 6.2.7 Seagrass meadows .....                                  | 48        |
| 6.2.8 Macroalgae & sponges on sandy hardgrounds.....          | 51        |
| 6.2.9 Cyanobacteria mats on sand.....                         | 52        |
| 6.2.10 Mangroves and near-shore vegetation .....              | 52        |
| 6.2.11 Scoured channels .....                                 | 55        |
| 6.2.12 Carbonate hardground and reef flats .....              | 55        |
| 6.2.13 Shallow sand sheets .....                              | 56        |
| 6.2.14 Deep lagoonal sands.....                               | 56        |
| 6.2.15 Sand and mud flats.....                                | 57        |
| <b>7. Status of reef communities in the Red Sea.....</b>      | <b>58</b> |
| <b>7.1 Cover of benthic organisms.....</b>                    | <b>58</b> |
| <b>7.2 Coral community structure.....</b>                     | <b>61</b> |
| <b>7.3 Coral size structure.....</b>                          | <b>66</b> |
| <b>7.4 Coral Condition.....</b>                               | <b>68</b> |
| <b>8. Fish assemblages .....</b>                              | <b>69</b> |
| <b>9. Threats .....</b>                                       | <b>73</b> |
| <b>9.1. Human impacts .....</b>                               | <b>73</b> |

|                                                                                        |            |
|----------------------------------------------------------------------------------------|------------|
| <b>9.2 Natural stressors:</b>                                                          | <b>75</b>  |
| <b>9.3 Coral Diseases</b>                                                              | <b>75</b>  |
| 9.3.1 Descriptions of diseases                                                         | 75         |
| 9.3.2 White syndromes (WS)                                                             | 75         |
| 9.3.3 Ulcerative white spots (UWS)                                                     | 76         |
| 9.3.4 Black band disease (BBD)                                                         | 76         |
| 9.3.5 Brown band disease (BrB)                                                         | 77         |
| 9.3.6 Skeletal Eroding Band (SEB)                                                      | 78         |
| 9.3.7 Pink Line disease (PLD)                                                          | 79         |
| 9.3.8 Arabian yellow band disease (AYBD)                                               | 79         |
| 9.3.9 Pacific yellow band disease (PYBD)                                               | 79         |
| 9.3.10 Dark spots disease (DSD)                                                        | 80         |
| 9.3.11 Growth anomalies (GAs)                                                          | 80         |
| 9.3.12 Coral disease prevalence in the Red Sea                                         | 81         |
| <b>9.4 Competitive Interactions</b>                                                    | <b>86</b>  |
| <b>10. Resilience indicators</b>                                                       | <b>93</b>  |
| <b>10.1 Biological attributes of resilience</b>                                        | <b>93</b>  |
| <b>10.2 Oceanographic and environmental parameters</b>                                 | <b>94</b>  |
| 10.2.1 Tides                                                                           | 94         |
| 10.2.2 Water exchange                                                                  | 94         |
| 10.2.3 Water Temperature                                                               | 95         |
| 10.2.4 Salinity                                                                        | 95         |
| <b>10.3 Physical attributes</b>                                                        | <b>97</b>  |
| <b>10.4. Coral reef fisheries</b>                                                      | <b>99</b>  |
| 10.41 Types of fisheries                                                               | 100        |
| 10.42 Fisheries landings                                                               | 101        |
| 10.43 Threats to fisheries and fishery resources                                       | 102        |
| <b>11. Role of geology and historic reef structures in modern day reef communities</b> | <b>109</b> |
| <b>11.1 Background</b>                                                                 | <b>109</b> |
| <b>11.2 Paleoclimate and sea level</b>                                                 | <b>110</b> |
| <b>11.3 Landform modeling</b>                                                          | <b>111</b> |
| <b>12. REFERENCES</b>                                                                  | <b>114</b> |



|                                                                                                         |            |
|---------------------------------------------------------------------------------------------------------|------------|
| <b>Appendix 1. Partners .....</b>                                                                       | <b>122</b> |
| <b>Appendix 2. List of scientists conducting research during the four year Red Sea Expedition. ....</b> | <b>123</b> |
| <b>Appendix 3 Research platforms.....</b>                                                               | <b>124</b> |

## Acknowledgements

The Saudi Arabian Red Sea coastline is the result of a collaborative four year research project between the Khaled bin Sultan Living Oceans Foundation, the National Commission for Wildlife Conservation and Development (NCWCD), the Regional Organization for the Conservation of the Environment of the Red Sea & Gulf of Aden (PERSGA), Kingdom of Saudi Arabia Ministry of Agriculture Marine Fisheries Department (MFD), the National Coral Reef Institute (NCRI), NOVA Southeastern University, the International Union for Conservation of Nature (IUCN) and Cambridge Coastal Research Unit, University of Cambridge. The four year research mission would not have been possible without the generous support of His Royal Highness Prince Khaled bin Sultan bin Abdulaziz. Prince Khaled supported the Foundation's efforts in Saudi Arabia to complete the characterization and mapping of marine habitats and to assess the structure, composition and condition of shallow coral reef ecosystems along the Saudi Arabian Red Sea coastline. Prince Khaled provided the research team with full access to the M/Y *Golden Shadow* for use as the research platform for the four Expeditions, with additional support for airborne hyperspectral surveys with the Cessna 208 amphibious sea plane, the *Golden Eye*. We are extremely grateful for the professional logistical support, both onboard and ashore, provided by the Saudi Arabian Military Air Defense and Coast Guard. Additionally, we could not have completed the extensive field work without the strong support and direct participation of the Said Wildlife Commission (SWC) under the leadership of the Secretary General, His Excellency Prince Bander bin Saud bin Mohammed. Special thanks to Mr. Omar Khushaim, Marine Manager of NCWCD, for his diligent preparation of the research applications and his onboard support throughout the expeditions. We are also grateful to the captains and crew of the M/Y *Golden Shadow* and pilots of the *Golden Eye* for facilitating data acquisition. High spatial resolution (2.4m pixel) multispectral Quickbird imagery was obtained from DigitalGlobe, Inc., Longmount, Colorado, USA. The CASI hyperspectral instrument was operated during the Farasan Islands research (2006) by Hyperspectral Data International (HDI) Canada and the AISA Eagle hyperspectral instrument was operated during the Al Wajh research (2008) by SpecTIR LLC.

## Preface

Between May 2006 and October 2009, the Khaled bin Sultan Living Oceans Foundation (Foundation) conducted four major research missions to the Saudi Arabian Red Sea coastline. These missions were conducted in partnership with the Saudi Wildlife Commission (SWC)<sup>1</sup>, the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), the National Coral Reef Institute (NCRI), the World Conservation Union (IUCN), the Cambridge Coastal Research Unit, and several other non-governmental partners, operating under the *Science Without Borders*® program. Each expedition focused on a different region, beginning in the Farasan Islands (2006), followed by Ras Qisbah (2007), Al Wajh and Yanbu (2008) and the Farasan Banks (2009). The primary goal of the research was to obtain the data and information needed to create high-resolution paper and electronic marine benthic habitat maps for shallow coral reef ecosystems in the Saudi Arabian Red Sea environment. These maps encompass habitats located from the shoreline up to approximately 100km offshore. They were derived from a combination of QuickBird multi-spectral satellite imagery, hyperspectral imagery (Farasan Islands and Al Wajh), and *in situ* ground-truthing. A second major goal was to conduct detailed underwater surveys in coral reef habitats to characterize species assemblages and the health, major threats, and resilience indicators, with emphasis on an assessment of the impacts of recent disturbances and mortality events, and patterns of recovery.

Throughout the four year project, the Foundation provided invaluable logistical support and access for scientists conducting marine research through a highly capable research ship and embarked seaplane. The four Foundation expeditions involve many different scientists collaborating in gathering different types of data, which together provide a detailed picture of the locations of major habitats, their condition, threats, patterns of human use, and indicators of health and resilience. Throughout the project, the Foundation pioneered new methods of habitat mapping that have provided us with the potential to cover very large areas in a cost effective manner, and create very detailed maps that can form a basis for management. Scientists' plans are often circumscribed by lack of access to an adequate research platform. The Foundation's emphasis on remote sensing technologies is a direct outgrowth of the accessibility of a ship and

---

<sup>1</sup> SWC was formerly known as the National Commission for Wildlife Conservation and Development (NCWCD).

aircraft capable of accessing remote locations for extended durations along with a unique partnership with the world's leading remote sensing scientists located at NCRI<sup>2</sup>.

During these missions, the Foundation placed a major emphasis on conducting applied marine science. Our research supports projects that prove a clear linkage between knowledge gained and practical applications of that knowledge to the issues of conserving and managing local marine resources. More importantly, the Foundation undertook opportunities to develop state-of-the-art tools and methods of oceanographic research that have applications in *any* geography, improving our capabilities with novel, state of the art tools, sensors, and survey approaches.

One of the first principles in managing marine resources is to gain a fundamental understanding of what exists in the region of interest. It has been well established that mapping of marine resources yields a critical baseline of knowledge. One of the unique capabilities of the Living Oceans Foundation is application of remote sensing techniques combined with synchronized “ground-truthing” field work to create high resolution maps of seabed habitats. These maps provide important baseline information about coral reef ecosystems. Scientists and managers use high resolution habitat maps to design research and management plans, assess damaged coral, monitor reef health, and evaluate the results of their work.

The overarching objective of this research project is to provide stakeholders with the first modern high-resolution benthic habitat maps for incorporation into marine ecosystem management plans. These maps, and the associated information, provide guidance to decision makers on the level of conservation and management which should be afforded to this region. These maps were incorporated into a geographic information system (GIS) database that contains detailed datasets, still images, video and information on Red Sea coral reefs and associated habitats. This new tool allows resource managers to quickly retrieve complex data sets and use the tool's visual presentation to highlight existing or potential problems and formulate strategies. In addition, the project team is integrating the rich array of available marine data from other sources, thereby placing an astounding range and breadth of information at the fingertips of scientists, resource managers, and policy makers.

---

<sup>2</sup> NCRI is part of Nova Southeastern University, Ft. Lauderdale, Florida USA

## 1. Introduction

Shallow water coral reefs are found in tropical areas, between the Tropics of Cancer and Capricorn to a maximum of about 50-75m depth, in environments with suitable temperatures, salinity, light, nutrients, sediment, hydrodynamics, and seawater carbonate chemistry. Coral reefs are estimated to cover from 284,300km<sup>2</sup> (Spalding et al. 2001), and about 920,000km<sup>2</sup> when associated habitats (e.g. grassbeds and mangroves) are included in calculations (Costanza et al. 1997), with 91% of the world's coral reef ecosystems occurring in the Indo-Pacific region. The Red Sea, which is considered part of the Indo-Pacific region, contains the most biologically diverse reef communities outside of the Southeast Asia coral triangle; it shares many of the species found in other Indo-Pacific locations and also contains approximately 10% species level endemism (Devantier et al. 2000a). The Kingdom of Saudi Arabia has the largest area of coral reefs (6660km<sup>2</sup> reef area) in the Red Sea, extending over 1840km from the Gulf of Aqaba in the north to the Farasan Islands in the south.

The Red Sea is a relatively young ocean, created by the formation of a new sea floor along a ridge that separates the African and Arabian tectonic plates. It has a width of approximately 354 kilometers at its widest point, becoming gradually narrower southward to the Strait of Bab el-Mandab, where it connects with the Indian Ocean. Environmental conditions can be extremely harsh, with little rainfall, high solar radiation, strong evaporation and unusually high salinities and temperatures. Because the Red Sea is a relatively isolated body of water, water temperatures can be unusually hot, with peak seawater temperatures in shallow bays and reef flat communities approaching and occasionally exceeding 40°C. Winter seawater temperatures drop to about 20°C in the north and 27°C around the Farasan Banks and Farasan Islands.

The Red Sea is one of the most important repositories of marine biodiversity in the world. The relative isolation of the Red Sea, highly variable physical and environmental conditions, and abrupt changes in depth from nearshore shallow habitats to deep sea environments that exceed depths of 2,000 meters in the central rift, have given rise to an extraordinary range of ecosystems and biological diversity. The most renowned facet of the Red Sea is the elaborate system of coral reefs. These reefs exhibit striking contrasts in their biology and environmental attributes, and in the degree of human influence. They include some of the most northerly reef

communities, which are subjected to harsh climatic conditions such as unusual temperature extremes, some of the highest salinities known to occur in tropical seas, and high levels of solar radiation. Much of the Red Sea is characterized by narrow coastal fringing reefs that extend tens of meters from shore before dropping into deep water, yet several locations off the Saudi Arabian coastline contain extensive seagrass beds, offshore reef habitats and mangroves, all of which are integrally linked. The Red Sea contains a wide range of reef morphologies such as barrier reefs, patch reefs, ridge reefs, atolls, pinnacles, pillars, and spur and groove structures, as well as algal-derived limestone structures. These habitats often support unique species assemblages, with at least 300 species of scleractinian corals and 1400 species of reef fish identified throughout the region thus far (Devantier et al. 2000a; Kotb et al. 2004).

Red Sea coral reefs have supported artisanal fishery harvests for thousands of years (NCWCD 1995), and most of these fisheries were considered sustainable until recent years. This is partly due to the low density of human populations living along the coasts (Behairy et al. 1992). In the last few decades, increased human settlement in coastal areas and the resultant increase in artisanal and commercial fisheries, for local consumption and to supply a growing international trade in coral reef species and products, have led to depletion of many commercially valuable species. Threats from overfishing and destructive fishing practices have major impacts on the trophic structure and ecological functions of coral reefs, and they may lead to a cascade of deleterious changes unless properly managed. Although large parts of the Red Sea coastline are still undeveloped, many locations face increasing levels of threat from industrial and urban development, untreated sewage, sedimentation associated with land reclamation, dredging, mining, and other industrial activities. Desalinization plants are particularly problematic, as they are critical for freshwater production, but they release warm, highly saline water and toxins such as chlorine. The region encompasses the world's largest oil and natural gas production area and exporter, and one of the largest global shipping routes, with substantial risks from oil pollution, ship groundings, and ballast water discharges (Dicks 1987; Sheppard et al. 1992).

Over the last decade, reefs worldwide have also witnessed an increased frequency of large scale disturbances associated with climate change. This includes catastrophic episodes of mass bleaching, disease outbreaks, plagues of coral-eating predators, and more severe storm damage (Harvell et al. 2007; Rotjan 2008; Baker et al. 2008). When compounded by anthropogenic

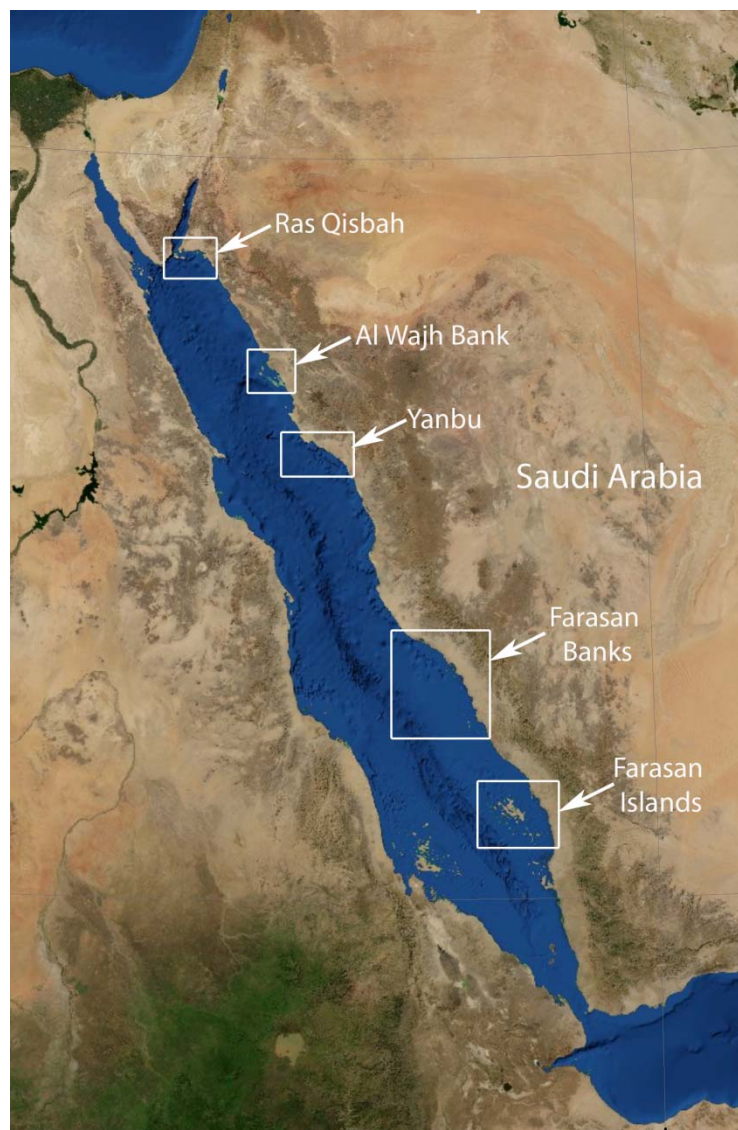
stresses, dramatic, long-lasting changes in community composition and structure have occurred (Hughes 1989, 1994; Knowlton 1992; Aronson et al. 2004; McClanahan et al. 2007). Persistence of reefs as coral-dominated systems, and continued functioning after large, stochastic perturbations depends on four primary factors: the extent of damage, synergistic impacts of anthropogenic and natural stressors, the health and resilience of reef building corals, and the communities' capacity for recovery (Smith et al. 2008). Ecological recovery of normal reef processes has been documented in coral reefs with intact functional groups and a high degree of spatial heterogeneity and connectivity (Nystrom et al. 2008), while degraded, overfished reefs fail to recover, even after several decades of protection through MPA designation.

Given the recent expansion of dive tourism in the Red Sea, and a greater recognition of the importance of coral reef ecosystems for socioeconomic development, new approaches to enhance management and conservation are being considered (Kotb et al. 2008). The recent *Regional Action Plan for the Conservation of Coral Reefs in the Red Sea and Gulf of Aden* (the Regional Plan encompasses all countries except Eritrea; PERGSA 2003) defines priority actions for the conservation and sustainable development of coral reefs pertaining to six major objectives: 1) integrated coastal zone management; 2) education and awareness; 3) marine protected areas (MPAs); 4) ecologically sustainable reef fisheries; 5) impacts of shipping and marine pollution; and 6) research, monitoring and economic valuation. The overall objective of the Regional Plan is to maintain the intrinsic biodiversity, ecological integrity, and aesthetic beauty of coral reefs, while ensuring their continued use and provision of ecosystem services (Gladstone 2000, 2002; Roupheal and Al-Yami 2000a; Kotb et al. 2008). Several other action plans for the region provide recommendations on systems of protected areas, fisheries measures and other conservation actions (Child and Grainger 1990; Gladstone 2000; Gladstone et al. 1999).

Over the last two decades a number of coral reef studies have been completed off the Red Sea coast of Saudi Arabia, including baseline characterizations of reef types and coral community structure (Sheppard & Sheppard 1985, 1991; Devantier et al. 2000 a, b; Roupheal and Al-Yami 2000 a, b), identification of coral diseases (Antonius 1985) and coral predators (Al-Yami and Roupheal 2000), characterization of the extent and impact of bleaching, and assessment of fisheries (Kedidi 1984; Gladstone 2002). Between 1997 and 1999, the distribution and composition of coastal and marine habitats of the central-northern Red Sea (north of Jeddah to



Haql in the Gulf of Aqaba) were assessed through a joint study conducted by the Saudi Wildlife Commission (SWC) and the Japanese International Cooperation Agency (JICA 2000). This study produced detailed biological inventories for corals, fish, marine mammals, turtles, birds, algae, seagrass, mangroves and coastal vegetation. The research combined socio-economic assessments of patterns of human use and detailed habitat maps prepared from aerial photos and satellite images to define marine areas of high conservation significance for MPA planning (JICA 2000). The current project implemented by the Khaled bin Sultan Living Oceans Foundation builds upon the JICA study, evaluating some of the same areas examined by the JICA researchers, as well as other locations in southern Red Sea.



**Fig. 1a. Five major areas examined by the Living Oceans Foundation during the four year research mission. Base image provided by Google.**

The main purpose of the current research conducted by the Foundation was to provide current and updated information on the status and trends of Saudi Arabian coral reefs and to develop higher resolution habitat maps that could be used for development of a landscape-scale plan for management and conservation. The efforts included 1) collection of baseline data from remote, offshore locations in the southern Red Sea around the Farasan Banks and Farasan Islands; 2) collection of updated information on nearshore coral reefs off the central and northern Saudi Arabian coastline, including the Yanbu, Al Wajh and Ras Qisbah sections of the Red Sea; 3) characterization and mapping of shallow marine habitats; 4) compilation of the knowledge and development of tools that can assist in implementing spatially-based conservation measures; 5) identification of measures that will help promote conservation and sustainable use of coral reef ecosystems and resources, and provide insurance against catastrophic declines of coral reefs and losses of ecosystem services that may be induced by large scale global disturbances; 6) education on the findings of this work for the public, non-government conservation agencies and government agencies responsible for marine resource management; and 7) guidance and training in the use of the GIS database and other deliverables resulting from the research missions.

The following report summarizes the major objectives, findings, outcomes, and relationship with other plans developed for the Red Sea. The *Executive Summary* provides an overview of the work completed, major findings and ten summary recommendations for conservation action. This is followed by introductory materials that set the stage for the report as follows: Section 1, *Introduction* highlights the main features and attributes of the Red Sea. Section 2, *Objectives* identified the primary activities and why these were undertaken. Section 3, *Outcomes* discusses the value and use of the information. Section 4, *Relationship with existing plans and recommendations* establishes linkages between this project and other projects and initiatives for this region. A detailed section on methodologies used to complete the ground-truthing, habitat characterization and development of high resolution habitat maps, along with a summary of methods used for underwater SCUBA assessments follow the introduction. This document is divided into a section on general trends, including 1) major habitats observed in the shallow marine environment off the Red Sea coastline, 2) status and trends of reef communities, 3) population dynamics of corals, reef fishes and other organisms, 4) threats, 5) resilience indicators, 6) sea turtles, 7) marine mammals, and 8) geological findings. Detailed assessments of each region are summarized in a separate document.

## 2. Objectives

**A. *Assess and map the shallow water benthic habitats of the Saudi Arabian Red Sea coastline, from the shoreline to offshore reef systems up to 100km offshore.***

In addition to acquisition of multispectral satellite imagery and detailed hyperspectral datasets, acoustic bathymetry, underwater ground referencing information using drop cameras and photo-transects, seafloor optics of major habitat features, and measures of specific oceanographic parameters (e.g., salinity and temperature) were undertaken.

**B. *Conduct fish-census surveys to document a baseline of fish types and populations.***

This baseline will prove important to measure future changes in fish populations resulting from any management actions in the Farasan Islands MPA subsequent to this research project. The fish census focused on (i) aquarium species, (ii) key functional species such as parrotfishes and surgeonfishes, and (iii) commercially important species, including higher trophic level predators (e.g. grouper, barracuda, snapper).

**C. *Characterize reef building corals within representative locations throughout the Saudi Arabian Red Sea.***

Benthic cover, population dynamics, size structure, species diversity and abundance of dominant genera of corals were assessed in representative locations.

**D. *Conduct a comprehensive survey of coral bleaching, disease and predation by *Drupella* spp. gastropods and *Acanthaster planci* sea stars.***

The prevalence and impacts of these stressors were quantified for each site. This provides a measure of the current health of these communities and will serve as an important baseline for future monitoring of natural stressors.

**E. *Conduct a survey of associated coral reef habitats to characterize their locations, size and composition.***

Coral reefs, mangroves, sea grasses and sand beaches are identified on habitat maps and representative coral reefs were assessed in detail. Additionally, these habitats were catalogued and mapped using georeferenced satellite imagery, hyperspectral surveys, and boat surveys.

**F. *Conduct a survey of marine mammals and turtles***

Sitings of turtles, dugongs, whales and dolphins occupying marine environments within each study location were identified and recorded using GPS.

**G. *Create a high-resolution paper and electronic benthic habitat maps for shallow Red Sea marine environments off the coast of Saudi Arabia.***

Habitat maps were derived from high resolution QuickBird multispectral satellite imagery using (DigitalGlobe Inc.) and airborne hyperspectral imagery correlated (“supervised”) with in-situ survey data. The electronic habitat atlas was created using advanced Geographic Information System (GIS) technology with linkages to other datasets compiled during the mission. A hard copy atlas was also created to facilitate viewing of the distribution of habitats within each region.

**H. *Conduct a national and international education and outreach campaign.***

The education program conveyed the importance of this project to the scientific community at large and, more importantly, to the general public with the aim of enhancing marine conservation awareness. A film documentary of one component of the research expedition (Farasan Islands) was commissioned and a scientific symposium was conducted in Jeddah (January 2012) to inform local constituents of the importance of this work.

**I. *Analyze and compare the similarities and differences between similar benthic habitat types within the five regions of the Saudi Arabian Red Sea coastline.***

Using data obtained over the four years on the structure, composition, health, threats and resilience, the state of marine benthic habitats were compared and contrasted among regions and also between developed and undeveloped coastal areas.

**J. *Identify indicators of resilience for the Red Sea and characterize the “resilience” of coral reefs in the Saudi Arabian Red Sea.***

Measures of the diversity, abundance and cover of corals and abundance of specific biological indicators [e.g., mobile invertebrates, algal functional groups including crustose coralline algae (CCA), corallivores, herbivory, recruitment], physical indicators (depth, reef slope, rugosity, distance to neighboring reefs etc.), and oceanographic indicators (current patterns, upwelling, tidal change, temperature) were measured using a quantitative and/or semiquantitative approach and differences between depths, exposure, and levels of anthropogenic stressors were evaluated.

**K. *Provide recommendations on management options.***

Recommendations for marine spatial planning are presented. Potential sites that should be protected as MPAs are identified and justification for the protection of these sites is summarized. Fishery management options and best practices for management of land-based stressors are also summarized for each region. All recommendations are presented using a landscape scale approach, the GIS database and habitat maps.

### 3. Outcomes

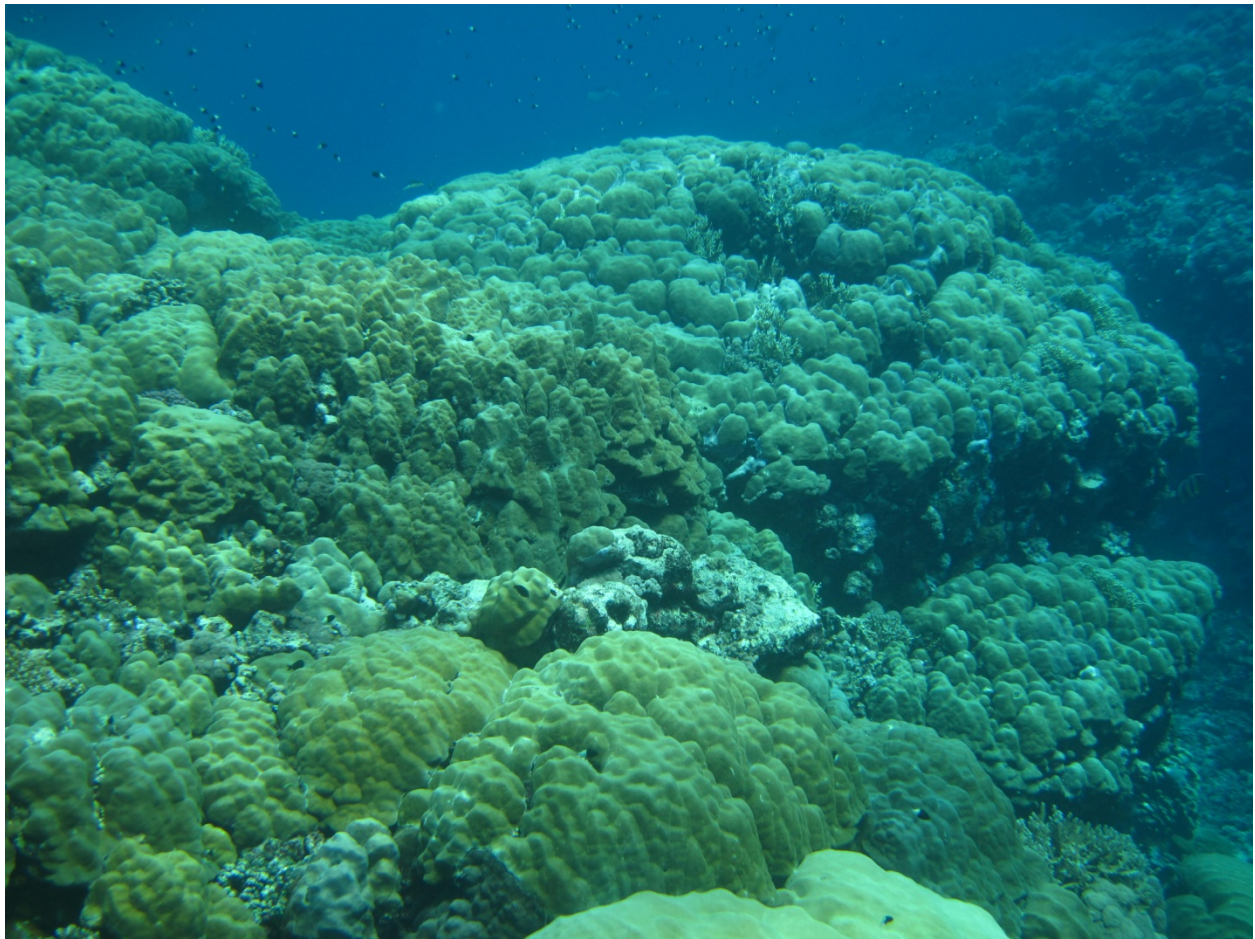
The four year Red Sea research mission collected information on 1) locations of coral reefs and other associated shallow marine habitats; 2) the spatial extent and distribution of different habitat types; 3) community structure and species composition of reef habitats; 4) coral condition; 5) impacts of past disturbance and ongoing threats; and 6) indicators of resilience for the major coral reef systems off the coast of Saudi Arabia. The resulting georeferenced high resolution habitat maps, imagery, digital images and video and associated information and data are compiled into a Geographic Information System (GIS) database that is available for use in management regimes and conservation actions, as well as a spatial framework for future monitoring and research activities. This GIS database will be provided to the Saudi Wildlife Commission (SWC)<sup>3</sup>, the Regional Organization for the Conservation of the Environment of the Red Sea & Gulf of Aden (PERGSA), Kingdom of Saudi Arabia Ministry of Agriculture Marine Fisheries Department (MFD), Presidency of Meteorology and Environment, Saudi Arabia (PME), and other relevant government agencies, universities, scientists, managers and NGOs in Saudi Arabia, as requested. In addition to the GIS database, other informational tools, including the *Khaled bin Sultan Living Oceans Foundation Atlas of Red Sea Marine Habitats* and accompanying CD of the maps in HTML format, a hardcover book on coral reefs of the Saudi Arabian Red Sea, underwater identification guides, conservation recommendations, and numerous peer-reviewed scientific publications from these studies will be made available.

This project involved a landscape scale analysis of coral reefs and associated habitats located off the Saudi Arabian Red Sea coastline. Over the four year mission, methods were developed, tested and improved, with the final methodologies forming a standardized approach being implemented globally during the Khaled bin Sultan Living Oceans Foundation's Global Reef Expedition. These include standardized assessments used to 1) identify shallow marine habitats and create habitat maps, and 2) SCUBA survey approaches to characterize the benthic cover of different organisms and substrates; evaluate the population dynamics and health of reef building corals and reef fishes; and it is our intent for this information to be used to assist local managers in implementing spatially-based management actions, such as the design and implementation of large-scale networks of marine protected areas. It can also aid in the designation of a monitoring

---

<sup>3</sup> SWC, formerly the National Commission for Wildlife Conservation and Development (NCWCD)

program and serve as a spatial framework for other management initiatives aimed at reducing human impacts. The coral reef assessment data can be used to forecast the future condition of these reefs, based on levels of recruitment, herbivory, threats, and other ecosystem attributes. The study also identifies the most urgent human impacts causing degradation and reduced resilience (e.g. land-based stressors and fisheries impacts), and provides recommendations on strategies to mitigate the impacts. By implementing recommendations on relevant spatial scales, and using the high resolution habitat maps as a landscape scale spatial framework, it will be possible to effectively manage these stressors and ensure the reefs are as healthy and resilient as possible. These actions can help minimize risks of global climate change by 1) protecting representative and replicated areas of major habitat types; 2) safeguarding key sources of larvae; and 3) maintaining ecological connectivity between habitats.



Large colonies of *Porites lutea* in the Farasan Banks. This is a critical frame builder in the Red Sea.



#### **4. Relationship with existing plans and recommendations**

The outcomes of this project align closely with several components of *the Regional Action Plan for the Conservation of Coral Reefs in the Red Sea and Gulf of Aden* (PERGSA 2003):

##### **Component 1: Integrated Coastal Zone Management (ICZM):**

The knowledge gained about the shallow marine benthic habitats in coastal waters as a result of this project should provide extraordinary detail by which the Saudi government, Saudi Wildlife Commission (SWC), the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), the Ministry of Fisheries, and other relevant environmental ministries may refine and improve national and regional ICZM plans.

##### **Component 2: Education and Awareness:**

The public outreach campaigns undertaken in conjunction with this research project are directly aligned with Component 2 of the Regional Action Plan with the stated objective of “The raising of public and government awareness of the importance of reefs and of their current threats is crucial to their long-term conservation.” We conducted multi-tiered education and awareness programs before and during the expedition (live webcasts and blogs), post-expedition meetings with government agencies, a professional documentary film about the research project, and a final Red Sea Coral Reef Symposium in January 2012. Our objective was to reach three tiers of audiences through our education and outreach efforts: national, regional, and global.

##### **Component 3: Marine Protected Areas (MPAs):**

One of the stated conservation objectives for MPAs is “Maintenance or restoration of reef communities, habitats, nesting and breeding areas and genetic diversity.” The high resolution multispectral and hyperspectral data and resulting bathymetric maps and habitat maps associated with this project provide keen insight into the location, spatial extent, type, and health of the various marine habitats throughout the Saudi Arabian Red Sea. The habitat atlas and associated GIS database will be of immeasurable help in creating meaningful zoning plans for existing and future MPAs.

**Component 4: Ecologically Sustainable Reef Fisheries:**

By combining existing fisheries data on commercially important stocks with the detailed habitat maps created from the Foundation's surveys and research, regional authorities will be able to logically develop "no-fishing" zones for the protection of reproductive stocks of commercially important reef fishes and will help ensure sustainable use of coral reef resources.

**Component 5: Impact from Shipping and Marine Pollution:**

Detailed habitat maps will be useful for regulating anchoring and they can also be very useful in positioning permanent mooring buoys in areas of low sensitivity, minimizing damage to valuable coral reefs.

**Component 6: Research, Monitoring, and Economic Valuation:**

The Regional Action Plan states that "Effective reef management needs the provision of accurate information on the present status of the ecosystems, both for ICZM and MPA planning and for the assessment and monitoring of reef status and reef fisheries and of the effectiveness of management itself." This project provided very accurate and detailed information on the present status of the coral reef ecosystems off the Saudi Arabian Red Sea coastline, with emphasis on the Farasan Islands MPA, Farasan Banks, Yanbu, Al Wajh Bank and Ras Qisbah. The resulting "baseline" habitat maps can help determine changes in the marine environment for years to come.



**Table 1. Types of scientific information collected during this mission for use in landscape scale habitat management and marine spatial planning.**

| Category                           | Value of information and use in management                                                                                                                                                                                                                                                                                                                                                                       |
|------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Habitat mapping                    | Provides a tool to identify habitat types, sizes and boundaries through development of high resolution habitat maps using multispectral satellite imagery and field validation of bathymetry, structural features, substrate types, environmental attributes and dominant species assemblages.                                                                                                                   |
| Characterize species assemblages   | Information on the composition, distribution and population structure of ecologically relevant organisms (corals, fish and algae) within representative habitats and differences across biophysical and anthropogenic gradients can help identify the biodiversity of a site and the vulnerability of that site to disturbance and human impacts.                                                                |
| Assess ecosystem health            | By understanding the major threats and synergistic impacts of multiple threats to ecologically relevant organisms, and characterizing how these stressors vary spatially (latitudinal, with distance from the mainland, and over depth gradients) and how they degrade coral reef resilience, managers can determine the most relevant stressors that need to be addressed.                                      |
| Characterize resilience indicators | Knowledge on key biological, ecological, physical, and environmental attributes that enhance coral reef health and resilience can be used to improve the design of management areas including networks of MPAs. These measures also can help characterize the vulnerability of sites and develop predictions on the stability and changes to sites under different management scenarios and disturbance regimes. |
| Evaluate the human dimension       | Existing scientific knowledge, management scenarios, and socioeconomic attributes of the management unit, targeting extractive uses (fishing) and non-extractive value of coral reefs (tourism) can help determine the economic implications of different management scenarios.                                                                                                                                  |
| Categorize and rank reef condition | A “report card” on the condition of individual sites within the larger management unit, can help raise awareness of the importance of the site for biodiversity conservation, connectivity, presence of unique or rare organisms, and intact trophic assemblages, and the need to address certain human impacts.                                                                                                 |
| Identify critical areas            | Habitat maps can assist managers in identifying possible marine protected areas, with consideration of optimal size, shape, representative habitat types, replication of representative sites, connectivity, and ecosystem attributes.                                                                                                                                                                           |

## 5. Methods

### 5.1 Vessel support and equipment

All field work was carried out using the 67m M/Y Golden Shadow and its various support vessels, generously donated by HRH Prince Khaled bin Sultan of the Kingdom of Saudi Arabia. The vessel carries multiple surface support vehicles, including two catamarans, inflatable hull boats, kayaks and wave runners. The Golden Shadow has a stern elevator platform used to



**Figure 5.1a. M/Y Golden Shadow**

launch and recover the Golden Eye, as well as its various tenders, and can handle loads up to 12 tons. The platform is also invaluable for diving access and recovery in difficult sea conditions. The Golden Shadow also contains a fully functional dive locker, with a compressor and storage bottles for standard air tanks, as well as a recompression chamber capable of

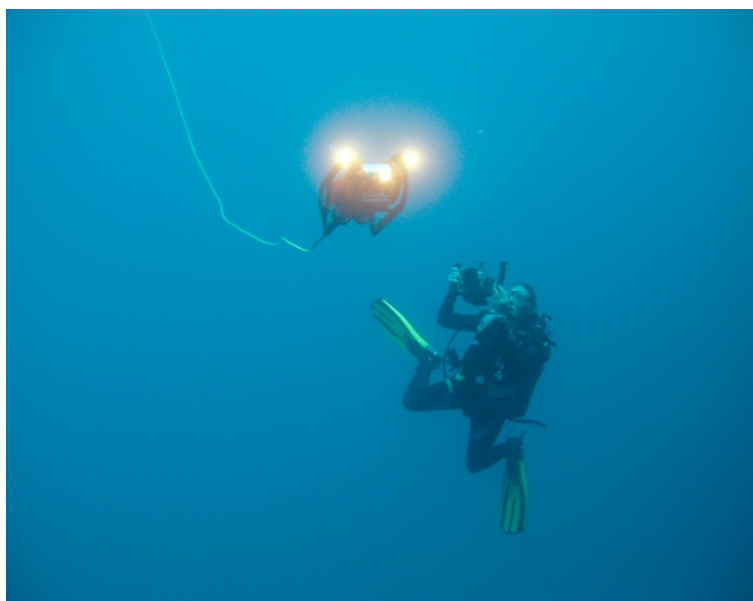
accommodating one casualty and a medic. The vessel also has a small laboratory, currently outfitted with a sterile hood, a flow-through sea water system and multiple aquaria. The vessel held up to 16 researchers in single and double berth cabins during research missions in Saudi Arabia, in addition to Saudi military and other support personnel. Fully qualified medical staff members were present during all dive operations, along with a dive safety officer, crew and officers.



**Fig. 5.1b. The Golden Shadow's stern elevator and dive boat.**

The Golden Shadow was also used to transport and deploy the Golden Eye, a Cessna sea-plane used for aerial photography and hyperspectral surveys off Al Wajh Banks and Farasan Islands.

The Foundation researchers also operated a small remote operated vehicle with a high resolution video camera, capable of accessing depths to 125m. Other equipment used to aid in mapping and groundtruthing included a drop camera for video imagery, a heavy duty laptop with Fugawi software for navigating in real time using multispectral satellite imagery, a portable depth sounder integrated with a high accuracy dGPS, and various sediment profilers. Portable water



quality monitoring equipment, a LICOR light sensor and high resolution digital still and video cameras were routinely used for *in situ* data collection. Further support was provided by a professional videographer during several legs of the expedition.

**Fig. 5.1c. SCUBA diver and a tethered remote operated vehicle (ROV)**

## 5.2 Image Acquisition

Most coral reef mapping is achieved through optical remote sensing using either aircraft or satellites. Remote sensing instruments provide a synoptic portrait of the Earth's surface by recording numerical information on the radiance measured from a series of picture elements (pixels) across a number of spectral bands. Sensors are broadly divided into hyperspectral and multispectral on the basis of the band windows in which they sample the electromagnetic spectrum. Multispectral sensors measure radiance data for several spectral bands for each pixel of the image (Rees 1999), while hyperspectral sensors sample many narrow sections within each band to provide a contiguous coverage across the spectrum (Mather 2004). The unique spectral response of each target, or in other words, the amount of light reflected by a surface at different wavelengths, is ultimately recorded by these sensors. Producing a map from remotely sensed imagery involves assigning pixels to classes of interest through the discrimination and isolation

of the unique spectral reflectance properties of coral reef benthic communities. Benthic habitat maps produced during this project for the Red Sea coast of Saudi Arabia were created through visual interpretation of high spatial resolution (2.4m pixel) multispectral QuickBird imagery and Hyperspectral imagery using a CASI sensor (Farasan Islands) and an AISA Eagle sensor (Al Wajh Bank).

### **5.2.1 Multispectral imagery**

The QuickBird satellite (DigitalGlobe Inc.) provided the bulk of imagery used for map making. The spatial resolution of QuickBird is around 60cm (pan-chromatic) and 2.4m (multispectral) across a wavelength range of 450-900nm. The swath width for each image scene is 16.5km × 16.5km. A total of 25,000km<sup>2</sup> of QuickBird imagery was purchased by the Khaled bin Sultan Living Oceans Foundation. The imagery is collected at 11-bit precision pan-chromatic and four-band multispectral with resolution of about 1m (Pan) and 2m (blue, red, green and NIR) with a  $\lambda$  range of 450-900nm. Satellite scenes spanned the length of much of the Saudi Arabian Red Sea coast, extending from the shoreline to depths of 20-30m, up to 100km offshore. Landsat ETM+ (NASA/U.S. Geological Survey) imagery was also used for navigation and site-selection in the field, as well as for habitat classification on occasions where cloud obscures reef features in the QuickBird scenes. Landsat imagery has a coarser spatial resolution of 30m<sup>2</sup>.

### **5.2.2 Hyperspectral imagery**

Airborne hyperspectral imagery is an emerging technology for classifying benthic habitats in coastal zones at a much higher resolution than possible with multi-spectral satellite imagery. Hyperspectral sensors generate datasets that typically contain hundreds of spectral bands; they have a spectral resolution (centre wavelength divided by the width of the spectral band) on the order of 100 and are composed of contiguous and narrow regularly spaced spectral bands, leading to a continuous spectrum for each pixel. Although the resolution obtainable using a hyperspectral sensor is very high, there are several limitations to this technology. Firstly, it is more time intensive and costly to obtain the imagery, as the sensor is mounted on a plane which must be flown in narrow, adjacent bands. The imagery requires additional field data to correct for the attenuation of incident and reflected light as it passes through the atmosphere and water column and to georectify the locations. To discriminate between reef communities, narrow (~10nm) spectral bands are necessary to detect subtle differences in reflectance between the

dominant organisms found in different habitats including differences between seagrass and algae and between coral and algae, and also between different types of algae such as brown vs. green algae. Classification of the major benthic assemblages and different habitats within coral reef ecosystems requires the selection of combinations of wavelengths (bands) that underscores the distinct spectral characteristics in the visible section of the electromagnetic spectrum (400-700nm). Using multispectral satellite imagery, single wavelengths within the green, blue and red bands are used to distinguish between features of interest in a coral reef environment. Because of a larger number of spectral bands and higher spectral resolution available with a hyperspectral sensor, it is possible to identify a larger number of habitat types and discriminate among substrate types and biota (e.g., live and dead coral) within individual pixels. Through spectral unmixing, it may also be possible to determine the contribution of specific organisms or other constituents to total benthic coverage (e.g. coral vs. algal cover) and to measure change in the coverage within specific habitat types. When combined with ground-truthing data on turbidity,



rates of sedimentation, and other physical processes, it may also be possible to identify the major factors responsible for the physical structure of these habitats.

**Fig. 5.22. Goldeneye sea plane deployed from the Golden Shadow and used to conduct hyperspectral surveys in the Farasan Islands and Al Wajh Bank**

The CASI 550 (Itres Inc.), an aircraft-mounted sensor was used in the Western Farasan Islands in 2006 to survey an area of approximately 3,200km<sup>2</sup>. Flying at an altitude of 1.3km, data were collected at 1.5m<sup>2</sup> pixel resolution, with 19 bands assigned between 400 and 660nm and 2 bands within the near-infrared (NIR) region (700-900nm), representing a non-contiguous 21-band hyperspectral dataset. The AISA eagle (SPECIM Ltd.), also an aircraft mounted sensor, was used in Al Wajh in 2008 to survey an area of approximately 2000km<sup>2</sup>. Hyperspectral data were acquired at a 1m<sup>2</sup> pixel resolution, with a maximum of 244 bands assigned between 400 and 1,000nm. This represented a continuous hyperspectral dataset spanning the visible and infrared spectrum. Both hyperspectral sensors were mounted on the Cessna seaplane.

### **5.3 Groundtruthing**

Field data collection, commonly referred to as “groundtruthing”, was necessary to facilitate the production of robust and regional-scale coral reef maps with a high degree of accuracy. Data acquisition focused on water depth soundings, optical measurements, and accurately located habitat census. The main emphasis of groundtruthing focused on localized acoustic measurements, photography and tethered-videos of the seafloor at defined points along the acoustic tracks, and light reflectance measurements. Geographic positioning, through use of differential Geographic Positional System (GPS) technology provided the means to link remote datasets with information collected on the ground.

#### **5.3.1 Single beam sonar**

Single-beam sonar, operated vertically directly below a small catamaran vessel was used in mapping Ras Qisbah, Al Wajh, Yanbu, the Farasan Islands and the Farasan Banks. A 200kHz acoustic echo-sounder was used during the first three expeditions. This emits a sound-pulse five times per second, collecting depth information with an accuracy of  $\pm 0.2\text{m}$  to a max operating depth of 60m. A more advanced hydrographic survey-grade acoustic sounder was used in the Farasan Banks. This also operated over the 200 kHz range, although the instrument emits an acoustic pulse ten times per second and delivers an accuracy of  $\pm 0.1\text{m}$  to an operating depth of 200m. Both devices were linked to a high accuracy dGPS unit, and run continuously during the ground-truthing process. Over 2.7 million depth soundings, covering a total 1,400km of survey track were acquired for the five locations. The survey vessel’s track was routed to include a range of depth contours across a variety of seafloor types.

#### **5.3.2 Sub-bottom profiler**

Within the Farasan Banks region, a portable sub-bottom profiler (StrataBox<sup>TM</sup> and HydroBox<sup>TM</sup>) was used to characterize sediment layers. This instrument emits a low-frequency acoustic wave that propagates through the seafloor and down into the underlying rocks and sediments, allowing it to detect different sediment layers at a resolution of 6cm with up to 40m sub-seabed penetration. By measuring the time taken between the instrument emitting a pulse and receiving the various echoes back, a two-dimensional digital representation of the structure beneath the seabed is generated. In addition, the profiler also provided deeper water depth soundings,

providing bathymetry measurements to 800m with an accuracy of  $\pm 0.5\%$ . Approximately 100km of sub-bottom survey was completed, using either a 10kHz or 3.5kHz transducer depending on depth and substrate hardness, targeting areas identified from satellite imagery as potentially containing suitable reef structures below the sediment layer. Transects run with the instrument were routed perpendicular to slopes, bisecting lagoon systems and other geomorphological features of interest.

### **5.3.3 Spectral reflectance measurements**

Using a submersible spectroradiometer, measurements of reflectance signatures (the quantity and quality of light reflected off of a small target) from terrestrial and submerged habitat-types were acquired. Reflectance spectra were captured for exposed bright beach sands, the dark deep ocean, live and dead coral, algae, seagrass and other features which represent the end-members in brightness encountered in the satellite imagery. These measurements, coupled to computer modeling, were used to aid in the atmospheric correction of the satellite and aircraft imagery and to enhance habitat mapping from the hyperspectral airborne scenes.

### **5.3.4 Photography and videography**

Direct seabed observation using photography and videography of the seafloor provided fine scale mapping resolution, but were only used in small areas of interest due to the time required to complete these assessments. The groundtruthing team used a combination of Remote Operated Vehicles (ROVs), tethered- video, and SCUBA-based photographic surveys as a means to collect more detailed information on specific habitats and the organisms found there.

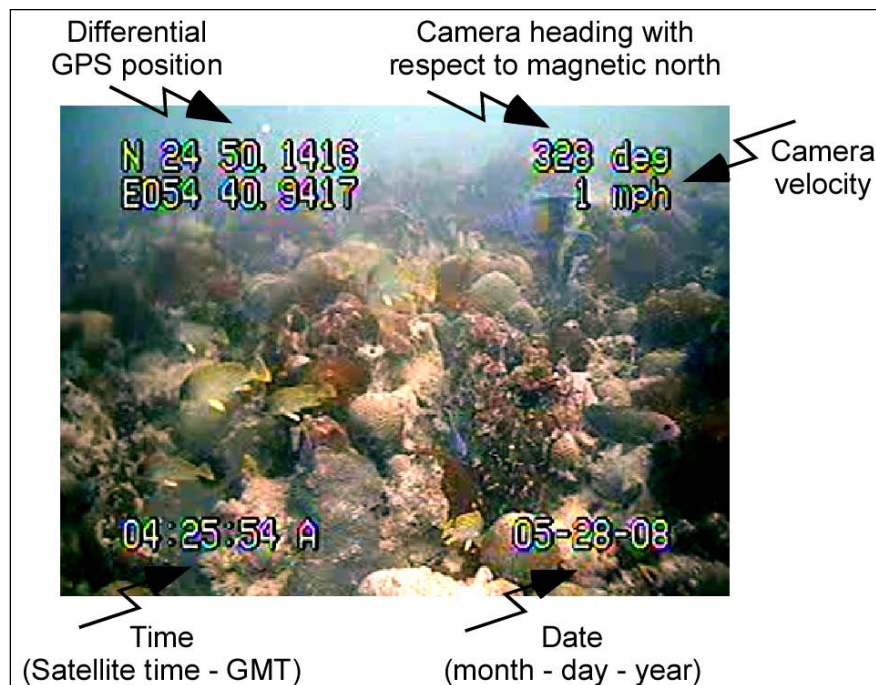
Tethered video cameras were deployed directly from the boat and recovered from depths of up to 50m. Using an accurate dGPS, coupled to navigation software, the survey team worked with the QuickBird satellite imagery in real-time, carefully targeting features with the tethered-video setup to acquire data encompassing the full range of seabed geomorphology and habitat encountered. At each survey point, a submersible tethered-video camera was lowered and ‘flown’ one meter above the sea-bed for a period of approximately 10-30 seconds. Over 3,500



individual points were videoed. The movie-clips were analyzed and classified into discrete habitat types, and used to develop a habitat classification scheme for the region.



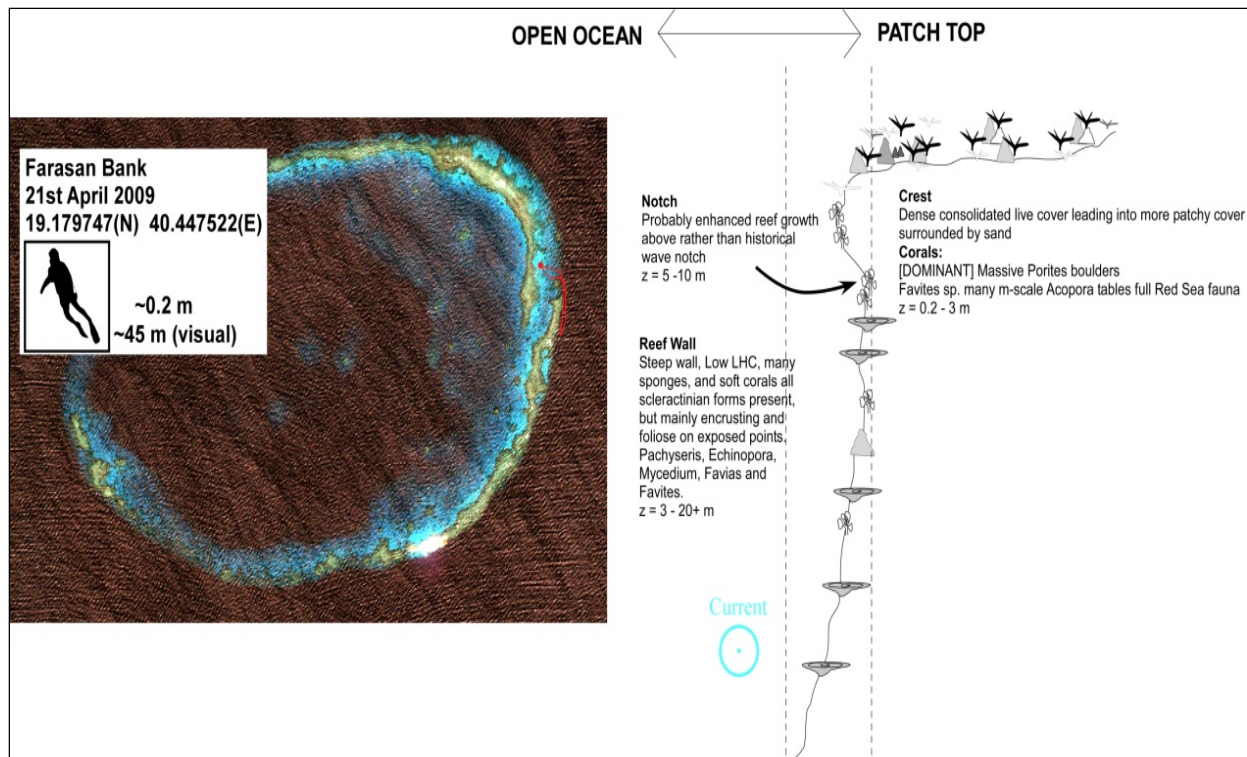
**Fig. 5.3a. Drop Camera:** The underwater camera is lowered into the water by a reinforced cable. Underwater, the rear fin ensures that the camera flies straight and does not spin, thus producing a stable picture.



**Fig 5.3b. Example frame from underwater video.** The GPS position, Heading, time and date are embedded onto the video imagery.

Reef areas of up to  $100\text{m}^2$  were also mapped to fine-detail using underwater photo-transects. Multiple digital photographs collected along transects were stitched together into mosaics two meters wide by 10 meters in length. Photo-transects provided a centimeter-scale audit of substrate diversity used as calibration for the vastly more expansive, yet coarser-scale, satellite and aircraft mapping.





**Fig 5.3c. Example of reef profiles generated from broad scale SCUBA assessment; site location, depth profile, species composition and relevant geomorphological information are shown.**

## 5.4 Initial processing of imagery

### 5.4.1 Optically derived water depth

Using multispectral or hyperspectral imagery and the relevant sub-set from the millions of acoustic depth soundings collected, seafloor topography was optically derived. A mathematical model was employed that involves taking the ratio between the log of the electromagnetic energy measured in the blue satellite wave-band, and the log of the neighboring green band. The output is an image containing values that vary strongly based on differing water depth, but only weakly as a function of seabed character. This ‘pseudo-bathymetric’ image is subsequently calibrated to real-world depth with reference to the large number of acoustic soundings obtained in the field. The resultant Digital Elevation Model (DEM) yields a calibrated and robust bathymetry to the maximum depth of green light penetration (i.e. the shorter of the two wavelength used in the band-ratio) which typically is on the order of 15 to 25m water depth. Accuracy is generally within  $\pm 50\text{cm}$  at depths below 5 meters, increasing to  $\pm 1.5\text{m}$  at 20 meters. DEMs calibrated on image data provide a good approximation of surface topography across all the areas mapped.

### 5.4.2 Water column correction

The spectral influence of the intervening water column may hamper seafloor habitat classification from optical sensors, requiring use of a correction algorithm which empirically accounts for the near-exponential attenuation of light by water with increasing wavelength. Spectral profiles of light attenuation were collected in the field using a submersible spectroradiometer to allow the selection of viable water-quality parameters for model-input. Using a *Divespec* submersible spectroradiometer, *in situ* measurements of reflected light were collected from different land-cover types, both above and below the water. Reflectance readings were taken from sand at the surface and at 10m depth, of coral and bedrock, and over deep water. These land cover types encompass the brightest and darkest ends of the spectrum, and may be viewed as invariant providing a frame of reference to assess radiometric and atmospheric corrections across the whole satellite image. The thickness (depth) of the water column was known based on from-image depth derivation calibrated by acoustic soundings. Spectral profiles extracted from the imagery over homogenous areas of seafloor substrate provided the means to validate the water column correction model.

### 5.4.3 Image masking

To maximize the efficiency of spectral classification algorithms, all areas irrelevant to the mapping algorithm were masked, including areas of land, cloud and shadow, and optically deep water (e.g. depths below the detectable reflective return from the seabed). Infrared light is fully absorbed within the first few centimeters of the water surface. Land and cloud pixels were easily separated from water-covered pixels using the significantly higher reflection in this region of the electromagnetic spectrum. In the case of the occurrence of clouds, a mask was repositioned to also eliminate areas of the sea-surface darkened by cloud-shadows. Shaded imagery may still contain spectral information relevant to habitat classification, but must be treated separately as comparable substrates in such areas will have very different reflectance values. Optically deep water was identified within the imagery by thresholding low values within the previously described two-band log-ratio image used for depth-derivation. By examining image-values across an area of sand-dominated and sloping seabed, it is possible to set a threshold at which there ceases to be any increase in band-ratio with increasing depth. This value was taken to represent the onset of optically deep water. Beyond this point, spectral based classification is no longer feasible and acoustic methods must be relied upon to interrogate seabed structure.

## **5.5 Production of thematic habitat maps**

Thematic habitat maps were produced by assigning image pixels from remotely sensed imagery to thematic habitat classes. Unlike a spectral-unmixing classification, each considered pixel in the image must be categorized as one, and only one, habitat class. As a first step in thematic habitat mapping process, a classification scheme was developed. A number of different techniques were then hybridized to create the most accurate map possible from the image and ground-truth data acquired. Spectral, textural, edge-detection, as well as landscape context, were all considered within the classification workflow.

### **5.5.1 Edge-detection**

Edge-detection, whereby boundaries are identified within an image corresponding to where brightness changes sharply across a narrow spatial threshold, was used principally to quickly identify objects with clearly defined (i.e. crisp) boundaries. This freed up processing time for defining more complex gradated habitat boundaries. Under ideal conditions the application of an edge-detecting algorithm would result in a set of polygons corresponding to boundaries between objects. This ideal is rarely attainable however, as many spectral discontinuities may arise due to differences in depth, orientation, illumination, as well as changes in the physical make up of the seafloor. Crisp boundaries between land cover types are uncommon in nature. This study therefore did not rely on edge-detection alone for mapping. The technique was used as an efficient way to delineating boundaries between spectrally very bright versus dark habitats, such as exist between sand and seagrass.

### **5.5.2 Spectral Classification**

Different substrates vary in the amount of light they absorb (and reflect) at different electromagnetic wavelengths. Building on this fact, spectral classification algorithms are common and powerful tools in optical remote sensing. Such mathematical models use from-image statistics of reflectance to train probability-driven classifiers. Training classes, groups of pixels with similar spectral character, were taken from homogeneous areas representative of a given habitat as defined by tethered-video observations. Training classes were split based on habitat and depth, to avoid the inadvertent classification of depth thresholds that may remain in areas where water-column correction had not been completely successful. Training classes are

commonly referred to as regions of interest (ROIs). Prior to running a classification, the reflectance spectra described by the different ROIs were explored within bi-spectral plots, which depict the pixel values of one spectral band plotted against another. In the ideal situation, points within these plots would cluster tightly together as a function of seabed type, with little to no overlap between different classes. Where overlap occurred however, this was taken as a strong indication that additional classification tools, such as edge-detection and textural analysis, were necessary. A maximum likelihood classification algorithm was used to calculate the probability that a given pixel belonged to a specific class. The algorithm was not applied to areas that had already been masked as containing terrestrial, deep water, or cloud-contaminated pixels. Each pixel was assigned to the class with the highest probability value output by the maximum likelihood algorithm. Classified pixels relating to the same habitat but at different depths were joined in a subsequent editing step.

### **5.5.3 Textural analysis**

Texture-based classification considers the systematic variation of brightness within a square of numerous image pixels, termed a 'kernel'. Within the kernel, the brightness values recorded by the sensor may be regular and auto-correlated, or else disparate and random. As for the spectral component of the imagery, this textural property varies as a function of seabed type. Through processing with a textural-extraction algorithm, an additional 'textural' image was produced from the original spectral data. This was classified in a similar way to the optical scenes. Unlike spectral classification that considers multiple image-bands however, the textural extraction is conducted on a single band; for these maps the blue band was used because it conferred the greatest penetration into the water column.

### **5.5.4 Contextual editing**

Landscape contextual editing draws on the fact that geomorphological and ecological zonation across a depositional system follows generic and logical rules (near-shore sediments for example are not encountered on the reef-edge). The image was segmented into zones based on reef geomorphology (for example, near-shore, lagoon, back-reef, reef crest, and reef-slope). A small degree of habitat miss-classification is unfortunately inevitable even when both spectral and textural classifiers are employed. Contextual editing provides an efficient means for addressing such errors, placing pixels into classes appropriate to the zone in which they are located. Often a

habitat class would transcend multiple zones. Seagrass for example was never found on reef crests, but is found in both the lagoon and near-shore. Under the scheme devised, a pixel therefore could not be classified as seagrass within the reef crest zone, but would be permissible within the lagoon and near-shore. Similarly, fine-grained sediment such as mud does not accumulate in high energy zones such as the fore-reef and shallow slope, and a decision-rule based on this partitioning can be defined. Use of DEMs provides further contextual support. Sediments for example tend to accumulate at the base of slopes, and in troughs in the topography of the landscape, while being absent on topographic highs.

### **5.5.5 Filtering**

Misclassification due to localized aberrations in the remote sensed image (such as might result from a poorly corrected sea-surface-glinted pixel) must be guarded against. To this end, filters were used. A filter window refers to the number of pixels surrounding a focal pixel over which the filter operates. A convolution filter was most commonly used. This class of filter produces an output where the value of the focal pixel is a function of the weighted average of the surrounding pixels. In natural systems, areas of the same habitat tend to be clumped. If a number of neighboring pixels were similarly classified, it is therefore probable that a focal pixel was correctly classified. A median filter was used to remove the ‘salt and pepper noise’ or ‘speckle’ that arises in a noisy classification. The median filter replaced outlier pixel values in the habitat classification result, yet preserved any habitat patch-edges that were larger than the dimensions of the filter window. Typically a 3 x 3 median filter was used, whereby the pixel in the center of the window was replaced by the most prevalent value of the eight-surrounding pixels (i.e. the median value).

### **5.5.6 Quality control**

As a final step in the habitat classification process, map products were subjected to visual quality control, answering the broad question: did habitat demarcation follow identifiable patterns in the imagery? Where the answer to this question was clearly ‘no’, a second iteration of the classification process focusing specifically on the area of concern was carried out. To conduct this procedure, contrast enhancements were used to visualize different features within the spectral imagery at different water depths. A remote sensed image scene often contains substrates that are spectrally very different, such as land and water. Most remote sensing

software will apply a default linear contrast stretch across the whole of the loaded scene, thereby hiding from view most submerged features. By focusing a contrast stretch on a specific portion of a scene with a narrow range of pixel brightness, features that have similar but still subtly different in their reflectance characteristics were more fully exposed. The habitat classification was compared to imagery under a number of different contrast enhancements.

#### **5.5.7 Accuracy assessment**

An accuracy assessment was carried out using a selection of ground-truth data that had purposely not been used to support the classification workflow. A classification error matrix (also known as a contingency table) was used to quantify map error. Map pixels in the thematic classes were compared to ground-truth data. Overall accuracy, errors of omission (producer's accuracy) and commission (user's accuracy) were calculated for each class. Producer's accuracy is a percentage measure of how often a particular ground class was correctly classified, calculated by dividing the total number of correct pixels for a ground class by the total number of ground truth pixels for that class. User's accuracy refers to the percentage of a map class corresponding to the correct ground class. User's accuracy is calculated by dividing the number of correct pixels for a map class by the total pixels assigned to that class.

#### **5.6 SCUBA Surveys**

In each of the five regions examined during the research missions, teams of SCUBA-certified coral reef scientists conducted underwater assessments of the coral reef community structure. The main intention of this work was to 1) determine the status of organisms that create habitat used by other species (corals) and species that help maintain the health of the habitat (keystone invertebrates and fishes), 2) identify threats, and 3) characterize patterns of recovery from past disturbances. Over the four year program, a simple rapid assessment protocol combining methods from the *Atlantic and Gulf Rapid Reef Assessment* (AGGRA, Lang 2003) and the *IUCN Resilience Assessment of Coral Reefs* (Obura and Grimsditch 2009) protocols was developed and applied to coral reefs in the Saudi Arabian Red Sea coastline. SCUBA assessments were carried out in five major regions (Farasan Islands, 2006; Ras Qisbah, 2007; Yanbu, 2008; Al Wajh Bank, 2008; and Farasan Banks 2009). The final methodology used in the Farasan Banks is presented here, but it is important to note that there were some variations with earlier survey approaches. For example, during the first mission to the Farasan Islands, the only benthic

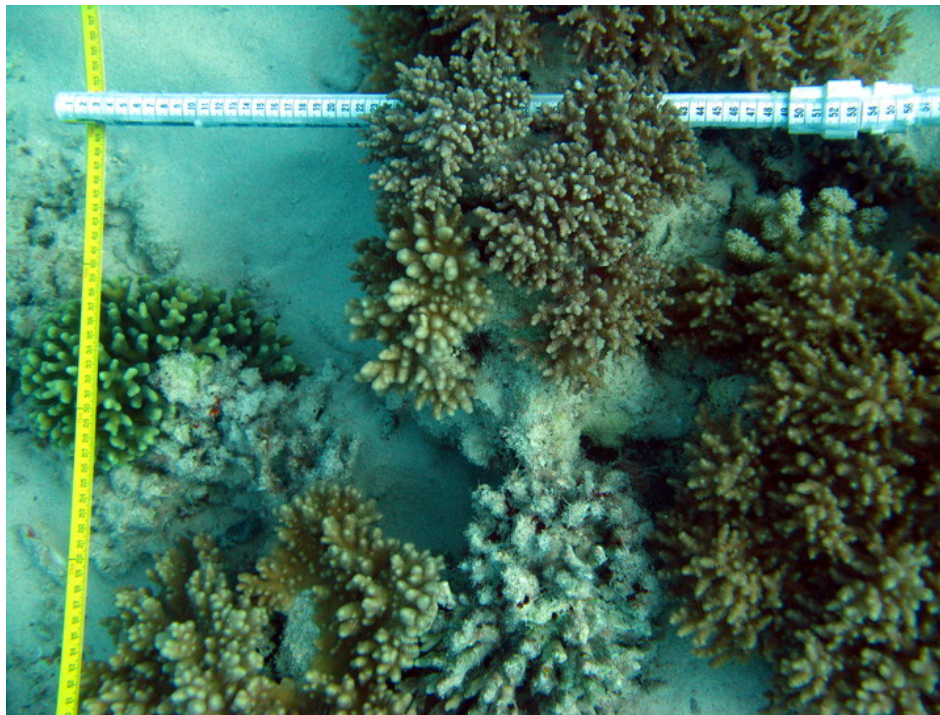
information collected was a series of photo-transects taken in representative sites at different depths and fish surveys evaluated all species of reef fishes observed. The survey approach became more comprehensive in subsequent missions, with researchers assessing 1) the diversity and ecological state (e.g., health) of these ecosystems, 2) the community structure and population dynamics of reef communities, 3) environmental tolerances and biological and spatial factors governing the responses of corals to stressors, and 4) life history traits and linkages with secondary disturbances such as predation and bioerosion. This information was determined in preselected study areas through the use of random stratified surveys. By targeting remote locations, and comparing these to nearshore sites, natural processes can be separated from confounding impacts of human stressors. This approach allowed an evaluation of relationships between community structure and natural processes that control reef functioning, as well as ecological, physical and chemical parameters (e.g., temperature, salinity, alkalinity, current patterns, wave action, and sedimentation) that mitigate or exacerbate responses to climate change.

The primary methods involve photo-transects and direct measurements of fish, corals and algae along belt transects. Coral and fish community structure were examined in randomly stratified locations (within target depths of 3-5 m, 10-12 m and 15-20 m depth) using three approaches: photographic transects, belt transects, and quadrats. Four measures were recorded for corals: 1) benthic cover; 2) coral community structure; 3) coral size class distributions; and 4) coral condition (Table 2a). For fish, a roving survey approach was used to assess overall diversity and abundance; size structure and abundance data were also collected along 50 m belt transects for about 100 species of species of fishes that have a major functional role on reefs. Other indicators recorded included large motile invertebrates (urchins) and cover of algae (fleshy macroalgae, turf algae and crustose coralline algae) (Table 2b).

#### **5.6.1 Benthic cover and population distributional patterns**

Transect tapes were extended along depth contours at approximately 15 m, 10 m and 5 m depths. The depth varied slightly between surveys, depending on the structure of the reef. Continuous digital still photographs were taken of the reef substrate, from a height of approximately 0.6-0.75 meters above the substrate, with photographs overlapping slightly to ensure coverage of the entire belt transect. The transect length (50 m , 25 m or 10 m long) and size of individual images

varied depending on the year of survey and the photographer. Initial phototransects, collected by Dr. Annelise Hagan and Phil Renaud, involved the use of a 0.5 m bar or a 0.5 m angle and a 50 m line. The bar was placed parallel to the transect tape and photographs were taken such that half the image was on the right side and the other half was on the left. The main advantage of this approach is that the observer was fairly close to the bottom and good detail was available in



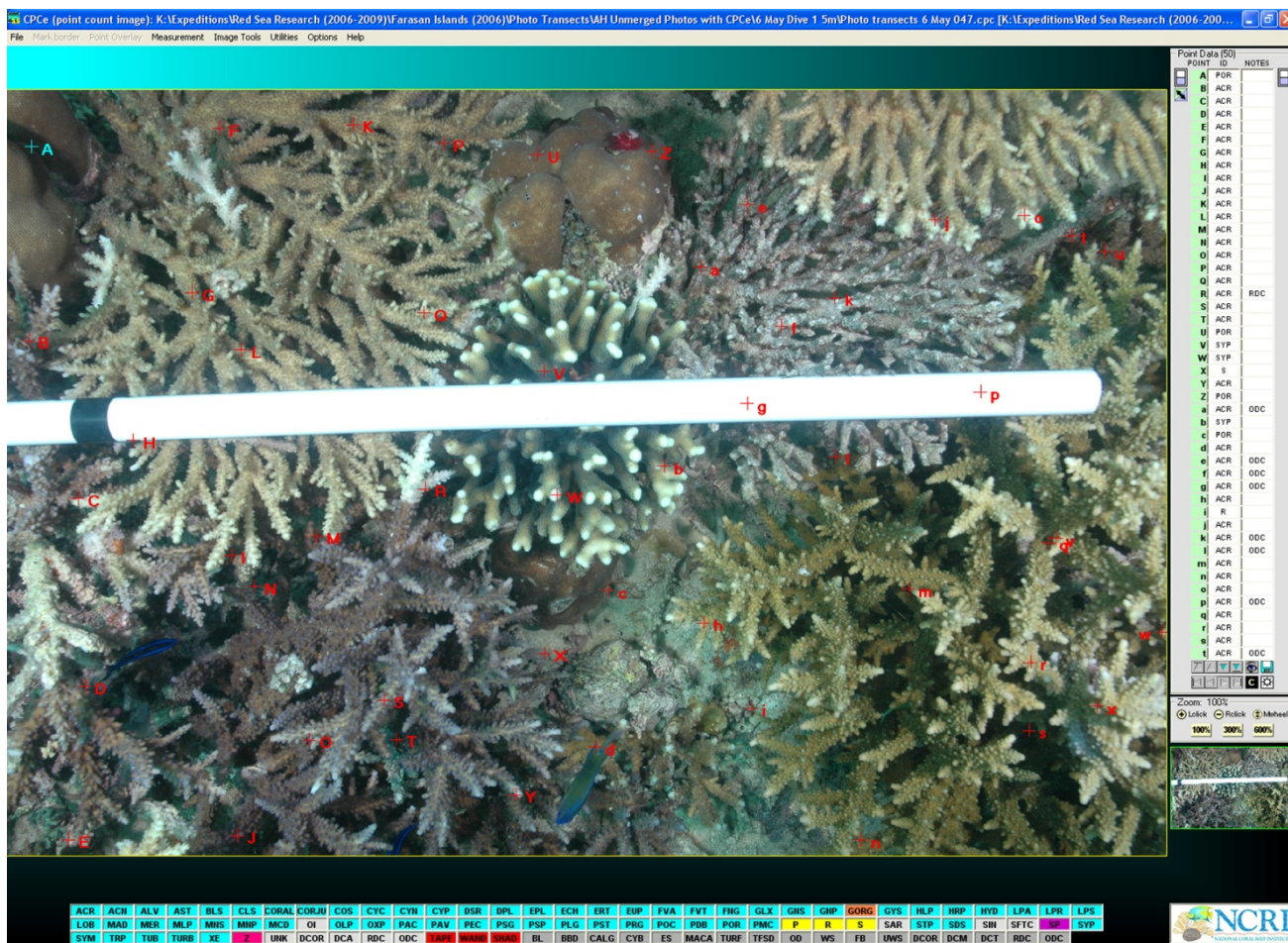
the images. There were also problems with this method, as any relief caused serious errors due to parallax issues and focus because of differences in the distance from the camera lens to the substrate. During analysis of photos, Bruckner

**Fig. 5.6a. Example of a photoquadrat with the scale bar placed perpendicular to the transect line.**

determined that this was not the optimal approach, as the bar obscured a significant portion of the image and the size of individual images was often too small to capture the larger corals. Another limitation was the length of these transects: 50 m tended to extend from coral areas into sandy habitats that are not colonized by coral, complicating measures of coral cover.



Bruckner modified the method to allow sampling of a larger width (10 m x 1 m belt). This involved use of a 1m bar or a one meter bar divided into 1-5 cm increments placed perpendicular to the transect tape for use as a scale bar (Fig. 5.6a). Approximately 20 photographs were taken per transect to allow for overlap between adjacent images. A minimum of two photo transects (each 10 m in length) were conducted per depth. These photographs allowed analysis of cover by major functional group (coral, other invertebrate, algae type), but were generally not adequate resolution to identify corals to species level. As a result, all corals were analyzed to genus level only, which is equivalent to the recorded benthic survey methods.



**Fig. 5.6b.** Example of a photoquadrat opened in CPCE point count software program. Random points are placed onto the photograph, with the placement (random, grid etc.) and total number of points assigned by the user. The codes are listed at the bottom, also developed by the user. In our case, we include coral genera and substrate characteristics as well as coral condition data. Points are compiled in two rows in the top right side of the window, and these can be exported to Microsoft Excel.

For all photo-transects, images were downloaded onto a computer and benthic community composition, including coral cover, cover of other animals and plants and substrate type, and also planar surface area of corals were assessed. Cover was determined by recording the benthic attribute located directly below a random point, with 30-50 points per photograph (depending on the size of the image; e.g. 30 points for 0.5 m<sup>2</sup> photo and 50 points for a 1 m<sup>2</sup> photo), using Coral Point Count (CPCE) software developed by the National Coral Reef Institute (NCRI) (Fig. 5.6b). This software also allowed an observer to trace the outline of individual corals to determine their planar surface area and size of live versus dead portions of the colony.

In addition, longer photo-transects (25 m length) were used to acquire more detailed information about: a) presence and absence of different taxa; b) size/frequency distribution of corals within transects; and c) neighborhood patterns (distribution of corals with respect to each other). These photo-transects provide a permanent record of coral condition at the site, and they also were used for data evaluation. Limitations of photo-transects include the resolution and ability to identify small corals, especially in sites with considerable three-dimensional relief. Often, corals could not be identified to species due to a) presence of similar species that require microscopic examination of skeletal features, b) small size of coral, and c) inadequate resolution, shading, or growth on vertical surfaces or in crevices (non-planar growth). Therefore, all recorded observations of corals were also made to genus level or functional group only.

One of the team members used belt transects to acquire data needed to incorporate into a Leslie Matrix and/or Beverton Holt model, which can be used to predict the future conditions at a site. For his work, data processing required the following steps: 1) mosaicking, which involved merging of photographs to form continuous, non-overlapping belt; 2) drawing of outlines of corals and other benthic organisms; 3) color-coding species or guilds of corals; 4) production of a single-layer black-and-white image for each species; 5) transfer into bitmap format; 6) import into Matlab or some other program for data processing; 7) evaluation of size-frequency distribution; and 8) evaluation of centroid distances to determine spatial distribution of corals.

For community modeling, the diverse species assemblage was lumped into the following guilds: 1) branching, tabular and arborescent *Acropora*; 2) encrusting corals; 3) massive faviids; 4) massive *Porites*; 5) mussels and 6) fungiids. The following information was evaluated and/or calculated for every transect:

- planar surface area of corals to determine size class
- species identity or guild identity (for soft and hard corals)
- substratum (non-coral area)
- presence of selected macroalgae (*Halimeda* etc)

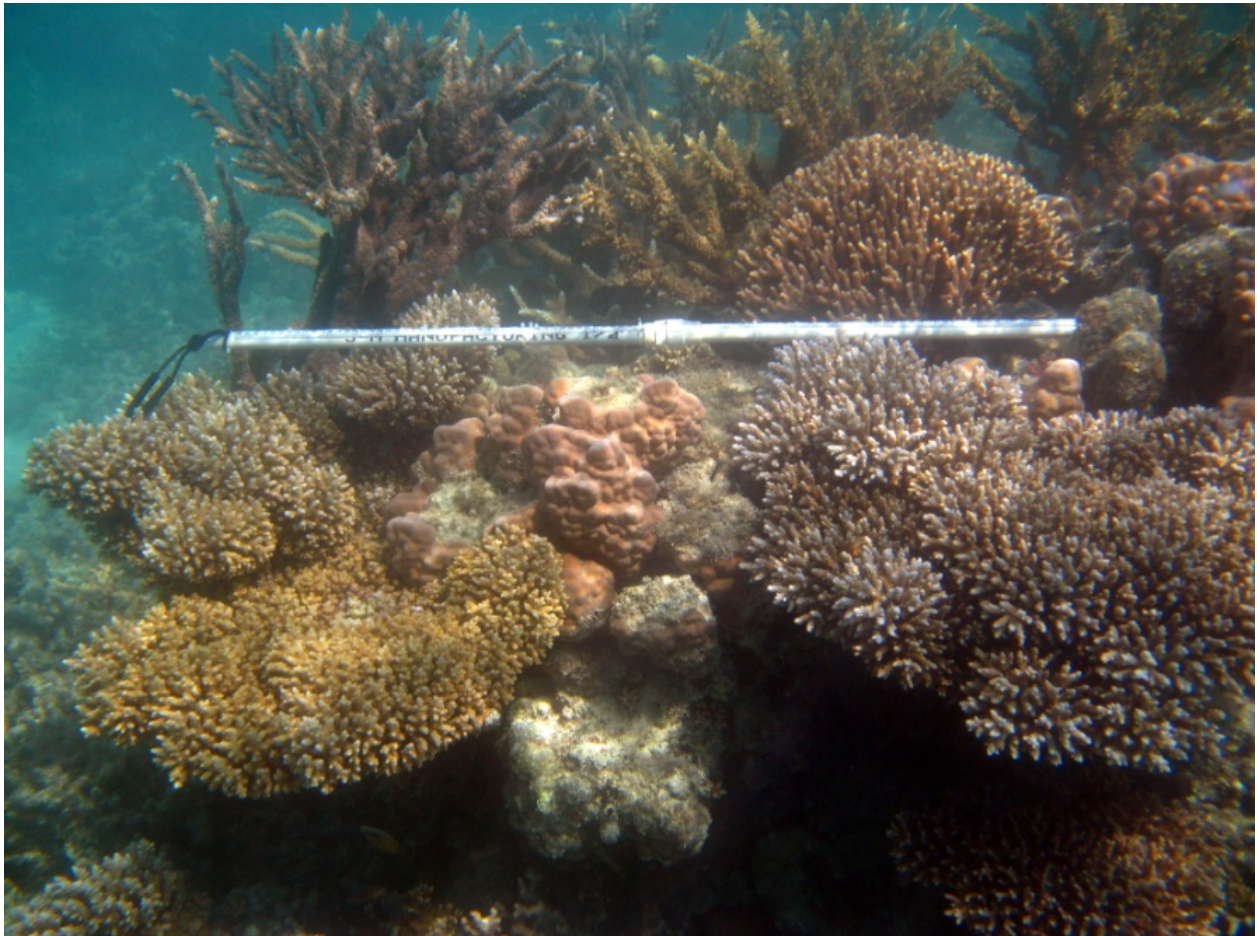


**Fig. 5.6.1. Bernhard Riegl, NCRI, measuring corals for inclusion in community modeling studies.**



### 5.6.2 Coral community structure and population dynamics

Multiple belt transects, each 25 m long and 1 m wide, were used to characterize the distribution, size and abundance of coral genera observed on each reef. In each belt transect a 1m bar is used to estimate colony size (Fig. 5.6c). Sampling for corals smaller than 10 cm is done using a minimum of six 0.25 m<sup>2</sup> quadrats per transect, with each quadrat located at fixed, predetermined intervals (e.g. at 0, 5, 10, 15, 20, and 25 m). Within the belt, each coral was recorded to genus and a single measure of its maximum diameter was recorded.



**Fig. 5.6c. Example of a section of reef showing the one meter bar (marked in cm increments) used to measure corals.**

For each coral that had experienced partial mortality, an estimate of percent mortality and condition was recorded, including identification of the type of disease, extent of bleaching, predation, competition, or other cause of mortality. If the coral exhibited recent tissue loss, the amount of remaining tissue, percent that recently died and percent that died long ago was

estimated for the entire colony surface. Each coral was carefully examined to identify cryptic predators such as snails, and recent lesions were examined to determine if the lesion is associated

**Resilience** can be defined as the rate at which a population returns to equilibrium after a disturbance takes it away from balance with its environment. It is a measure of how fast the population declines from equilibrium and how quickly it increases from below equilibrium. This term is frequently used to describe populations and systems, not individual organisms.

**Adaptation** can be thought of as any heritable, behavioral, morphological, or physiological trait that maintains or increases the fitness of an organism to live under a given set of environmental conditions. Adaptation, measured as fitness of the organism, is the result of natural selection. Adaptation of an organism to its environment is exhibited by its ability to function between some upper and lower limits in a range of environmental conditions. For corals, an adaptive trait could be its ability to shift its complement of zooxanthellae when stressed, such that the symbiotic relationship is maintained and properly functioning. This could include a strain of zooxanthellae that is better adapted to higher temperatures or light levels, making the coral less likely to bleach during periods of high temperatures.

**Tolerance** can be thought of as a range or gradient of particular environmental factors within which the coral can reproduce, grow and survive. These ranges are not fixed and can be dynamic over seasons or changing conditions. Some species exist within a broad tolerance range while others have a narrow range of tolerance.

**Acclimatization** involves short term responses or adjustments of the behavior, physiology or ecology of a coral in response to exposure to changing environmental conditions. The adjustments always occur within the normal, adaptive physiological limits of the coral.

with skeletal damage, color change, and unusual growth patterns. For colonies with band-like patterns of tissue loss, diseases were differentiated from other possible causes. For instance, a thorough search of the colony, its underside and the surrounding area was undertaken to identify *Acanthaster planci* (Crown of thorns sea stars, COTs). This voracious predator feeds primarily at night, except during outbreak conditions, retreating to crevices in the reef by day, making it difficult to find. Mortality from COTs sea stars can be misidentified as “white syndrome”, a virulent coral disease that is caused by factors that are unrelated to the occurrence of sea stars. These factors are difficult to manage, while COTs sea stars could feasibly be managed through removal.

### 5.6.3 Resilience assessments

Data were recorded on approximately 100 indicators that confer resilience. These measures include biological, ecological, environmental and physical attributes that are likely to help the system resist change when disturbed and also recover normal functions and processes relatively quickly. Basically, these assessments will provide information on the likelihood that 1) individual reefs will persist

into the future, under varying threat levels, 2) levels of changes that can be expected and what effect these changes will have on the productivity, functioning and ecosystem services reef ecosystem provide, and 3) types of actions that could be taken to preserve and/or improve resilience and enhance conservation of reefs.

A semi-quantitative scale (Likart) of 1-5 was used for estimation of all the indicators, where 1 = minimum, 2 = low levels, and 5 = maximum. Where an indicator can be quantified directly (e.g. visibility in meters, slope in degrees the actual quantity was recorded.

Data were collected on: 1) the relative abundance of every genera of corals, with data recorded on a five point scale and measurements of the diameter/height of the largest corals; 2) estimates of cover of broad categories, lumped into stony coral, soft coral, algae (subdivided into macroalgae, turf and crustose coralline algae), and substrate type (hardground, sand/mud, rubble, dead coral); 3) physical parameters including depth, temperature, turbidity, sediment characteristics, topographic complexity, slope, and shading; 4) coral condition including type of disease, overgrowth, physical injury, sedimentation, and bleaching, and presence of coral associates such as *Drupella* snails and crown of thorns (COTs) sea stars; and 5) anthropogenic stressors. Additional measures calculated from satellite imagery included the distance between reefs, the facing direction of the reef, distance to deep water and distance from the mainland (Table 2a-c).

**Table 2a. Biological resilience indicators for coral reef ecosystems. Attributes related to coral.**

| <b>Measure</b> |                          | <b>Description</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|----------------|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Stony coral    |                          | Genus-level identification of the composition, abundance, cover, size structure, condition, and level of recruitment within representative habitats.                                                                                                                                                                                                                                                                                                                                                                |
|                | Species composition      | The diversity and structural complexity of a site. Communities with higher numbers of functional groups (e.g. branching, plating, massive corals) and redundancy of these groups may support more associated species and be more resilient.                                                                                                                                                                                                                                                                         |
|                | Cover                    | Measure of amount of living coral, but provides limited information on population dynamics. Small changes in cover are difficult to document, but abrupt changes may reflect a major disturbance. Useful metric for comparison among reef habitats with a managed area.                                                                                                                                                                                                                                             |
|                | Size structure           | Maturity and ecological state of the taxa. Large numbers of large corals may be a sign of stable environmental conditions and long term persistence of the community; dominance by small corals suggests frequent disturbance or recovery from a recent disturbance.                                                                                                                                                                                                                                                |
|                | Recruitment              | Abundance of recruits reflects the reef's potential for growth and recovery after major disturbances and the influx of genetic diversity.                                                                                                                                                                                                                                                                                                                                                                           |
|                | Fragmentation            | Level of physical disturbance and potential for asexual propagation. Locations of fragments (accumulations in sand channels or on reef) and fragment condition (no tissue loss; fusion to the substrate; presence of new growth) reflect the potential survival and contribution of fragments to recovery.                                                                                                                                                                                                          |
|                | Dead standing coral      | Amount of dead standing coral can be used to hindcast past disturbance events up to a decade or more.                                                                                                                                                                                                                                                                                                                                                                                                               |
|                | Old mortality            | Presence of dead areas on corals that are colonized by other biotic agents (e.g. skeleton is not white) provide evidence of past disturbances. Species specific differences reflect the life history strategies, population dynamics and susceptibility to stressors. Old mortality may increase with colony size.                                                                                                                                                                                                  |
|                | Recent mortality         | Extent of recent mortality (white skeleton) reflects the severity and duration of a stressor. The rate of transformation from recent mortality (white, uncolonized skeleton) to old mortality is influenced by sedimentation, bioerosion and competition. Rates of mortality may allow prediction of rates of turnover of corals.                                                                                                                                                                                   |
|                | Bleaching                | Reef-wide bleaching may be associated with recent or ongoing temperature anomalies; extent of recent mortality in bleached corals may indicate the duration and severity of the temperature stress.                                                                                                                                                                                                                                                                                                                 |
|                | Disease                  | Spatial patterns of disease occurrence reflect potential for spread and level of contagion. Distinction can be made between background mortality (chronic stressors) and acute mortality caused by disease outbreaks. Presence of isolated small lesions reflects low-intensity stressors within the ability of the coral to regenerate new tissue; larger lesions are more likely to be colonized by other competitive organisms and may affect the normal functioning of the coral (e.g. reproductive potential). |
|                | Corallivores             | Abundance of coral predators ( <i>Drupella</i> and <i>Coralliophila</i> snails, <i>Acanthaster</i> seastars) indicative of the amount of recent mortality and possible changes to coral community structure and species diversity due to chronic high level infestations or outbreaks.                                                                                                                                                                                                                              |
|                | Competition & overgrowth | Negative factors inhibiting the growth and recovery of corals and causes of chronic mortality (e.g. algal competition) and bioerosion (e.g. sponges) of skeletons. Extent and composition of competitive organisms may reflect status of fish communities (herbivores), nutrient loading and sedimentation.                                                                                                                                                                                                         |

**Table 2b. Biological resilience indicators for coral reef ecosystems: invertebrates, algae and fish.**

| Measure              |                          | Description                                                                                                                                                                                                                                                                                                                                                                                                                               |
|----------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Coral associates     |                          | Obligate corallivores (butterflyfish) provide an indication of the health of the coral community or particular taxa.                                                                                                                                                                                                                                                                                                                      |
|                      |                          | Abundance and diversity of fishes and invertebrates within coral branches are indicative of the topographic complexity and health of the site.                                                                                                                                                                                                                                                                                            |
|                      |                          | An abundance of territorial damselfish within branches and large algal lawns indicate possible overfishing of piscivores.                                                                                                                                                                                                                                                                                                                 |
| Algae                |                          | Species rich, productive and functionally important components of benthic coral reef environments that may be involved in construction of the reef, components of the food chain, or space occupiers that are not eaten.                                                                                                                                                                                                                  |
|                      | Fleshy Macroalgae        | Indicators of grazing pressure, nutrients and levels of disturbance. Macroalgae should be low; macroalgal dominance reflects a loss of herbivores (urchins/fish), nutrient input, and a loss of corals.                                                                                                                                                                                                                                   |
|                      | Turf algae               | Low to moderate cover of turfs reflect moderate levels of herbivory; increasing biomass of turfs and trapping of sediments within turfs degrades substrate quality and reduces recruitment potential of reef-builders.                                                                                                                                                                                                                    |
|                      | Crustose coralline       | Cover of certain species of crustose coralline algae is linked to coral recruitment; CCAs bind sediments and consolidate the reef.                                                                                                                                                                                                                                                                                                        |
|                      | Erect coralline          | Taxa ( <i>Halimeda</i> ) produce sand that forms beaches and contribute to the infilling of reefs.                                                                                                                                                                                                                                                                                                                                        |
| Motile invertebrates |                          |                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|                      | Urchins                  | Abundance of key taxa of urchins ( <i>Diadema</i> ) are indicators of levels of herbivory and bioerosion, potential survival of coral recruits, and interactions among other herbivores. High densities of sea urchins associated with extensive bioerosion of reef substrates and low recruitment and survival of newly settled corals; macroalgae may increase in absence of sea urchins, especially sites with few herbivorous fishes. |
|                      | Molluscs and crustaceans | Abundance of commercially important species such as large crabs, lobsters and giant clams are indicators of fishing pressure and habitat quality.                                                                                                                                                                                                                                                                                         |
| Fish                 |                          | Fish community structure within sites can be attributed to environmental conditions, habitat complexity and quality, connectivity with other sites and intactness of adjacent habitats, fishing pressure, and management regimes.                                                                                                                                                                                                         |
|                      | Herbivores               | Suppress the growth of algae. Herbivore biomass is negatively correlated with macroalgal biomass and amount of cropped habitat. Each functional group prefers different taxa and growth forms of algae; grazing pressure varies based on bite size and frequency of feeding.                                                                                                                                                              |
|                      | Browsers                 | Feed on fleshy and filamentous macroalgae, controlling overgrowth and shading of corals by algae. Examples: <i>Calotomus</i> , <i>Leptoscarus</i> , and <i>Naso</i> .                                                                                                                                                                                                                                                                     |
|                      | Grazers                  | Remove epilithic algae from reef surfaces without removal of underlying reef substrate. Examples: <i>Acanthurus</i> , <i>Zebrosoma</i> , and <i>Siganus</i> .                                                                                                                                                                                                                                                                             |
|                      | Scrapers                 | Remove algae and small pieces of underlying reef substrate. Examples: <i>Scarus</i> , <i>Hipposcarus</i>                                                                                                                                                                                                                                                                                                                                  |
|                      | Excavators               | Consume coral and large pieces of reef substrate and play a key role in bioerosion and sand production. Examples: <i>Bolbometapon</i> , <i>Chlorurus</i> .                                                                                                                                                                                                                                                                                |
|                      | Omnivores                | Consume small invertebrates, fish, larvae, phytoplankton, benthic algae, and seagrass.                                                                                                                                                                                                                                                                                                                                                    |
|                      | Detritivores             | Feed on organic material in the sediment and on reef substrates. High numbers may reflect conditions of eutrophication. Examples: goatfish, <i>Ctenochaetus</i> .                                                                                                                                                                                                                                                                         |
|                      | Planktivores             | Indicative of the level of plankton in the water column, including larvae important for reseeding the reef, and water column nutrient levels. Examples: fusiliers, some triggerfish.                                                                                                                                                                                                                                                      |
|                      | Carnivores               | Carnivore density, size and biomass are sensitive indicators of the type of fishing pressure; control abundances of lower trophic level fishes.                                                                                                                                                                                                                                                                                           |
|                      | Invertebrate feeders     | Control populations of corallivores and bioeroders including snails, sea stars, and urchins. Some feed on sessile invertebrates like soft corals and sponges which compete with stony coral for space. Examples: triggerfish, snappers, sweetlips, wrasses, angelfish.                                                                                                                                                                    |
|                      | Coral feeders            | Provide indication of the health of the coral. Example: certain butterflyfishes.                                                                                                                                                                                                                                                                                                                                                          |
|                      | Piscivores               | Important control of lower trophic level fish; first indicators of overfishing.                                                                                                                                                                                                                                                                                                                                                           |



**Table 2c. Physical and environmental resilience indicators.**

|                                       |                            |                                                                                                                                                                                                                                                                                              |
|---------------------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Associated habitats                   |                            | Proximity, connectivity and size of associated seagrass beds, mangroves, and algal flats. Importance: stabilize sediments, reduce run-off to reef habitats, and translocate nutrients; feeding grounds, shelter, and nursery areas for reef-associated species during different life stages. |
| Physical and environmental parameters |                            |                                                                                                                                                                                                                                                                                              |
|                                       | Tides                      | Large tides may reduce thermal stress and increase nutrients in subtidal areas; frequent exposure at low tide may increase resistance to thermal, salinity, and light stress.                                                                                                                |
|                                       | Currents                   | Likelihood of connectivity with other sites; helps maintain cooler water temperatures.                                                                                                                                                                                                       |
|                                       | Wave action                | Affects distribution of species and growth form; enhance exchange of water and may maintain cooler temperatures.                                                                                                                                                                             |
|                                       | Deep water                 | Deep water adjacent to reefs associated with upwelling of cool, nutrient rich waters; pelagic fish that migrate and feed on reefs.                                                                                                                                                           |
|                                       | Temperature and salinity   | Unusual environmental features (pooling, extensive flats) can affect temperature and salinity, creating hot, hypersaline water that flows down the reef, impacting sessile organisms.                                                                                                        |
|                                       | Inter- reef distances      | Potential for connectivity with adjacent sites.                                                                                                                                                                                                                                              |
|                                       | Distance from mainland     | Gradient of anthropogenic stressors and exposure to open ocean conditions.                                                                                                                                                                                                                   |
| Reef attributes                       |                            |                                                                                                                                                                                                                                                                                              |
|                                       | Substrate type and quality | The potential for recruitment and survival of juvenile corals is controlled by the extent of sedimentation, turbidity, presence of rubble, and substrate surface features (smooth vs. rugose).                                                                                               |
|                                       | Rugosity                   | Amount of relief attributed to corals and reef structure. Flat, hardground habitats provide considerably less habitat for motile species that are important in controlling reef health, while high-relief spur and groove habitat provides key nursery, feeding and refuge sites.            |
|                                       | Reef slope                 | Proximity of deep water and potential for refuge populations; extensive shallow reef flats heat up during calm periods and hot, hypersaline water may flow down the reef slope.                                                                                                              |
|                                       | Shading                    | Above water features and canopy corals may shade understory corals, enhancing resistance to temperature-related stressors.                                                                                                                                                                   |
|                                       | Turbidity                  | Reduces penetration of UV, potentially reducing stress from thermal anomalies; may restrict vertical distribution of corals.                                                                                                                                                                 |
|                                       | Depth                      | Abiotic parameters (light, temperature, and wave exposure), coral composition and growth form, and habitats available for reef-associated fishes vary with depth.                                                                                                                            |
|                                       | Compass direction          | Angle of incidence of the sun and diurnal changes affect amount of solar radiation on the reef; easterly facing reefs exhibit more light stress than westerly facing reefs.                                                                                                                  |

#### 5.6.4 Fish Surveys

The method focuses on a detailed census of reef fish communities. The original assessments in the Farasan Islands, conducted by Ray Buckley, involved belt transects that examined every species of fish. Because many of the dominant fishes (by number) make up a relatively small portion of the biomass, and these are not commercially important and of limited importance in reef health and resilience, the assessment approach was modified to focus on approximately 100 species of reef fishes in the final list. Sampling combined qualitative roving surveys to identify presence of small cryptic fishes and larger pelagics, and quantitative belt transects to quantify size and abundance of dominant trophic guilds. For each survey, a diver slowly swims along a single depth gradient, slowly extending a 50 m transect. The observer records the total number and size of the target species (in 5cm size classes) within a 50 m X 5 m belt, repeating this at minimum, three times per site. The fish transects were done in the same location as benthic transects to allow comparison of fish utilization patterns with habitat structure and quality. In addition to data on the type of fish and size structure, an assessment of fishing pressure, was undertaken for each site. This includes data on the presence and type of fishing gear, entangled monofilament, fish traps and gill nets, and derelict gear, along with records of the number of fishing vessels and location of those boats.

An additional assessment of temporal changes in landings was undertaken to compare with fish dynamics observed in the wild and to determine potential implications of fish catch and population structure on reef health (Bruckner et al. 2011). In Saudi Arabia, the Ministry of Agriculture and Water, Marine Fisheries Department completes an annual assessment of fisheries, based on voluntary reporting by the industrial, investment, and artisanal sectors. All of the data were compiled into the annual *Fisheries Statistics of Saudi Arabia*, which were kindly provided for our use by the Ministry of Agriculture. In these statistics, investor and artisanal fisheries are pooled in fishery reports as “traditional fisheries”. Data were also compiled on numbers of foreign and national fishermen, size of the fleet, and gear type; landings are reported for four regions (industrial fisheries) or five regions (traditional fisheries) for up to 70 species or species complexes of fishes and six invertebrates, with data pooled into 35 groups for regional summaries. This information was analyzed in context of reef fishes (much of the data, especially commercial landings involved pelagic species and non-reef associated fishes) and compiled into a

manuscript included in a volume on Marine Fisheries that came out of the American Fisheries Society Annual meeting in 2009 (Bruckner et al. 2011), and a summary of the manuscript is provided here.

## **5.7 Coastal and Marine Surveys**

### **5.7.1 Marine mammals and turtles**

SWC scientists conducted surveys of marine mammals, marine turtles, birds and seagrass. Marine mammals were sighted and identified using binoculars and when possible, photographed. The location of the mammals and turtles was designated using GPS. Additional island surveys were undertaken to assess the numbers of nesting turtles.

**Fig. 5.7a. Ahmed Al Mansi measuring a hawksbill turtle in the Farasan Islands.**



### **5.7.2 Coastal vegetation**

Limited coastal and island surveys were undertaken as part of the ground-truthing to characterize the shoreline, including the type of flora and the geologic structure of islands.

## **5.8 GIS Database**

Habitat classifications were converted to GIS-ready vector-based map products using remote sensing and GIS software. Pixel-based products, termed ‘rasters’, were converted into vector-based data. Under this system of storage, clumps of adjacent pixels that comprise a single patch of habitat are grouped as a single vector shape or polygon. Because only information relating to the boundary coordinates of the polygon is stored, such data is less intensive and easier to use for a number of applications. Shape files were integrated with web based geographic media including geometric measures, for example area or perimeter of the habitat patch; measures of environmental context, such as distance from shore or distance from an urban center; as well as existing information on patterns of human use, localized environmental data including meteorological measurements, water depth across the polygon, water temperature, and results from fine-resolution photo-transects and survey data.

## **6. Results**

### **A. Habitats of the Saudi Arabian Red Sea**

#### **6.1 Reef Types**

The emphasis of the four year Research Expedition was on shallow marine habitats (0-20 m depth) located offshore, in areas with complex geomorphology and unusual reef types. Supplementary surveys were also conducted on nearshore fringing reefs. While most of the coastline along the Red Sea contains fringing reefs that extend 10s of meters before dropping into deep water, unusual, more complex reef systems with islands, lagoonal habitat, extensive reef flats, and both leeward and windward reef habitats were located in five regions off Saudi Arabia: a) Tiran area near Ras Qisbah; b) Al Wajh Bank; c) Umm Luj; d) Yanbu; e) Farasan Banks; and f) Farasan Islands. All locations except Umm Luj were surveyed; the team had intended on examining Umm Luj during the 2008 mission, but the weather prevented our access.

The northern-central Red Sea has a high diversity of reef and coastal habitat types, including large expanses of coastal marshes (sabkha), seagrasses, algal flats, sandy lagoons, and mangroves, as well as coral reefs that fringe the mainland and islands, offshore patch reefs, and barrier reefs. The area is renowned for the presence of the Al Wajh Bank, a large, relatively shallow area that extends 30-50 km offshore, is bordered by a barrier reef system on its seaward edge, and contains many islands, reefs and associated habitats. This area also includes a barrier reef system off Yanbu and complex reef systems off Ras Qisbah. The southern area, including the Farasan Banks and Farasan islands, exhibit a different bio-physical and geomorphological regime as compared to the northern area. The southern area has a wide, shallow shelf and more turbid sediment-loaded waters in nearshore areas primarily due to terrigenous input and water mixing across the coastal shelf. The highest sea temperatures are found in this zone and coral development is restricted to offshore locations. Notably, there was only minor variability in species composition among the assemblages, with the entire region exhibiting a high degree of homogeneity in terms of coral community composition, both latitudinally and longitudinally.

The marine environment, extending from north of Jeddah to Tiran at the mouth of the Gulf of Aqaba supports a near-continuous coral reef tract composed of mainland fringing reefs, along with numerous other reef types surrounding offshore islands, various patch reef communities,

coral pinnacles, and ‘ribbon’ barrier reefs. Mainland fringing reefs were often developed in the entrances and sides of sharms, a characteristic reef-form largely restricted to the Red Sea (Ormond et al. 1984b). Extensive mainland fringing reefs occur around Rabigh, Ras Baridi, Umm Luj, and Al Wajh; island fringing reefs are commonly developed in the Tiran area and also extend from Duba to Al Wajh Bank and Umm Luj. Circular and elongate patch reefs were quite numerous in offshore waters, including emergent reef systems with adjacent sand-coral islands (cayes), while other reefs were submerged (Riegl and Piller 1997). Both emergent and submerged reef systems were common in the Al Wajh Bank. ‘Reticulate’ patch reefs, composed of interconnected networks of reef matrix separated by sand, were particularly well developed in shallow waters (<10 m depth) near Ras Qisbah and at the southern end of Al Wajh Bank. Pinnacles were also present in Al Wajh Bank and Ras Qisbah.

Barrier reefs composed of platform and ‘ribbon’ reef structures were best developed in offshore locations, on the edge of the ‘continental’ slope. The best-developed barrier reef system was found at Al Wajh Bank. It consisted of a near continuous line of reefs stretching for about 100 km along the seaward margin of the bank (Ormond et al. 1984a; DeVantier et al. 2000a). Another barrier reef system commonly known as the ‘Little Barrier Reef’, occurs further south near Yanbu (Sheppard and Sheppard 1985). To the south of Jeddah, reefs become less well developed along the mainland coast, primarily as a result of differences in topographic features, higher sedimentation and turbidity, and a wide, shallow terrace (Price et al. 1998). Both the Farasan Banks and Farasan Islands have complex atoll-like structures or ‘tower’ reefs located offshore, along with other well-developed complex reef structures.

## **6.2 Habitat types**

Habitat maps created for the Red Sea coast of Saudi Arabia extend from the shoreline, at mean low water, to about 20-30 m depth. Habitats extend from the mainland up to 100 km from the coastline, and include reef and associated communities that fringe offshore islands, as well as submerged reef and hardground habitats. Both biological cover types and geomorphological structural types were merged to define the specific habitat. A ‘habitat’ was defined as ‘a unique combination of gross topographic structure, biotic community, and sediment/hardground composition occurring consistently across the scale of at least an image pixel (2.4m<sup>2</sup>).’ Habitat features that cover areas smaller than one image pixel (2.4m<sup>2</sup>) were not considered. The final

habitat classification scheme comprised fifteen different classes: 1) windward coral crests, 2) leeward coral crests, 3) dense *Acropora* thickets, 4) columnar frameworks, 5) reef walls and drop-offs, 6) sparse corals, rubble and sand, 7) seagrass meadows, 8) macroalgae and sponges on sand-covered pavement, 9) cyanobacterial mats on sand, 10) mangroves and near-shore vegetation, 11) scoured channels, 12) carbonate hardground and reef flats, 13) shallow sand sheets, 14) deep lagoonal sands, and 15) sand and mud flats. Many of the reefal habitats can be further subdivided into zones, depending on exposure, depth and biotic communities.

### 6.2.1 Windward coral crests

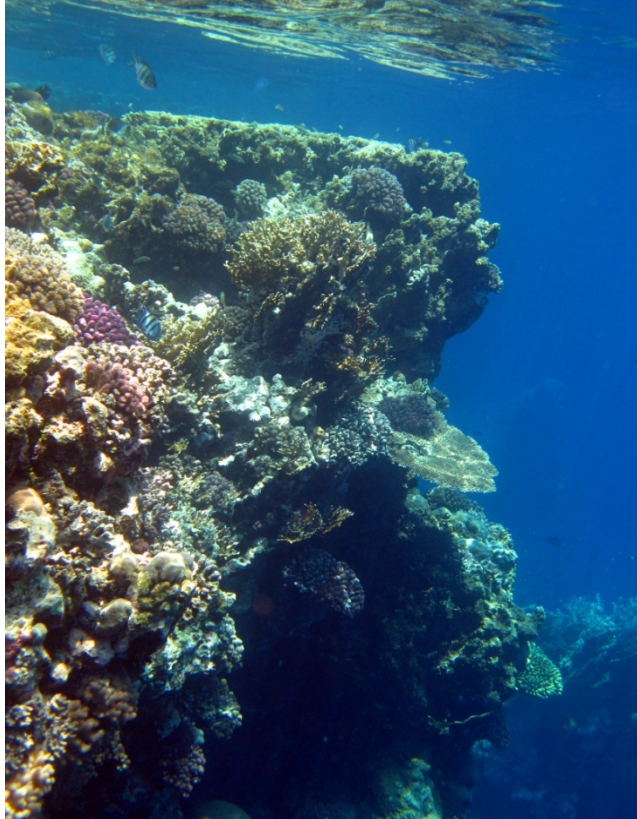
Windward coral crests are diverse, high-energy assemblages dominated by hermatypic corals built upon columnar and massive *Porites* frameworks. Corals tend to be low-relief massive species interspersed with branching, plating and columnar species that have short, stout branches or columns. Live massive *Porites* corals are interspersed with *Acropora* spp., *Pocillopora* spp., *Stylophora* spp., and *Favia* spp. Other corals, including, *Favites* spp., *Seriatopora* and *Fungia* spp. may also occur. Live coral cover is typically high (50-80%) and macroalgae is rare. On certain southern reefs (Farasan Banks and Islands), macroalgae may be more abundant and intermixed with coral, with a dominance of stout brown algae including *Sargassum* and *Turbinaria*; these algae taxa generally form dense assemblages on the adjacent reef flat,

especially on nearshore reefs. Typical depth: 1-3 m.



**Fig. 6.21a. Example of a windward coral crest located off Al Wajh Bank. The most common corals in this area include *Goniastrea*, (foreground), *Acropora*, *Pocillopora*, *Millepora* spp., and *Seriatopora* spp.**





**Fig. 6.2.1b.** Example of a windward coral crest on an offshore reef in the Farasan Banks. The most common corals in this area include *Acropora*, *Pocillopora*, *Millepora* spp., and *Seriatopora* spp. Reef communities in these areas often plummeted to the depths with the crest leading to a near vertical wall.

### 6.2.2 Leeward coral crests

Leeward coral crests are characterized by rich, hermatypic coral cover dominated by small *Acropora* spp. colonies, also *Porites* spp., *Favia* spp., *Favites* spp., and *Seriatopora hystrix*. Live coral cover is typically 50-80%. The most diverse crests are found on shallow lagoonal fringes. Typical depth is 1-3 m.

**Fig. 6.2.2a.** A leeward coral crest off Ras Qisbah, Saudi Arabia. The community is dominated by *Millepora*, *Acropora* and *Porites*.





### 6.2.3 Dense *Acropora* thickets

Dense *Acropora* thickets can be found on inner protected lagoonal patch reefs, shallow terraces with low to moderate wave exposure, and some exposed fringes and ledges. These areas are characterized by dense patches of interdigitated coral branches, often with multiple canopy layers, comprising about 25-75% or more of the substratum. Live coral cover is typically 40-80%, but may exceed 100% as a result of the canopy layers and dense branching patterns. The community is diverse, but often is dominated by *Acropora clathrata*. Typical depth is 5-15 m.



**Fig. 6.2.3a.** Example of a dense thicket of branching *Acropora* spp. on an exposed fore-reef community in the Farasan Banks, Saudi Arabia, at about 8 m depth.

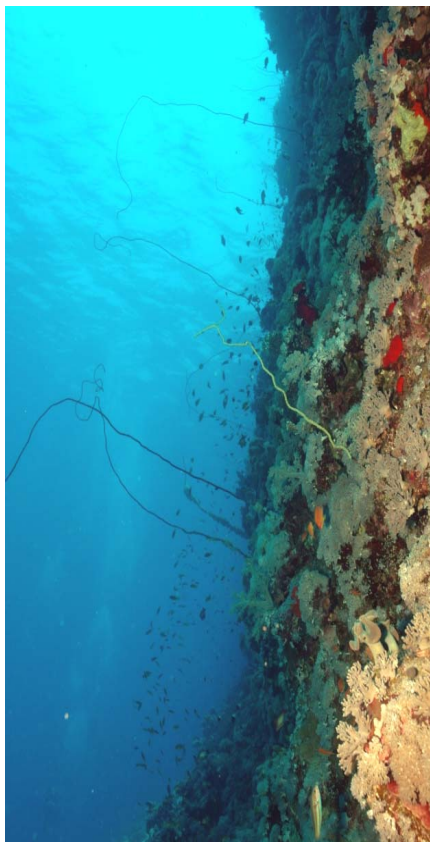
### 6.2.4 Columnar frameworks

Columnar frameworks are topographically complex habitats constructed of high-relief columnar *Porites* colonies. Live coral cover is low, generally less than 15%. Columns are often partially colonized by small corals, including numerous plating, encrusting, and submassive growth

forms. Columnar structure becomes shorter and broader with increasing depth. Depressions in the framework are sediment filled with deeper areas characterized by fine-grained to muddy sediment sheets. Antecedent morphology could be karstic, but the sediment-filled depressions also suggest that the landscape is purely accretional. Typical depth is 5-40+ m.



**Fig. 6.2.4.** Example of a columnar *Porites* framework, 12 m depth off Ras Qisbah, Saudi Arabia. The colony of *Porites* spp. in the foreground is partially alive, with living coral on the tips of the columns; exposed skeletal structures are colonized by other stony and soft corals.



#### **6.2.5 Reef walls/drop-offs**

Steep, near-vertical wall with coral cover ranging from 10-70%. All coral forms present, but mainly encrusting and foliose growth forms on exposed points. Coral community consists mainly of *Pachyseris* spp., *Echinopora* spp., *Mycedium* spp., *Favia* spp., *Favites* spp., and *Millepora* spp.. Space between coral colonies can be bare or occupied by sponge, macro-algae, coralline algae, *Xenia* sp. and other species of soft coral. Low-relief grooves run sporadically down the vertical reef face. Coarse rubble debris originating from the reef crest accumulates at the base of these furrows. Typical depth is 3-40+ m.

**Fig. 6.2.5a.** A reef wall on a Pinnacle Reef, south of Al Wajh. The wall extends from the reef crest (2 m depth) to 40 m depth, where the slope becomes more gradual and substrates are covered by sediment, rubble and isolated corals.



### 6.2.6 Sparse corals, rubble, and sand

An unconsolidated matrix of coarse sand and coralline rubble found down-slope from live coral crests or deposited inshore in moderately sheltered areas. Sediment may be cemented by coralline algae or sponges, allowing for some coral colonization, leading to a sparse coral community composed mainly of *Favia* spp., *Favites* spp., *Fungia* spp., *Acropora* spp., and *Xenia* sp. (soft coral). Typical depth is 3-10 m.



**Fig. 6.2.6. Shallow (10 m) sand flat located at the base of the reef. Isolated rubble accumulates in the sand at the base of the reef. This may be consolidated and colonized by stony corals and soft corals, but live cover is generally low due to the continual movement of sediment sheets.**

### 6.2.7 Seagrass meadows

Seagrass beds are most commonly found in soft bottom habitats in shallow waters, at generally less than 7 meters in depth, although some species also occur in deep water (10-20 m depth; up to 70 m in the Gulf of Aqaba) in the Red Sea. Some species can also tolerate brief aerial exposure at low tide. They comprise only about 50 species worldwide (Den Hartog 1970), with 11 species reported from Saudi Arabia (Sheppard et al. 1992), although only four species are found in the south, around the Farasan Islands. Factors controlling their distribution include depth (a function of light levels), sediment grain size, substrate depth, and water movement. There are also other latitudinal controls, such as solar radiation, salinity extremes and high temperatures. Even though fewer species of seagrass occur in the southern Red Sea, grassbeds are larger, much better developed, and more extensive in cover and biomass due to a wider and shallower shelf, more unconsolidated sediments and less extreme temperatures and salinities.

Meadows of seagrass, often intermixed with green and brown macroalgae, are typically found atop muddy organic-rich carbonate sands. Seagrass species in the Red Sea include *Thalassodendron ciliatum*, *Thalassia hemprichii*, *Cymodocea serrulata* and *C. rotundata*, *Halophila ovalis*, *H. decipiens*, *H. minor*, and *H. stipulacea*, *Halodule uninervis*, and *Syringodium isoetifolium*. *Caulerpa racemosa* and *Halimeda* spp. can be dominant members of the green macroalgal community in soft bottom habitats. Seagrasses may occur as monospecific stands or several species of grass may be intermixed. Individual species also exhibit preferences to certain depths and sediment types. For example, *Thalassodendron ciliatum* and *Thalassia hemprichii* inhabit coarser sediments while *Enhalus acoroides* is found in soft muds (Prince et al. 1988). Two species of *Halophila* (*H. stipulacea* and *H. ovalis*) are known to occur to depths of 70 m and 28 m respectively (Hulings and Kirkman 1982), while *Halodule uninervis* is found in both intertidal and shallow subtidal habitats. Several species (*T. hemprichii*, *T. ciliatum*, *H. ovalis* and *H. uninervis*) can form dense monospecific assemblages, while mixed assemblages (*T. hemprichii*, *Cymodocea rotundata*, *Syringodium isoetifolium* and *H. stipulacea*) also occur. Patch density of grasses ranges from 15-60% cover. In shallow regions, dense patches (>50% cover) of seagrasses are relatively small in size (5-10 m<sup>2</sup>), while at depths below 10 m such patches may



be more extensive. Typical depth is 1-10 m, to 40 m in clear water.

**Fig. 6.2.7a.** Low density patch of seagrass at the base of a reef (12 m depth) in Ras Qisbah, Saudi Arabia.

Seagrass beds are among the most productive areas of aquatic ecosystems (Zieman and Wetzel 1980). They are important in providing food resources for resident fauna and temporary visitors (Klumpp et al. 1989), with much of the biomass



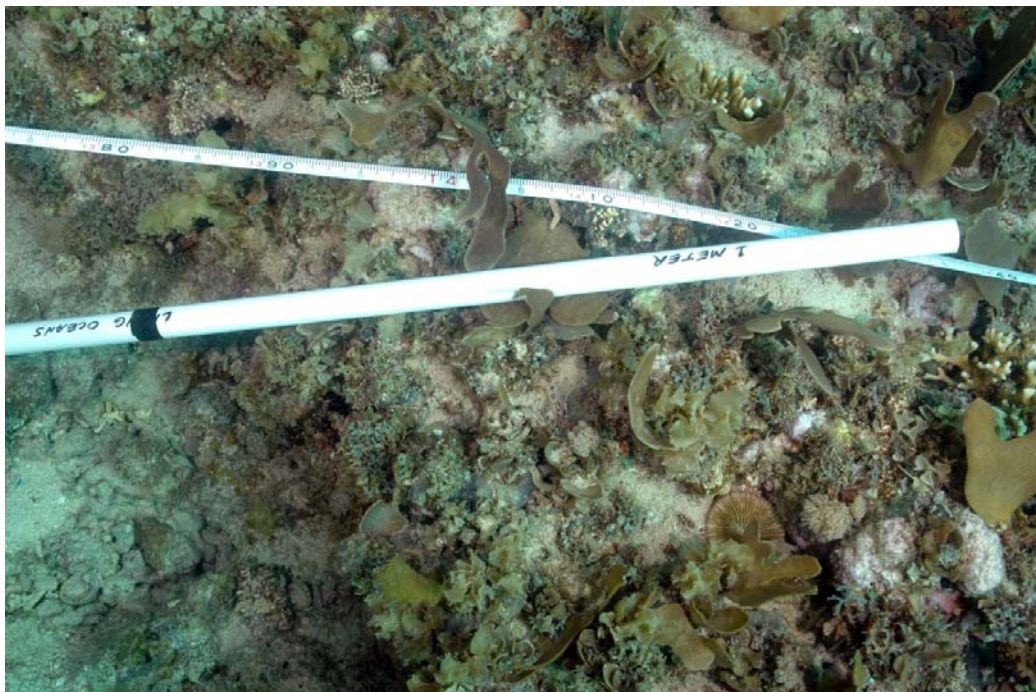
exported to neighboring reefs. Grass beds also serve as well as nursery habitat and shelter for adult fishes and invertebrates (Orth et al. 1996), juvenile fishes (Bell and Pollard 1989), and other marine species such as the green turtle (*Chelonia mydas*) and dugong. Some of the dominant herbivores include the sea urchin *Tripnuestes gratilla*, surgeonfish (*Zebrasoma xanthurum* and *Ctenochaetus striatus*) and rabbitfish (*Siganus rivulatus*). The leaves support an array of attached organisms (epiphytes) including various species of algae, cyanobacteria and diatoms, and filter-feeding invertebrates like bryozoans, sponges, and hydroids, and they also serve as a site of attachment for eggs of ascidians (sea squirts) and molluscs. The flora and fauna associated with grass blades provide an important food source for small fish, herbivorous molluscs, crustaceans and other invertebrates. Seagrasses also help in stabilizing sediments and preventing coastal erosion and siltation of coral reefs (Fonseca and Fisher 1986).



**Fig. 6.2.7b. A dense patch of seagrass at 10 m depth off Ras Qisbah, Saudi Arabia.**

### 6.2.8 Macroalgae & sponges on sandy hardgrounds

Extensive areas dominated by macroalgae occur on reefs and other hard substrates and also in certain subtidal soft bottom habitats. Algal communities in the Red Sea are highly diverse, consisting of over 500 described species and many undescribed species. In the northern and central Red Sea, algal lawns consist primarily of filamentous green algae and small brown algal species, while large brown algae (e.g. *Sargassum* and *Turbinaria* spp.) dominate shallow reef flat communities in the southern Red Sea. While standing stock generally tends to be low, with a high turnover as a result of intense grazing pressure, productivity is high. Most algal communities show a strong seasonality, with a direct correlation to water temperatures; fronds of many species tend to be annual, although stipes and holdfasts may remain attached to the substrate for many years. Algal cover on hard substrates drops precipitously from 50-90% to <5% cover at depths greater than 5 m. However, much higher cover can occur in reefal habitats that have experienced recent disturbances, and in areas with low herbivory and high nutrient input. Soft bottom subtidal communities can also contain rich biological assemblages with high productivity, due to the presence of diatoms, mats of cyanobacteria and filamentous algae.



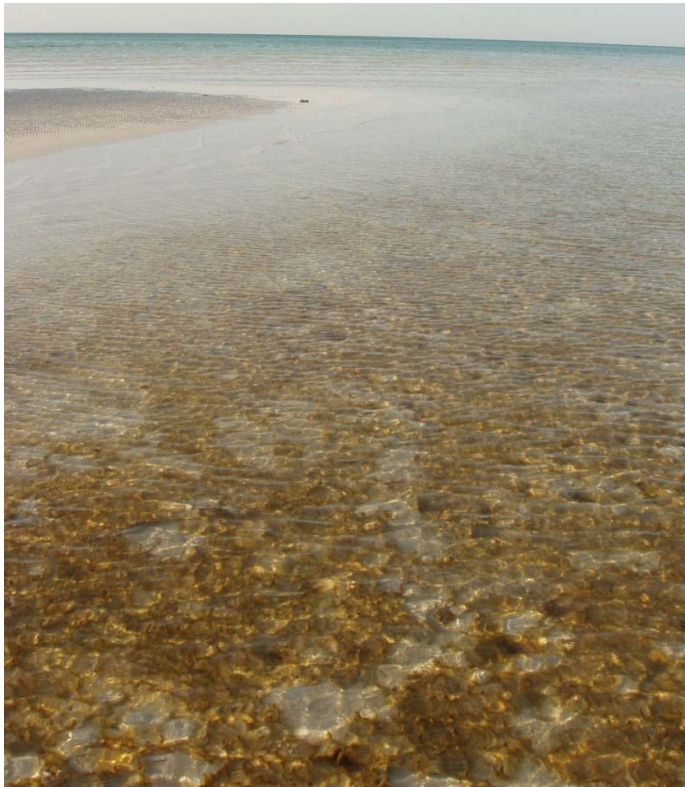
**Fig. 6.2.8.** Hardground in the Farasan Islands at 10 m depth. The community is dominated by brown macroalgae such as *Sargassum* and *Padina*, green macroalgae and red crustose coralline algae, intermixed with small isolated corals, sand patches containing rubble, and coral fragments atop the hard substrate.



Reef flat communities, platform reefs and other shallow marine habitats often contain hardground areas interspersed with patches of sand that are colonized primarily by macroalgae and sponge assemblages. In shallow habitats (0-5 m), *Sargassum* and *Padina* are dominant and typically found in equal proportions. Patches are 1-5 m in diameter, <50 cm height, and separated by less than 1 m of sand on platform tops. Deeper areas (5-15 m) are dominated by *Sargassum* and *Padina* on a limestone substrate, and are often intermixed with *Drysidea* sp. sponges, *Xenia* soft coral and small isolated stony corals. Typical depth is 1-15 m.

#### **6.2.9 Cyanobacteria mats on sand**

Extensive cyanobacteria or filamentous algal mats dominated by *Rhizoclonium tortuosum*, *Chaetomorpha gracilis*, *Cladophora coelothrix*. Typical depth is 1–40 m.



**Fig. 6.2.9. Shallow sandflat located off the leeward side of Umm Qusur Island in the Ras Qisbah region. Sediments have been colonized by a mat forming cyanobacteria.**

#### **6.2.10 Mangroves and near-shore vegetation**

Mangroves are found throughout the Red Sea, occurring mainly in sheltered areas behind reef flats, in bays or creeks, and on the leeward side of offshore islands. In most locations, mangroves grow as relatively thin forests along the shore-line, on near and offshore islands, and



at the margins of fringing tidal creeks and channels of various size. The largest concentrations of mangroves are found in inner protected lagoons and sheltered embayments where water depths range from 0.5-1.5 m, especially in the south. Mangroves are also often associated with seaward terminations of wadis. Mangroves form two distinct assemblages, one occurring in soft bottom habitats and a second, found primarily in the northern Red Sea, in hard bottom habitats behind reef flats. The latter, often referred to as “reef mangals” (Por et al. 1977) grow as a thin veneer overlaying uplifted rock or fossil reefs, with stunted trees anchoring in small sediment filled cracks and crevices.

Mangrove development increases towards the south, coinciding with the gradual disappearance of stony corals, a wider continental shelf, warmer temperatures, increased availability of muddier substrate, higher nutrients, and more freshwater. These stands can be 100-500 m wide, with trees that range in height from 5-7 m. In general, mangrove distribution is patchy north of Al-Lith (Farasan Banks), with the largest and best developed stands found near Sharm Zubeir, on the shoreline between Al Wajh and Umm Luj, Al Wajh Bank, near Yanbu, between Rayyis and Mastura, Rabigh area, south of Jeddah, and Qishran Bay. Mangroves are denser to the south of Al Lith, fringing most of the shoreline and forming a semi-continuous belt. The largest and most dense stands in the south have been found at Khor Abu Saba, Midaya, Besari (Mandura et al. 1987), Al-Quham, Khor Itwad, Shi'b-al-Kabir and Khor Al-Ja'afirah (Price et al. 1987).

There are four species of mangroves reported to occur historically along the Saudi Arabian Red Sea coastline, *Avicennia marina*, *Rhizophora mucronata*, *Bruguiera gymnorhiza* and *Ceriops tagal*, of which *A. marina* is by far the most common species. This species flourishes in extreme environments, surviving high salinities (40-50 ppt) and extreme water temperatures (12-40 °C). The northerly limit for distribution of *A. marina* is along the Sinai Peninsula near Sharm Zubeir (27°25' N), with a southern range that extends beyond the Farasan Islands and into Yemen. *R. mucronata*, which is much less widespread, typically coexists with *A. marina* in 11 locations (Al-Wataid 2003) with the most extensive *R. mucronata* stands found in the Farasan Islands and Al Wajh Bank. On the landward edge, mangroves merge with a salt-tolerant plant community dominated by *Halopeplis* and *Zygophyllum* species.



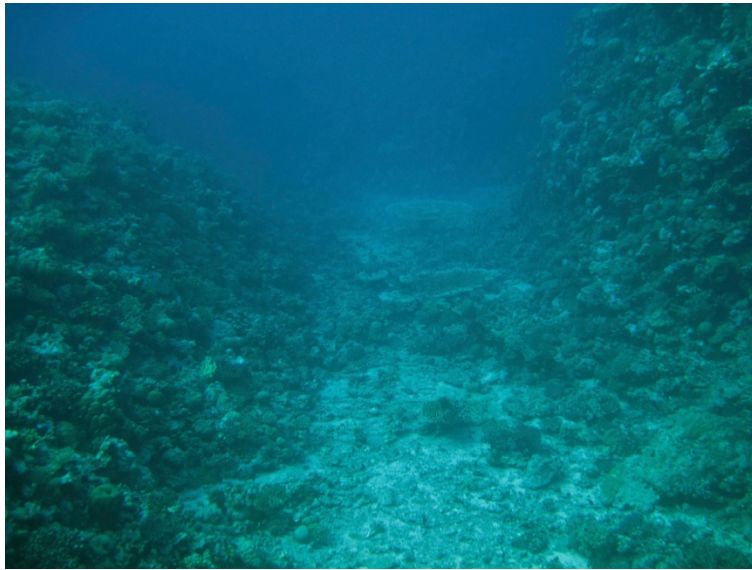
**Fig. 6.2.10a. Mangrove community located on the leeward side of an island in Al Wajh. Pneumatophores. Vertical projections from the extensive root system are visible between the water and mangrove forest: these structures allow the trees to survive in anaerobic sediments.**



**Fig. 6.2.10b. Another mangrove community located at the edge of a sandy beach in a protected lagoonal environment off Al Wajh Bank.**

### 6.2.11 Scoured channels

Flat-relief hardground with a sparse community of soft coral (predominantly *Xenia* sp.), *Padina* and other macroalgae with a sparse hard coral community of low diversity. Tidally driven water moves through narrow channels between lagoons and the open ocean. This high velocity flow removes unconsolidated sediment and scours the seabed. Typical depth is 1-20 m.



**Fig. 6.2.11.** Narrow channel at 15 m depth located between two reef slopes. The substrate has a veneer of sediment, rubble and isolated corals.

### 6.2.12 Carbonate hardground and reef flats

These hardground areas are just below low tide line or are often emergent at low tide. This habitat is characterized by centimeter-thin veneers of sediment, small patches of macroalgae,



small isolated corals, and filamentous turf algae.

**Fig. 6.2.12a.** A reef flat community close to the mainland in the Farasan Islands. Carbonate surfaces are colonized by *Sargassum* and are exposed at extreme low tides.



Exposed flats are largely devoid of sediment and tend to have algal turfs only in areas of moderate exposure, primarily at the edges of coral and in depressions. Offshore reef flats in areas with high wave action and strong currents have minimal colonization by macroalgae and sparse small coral colonies, especially *Pocillopora*. Nearshore reef flats, especially in the southern Red Sea around the Farasan Islands and Banks, may be colonized seasonally by brown macroalgae, especially *Sargassum*. Shallow exposed fringes may exhibit a narrow (1-2 m) raised rampart of calcareous red algae. Typical depth is 0-1m.



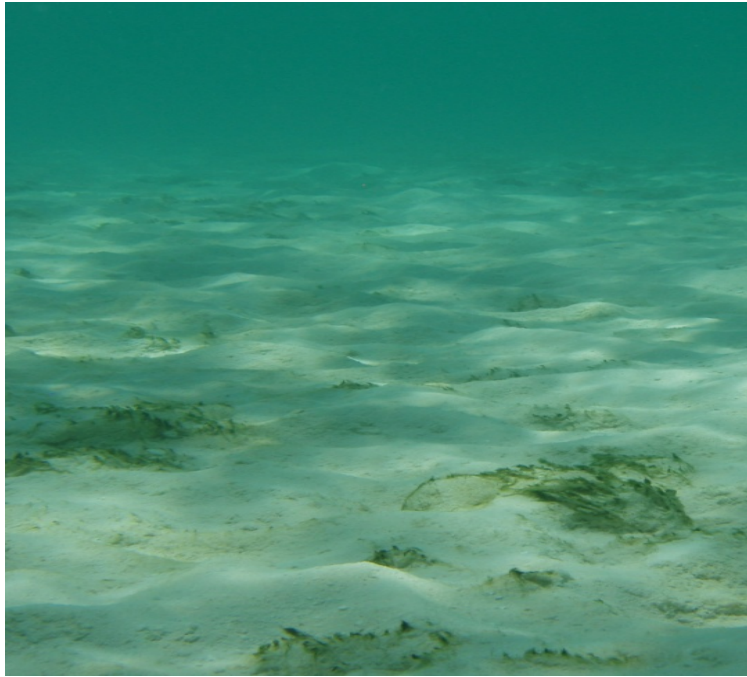
**Fig. 6.2.12b. Reef flat community off Danak Island, in the northern Farasan Banks. The community is a hardground, with low relief, low algal cover and isolated colonies of *Stylophora* spp.**

#### **6.2.13 Shallow sand sheets**

Unconsolidated sand sheets consisting of debris from corals, calcareous algae, molluscs and echinoderms. Meter-scale patches of macro-algae (*Laurencia* sp., *Caulerpa racemosa*, *Cladophora* sp.) and sediment-resistant corals, such as *Favia* spp., are seen. In areas of low energy, sands may be covered by sparse, meter-scale algal mats (*Rhizoclonium tortuosom*, *Chaetomorpha gracilis*, *Cladophora coelothrix*). Typical depth is 0-20 m.

#### **6.2.14 Deep lagoonal sands**

Fine, skeletal coralgal sand and mud. Sporadic patches of seagrass (predominantly *Cymodocea serrulata*), green macroalgae such as *Halimeda*, coral rubble and coral frameworks with low live coral cover are seen. Typical depth is 20-40 m.



**Fig. 6.2.14.** An example of deep lagoonal sands. This sandflat is located off Ras Qisbah at about 25 m depth. The clean, fine sediment occasionally contains rubble and small coral heads and the sand may be colonized by small patches of algae.

### **6.2.15 Sand and mud flats**

Skeletal coralgall sand and mud sediment commonly exposed at low tide. Sediment depth varies. Where sediment is thin, meter-scale patches of hard or semi-consolidated substrate covered with a thin veneer of filamentous or calcareous macro-algae are seen. Semi-emergent areas may form sabkhas (salt flats).

Typical depth is 0-1 m.

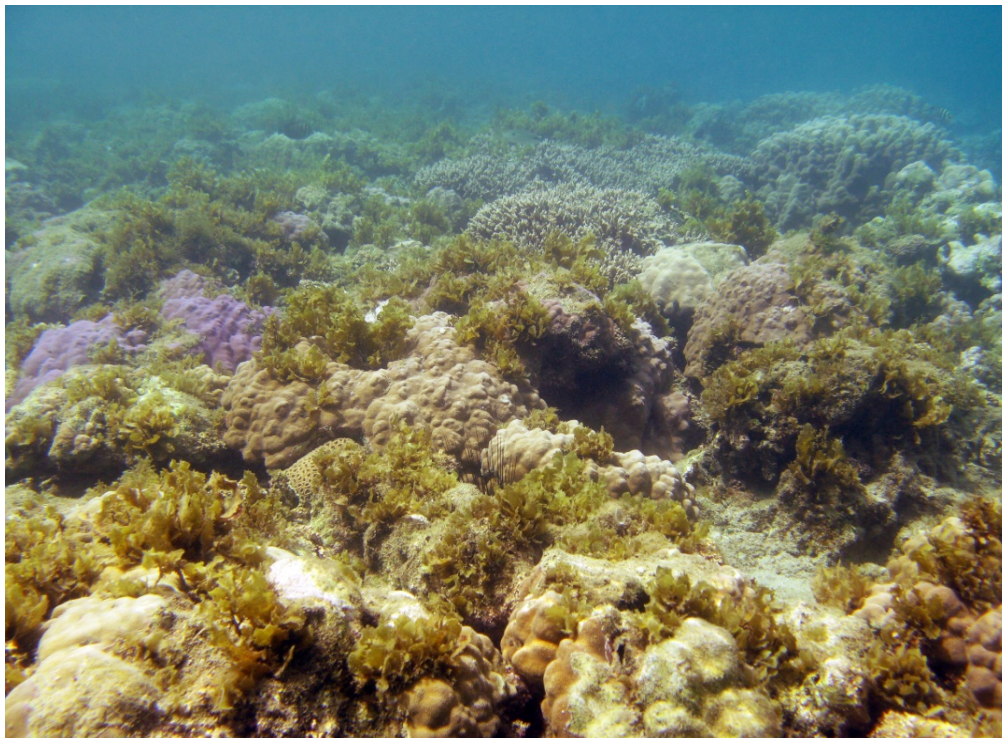


**Fig. 6.2.15.** Shallow sand flat located adjacent to an offshore island, on the leeward side, off Al Wajh Bank. The sediment is clean and relatively coarse.

## 7. Status of reef communities in the Red Sea

### 7.1 Cover of benthic organisms

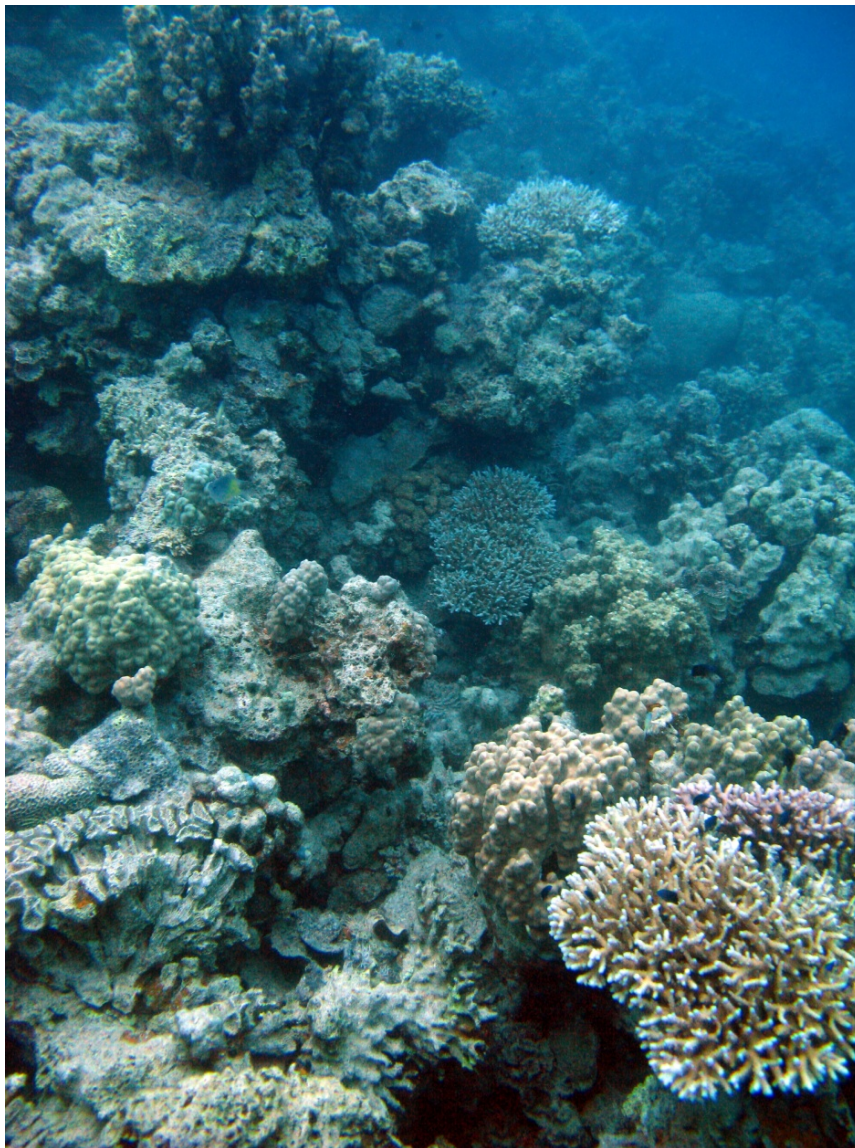
Regional averages in living coral cover observed between 2006-2009, based on visual estimates, ranged from <5% to over 70%. In general, the reef crest and shallow reef slope (3-10 m depth) had the highest coral cover, often approaching 100% at the edge of the slope (1-3 m depth) with lower cover and diversity on the reef flat, and a rapid decline in coral cover below 10 m depth. Certain inner patch reefs (<5-10 m depth) and other semi-protected shallow habitats were dominated by mixed species of *Acropora* and had extremely high cover. Other shallow areas, especially near the coastline in the south (Farasan Islands), had higher cover of macroalgae and less coral; these sites were typically associated with the shallow shelf platform and higher levels of siltation. The average cover at 8-12 m depth was approximately 20-28%, with approximately 10% of the benthic cover consisting of long dead corals and <1% recently killed corals. However, there were numerous sites where the framework consisted largely of dead corals, interspersed with colonies containing small remnants of live tissue, new recruits, and isolated tolerant massive corals such as *Diploastrea*. In addition, many of the reef habitats located in the south, off the Farasan Islands, consisted primarily of hardgrounds and rubble fields with little living coral and sporadic patches of macroalgae.



**Fig. 7.1a A typical shallow reef flat habitat off the Farasan Islands. Corals compete with seasonal blooms of macroalgae.**



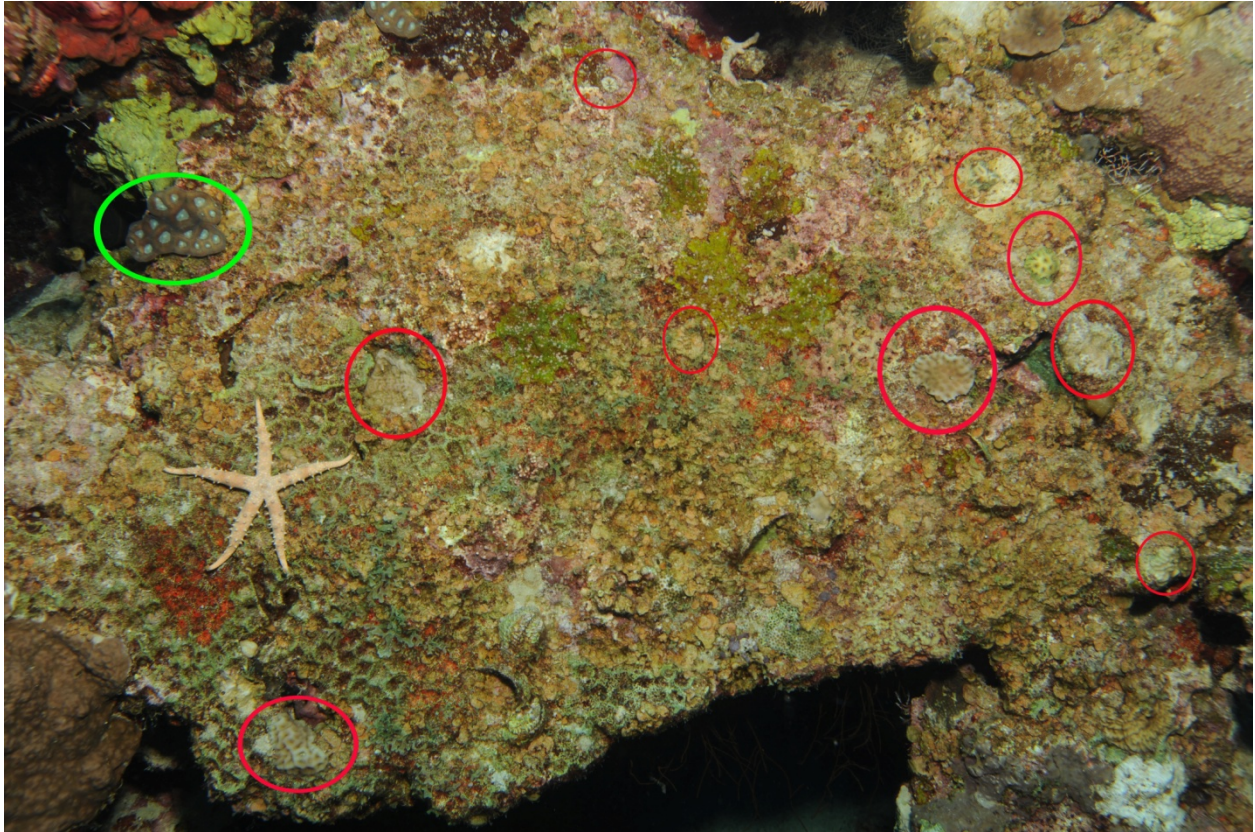
Fleshy macroalgal cover at 8-12 m depth was typically low (<5%), with exception of some inshore reef flat communities, a few highly degraded sites, and shallow habitats near the Farasan Islands. Low amounts of macroalgae are suggestive of low nutrient conditions and/or high herbivory. In addition, turfs (1-10% cover) and crustose coralline algae (8-20% cover) were fairly high in most sites. Soft corals accounted for 5-20% of the bottom cover at 8-12 m depth, although cover of *Xenia* soft coral and other species was higher on vertical walls and it exceeded 50% in some deeper (<12 m) reef environments; especially sites that had been damaged by previous disturbances.



Distinct differences in cover and size distribution of corals were related to site-specific characteristics and disturbance histories, and in species-specific tolerances to a variety of physical, biological and environmental stressors. Some differences were associated with nearshore to offshore gradients; and were also affected by the angle of the reef slope (e.g. vertical walls supported a different community than a gradual slope); facing direction of the reef (due to variations in sun-light regime); wave exposure; proximity to deep water,

**Fig. 7.1b.** A coral reef off Ras Qisbah with a dead *Porites* framework colonized by new corals (lower right; *Acropora*, *Porites*).





**Fig.7.1c. Colony of *Favia* spp. that lost >99% of its tissue. One small tissue remnant is still surviving (green circle). Numerous coral recruits have colonized the exposed skeleton (red circles).**

distance to nearest neighboring reef and other variables. A number of reefs in the central (lagoon sites in Al Wajh) and northern Red Sea (certain sites in Ras Qisbah) had very low living coral cover; these sites were characterized by dead *Porites* framework with isolated remnants of live *Porites* tissue, and small massive faviid corals and isolated branching acroporids and pocilloporids growing on *Porites* skeletons.

Many of the surviving massive corals, especially *Goniastrea* and *Echinopora*, had lost large portions of their tissue but small remnant patches (<5 cm diameter) had survived and were continuing to grow. Similar areas of dead coral were identified on a number of exposed, outer reef walls; these often contained fields of dead plating corals (*Mycedium*, *Echinopora*, *Echinophyllia*, etc.) still in growth position reefs. Corals on these reefs appear to have been dead for 5-10 years, possibly indicating they experienced extensive mortality during or immediately following a bleaching event. Other reefs, especially in the midshelf and offshore portions of the Farasan Banks had very low cover (<5%) and a high amount of dead coral. Nevertheless, these



sites had unusually high numbers of coral recruits (often 100 or more m<sup>2</sup>) which suggests the reefs experienced a major disturbance in the last 3-5 years, but they were exhibiting recent rapid recovery.



**Fig. 7.1d. Completely dead colony of *Echinopora forskaliana*. The coral died 3-5 years ago and is colonized by filamentous algae, but it still has recognizable corallites.**

## **7.2 Coral community structure**

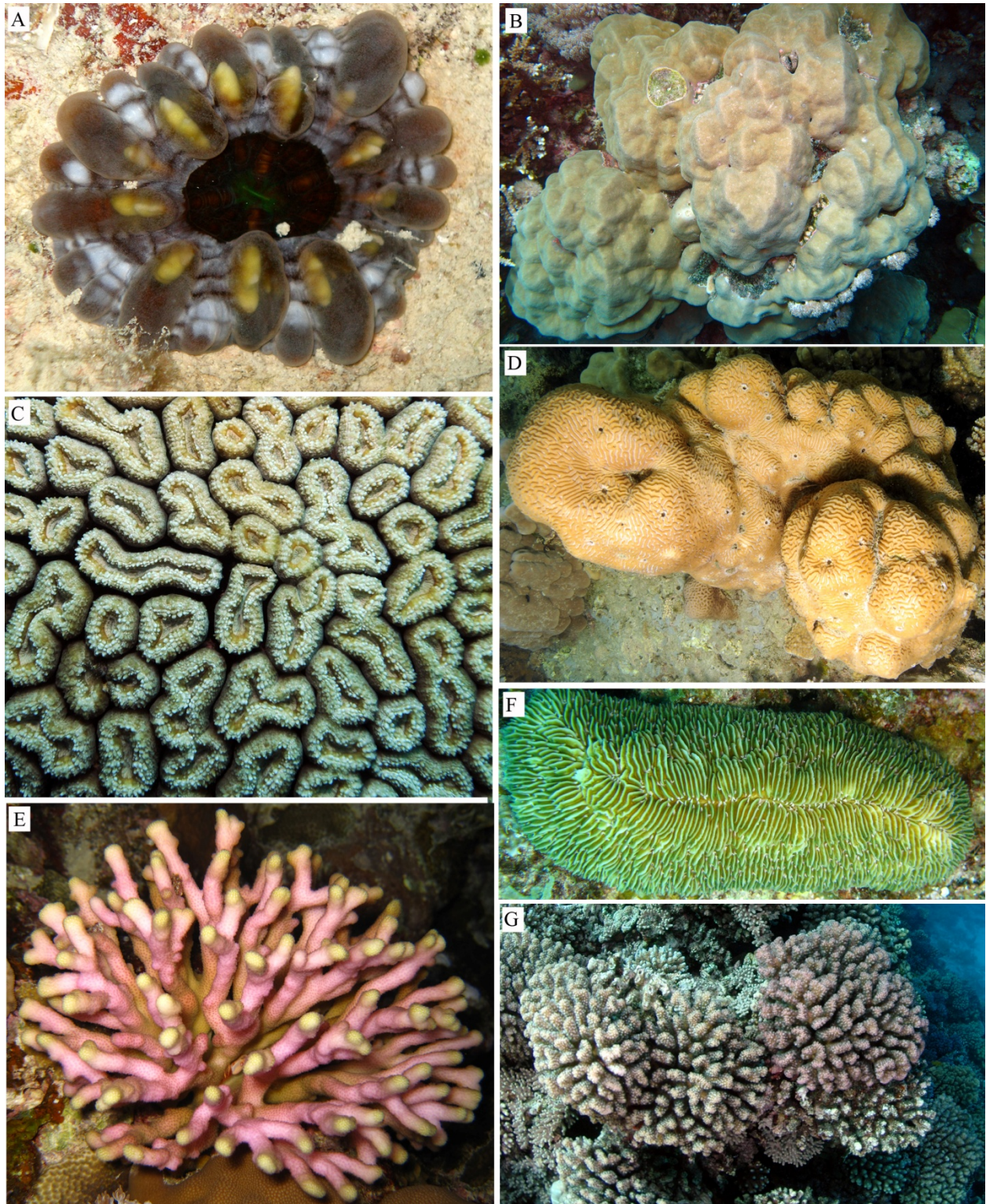
Scleractinian corals are the most important building blocks of coral reefs in the Red Sea. They play a critical role in forming the structure of reefs and provide substrate and shelter for many motile and sedentary organisms. Corals can live hundreds of years, but it is very difficult to determine their actual age. As a surrogate of age, researchers often rely on size data, as the growth rates of most corals are known and knowledge of size can be translated into approximate age. However, this estimate can be off, depending on the degree of partial mortality, fragmentation and regrowth, as a branch of a coral that breaks off may be very small in size but it could have come from a coral that is decades old.

To better understand the status of Red Sea coral reefs, threats and susceptibility of corals to these stressors, and the likelihood for recovery following disturbances, the Khaled bin Sultan Living Oceans Foundation characterized coral population dynamics across gradients of physical and environmental exposure. Coral population dynamics are influenced by colony growth and number of colonies within a population, both of which reflect rates of settlement of planula larvae, survival, and mortality, reproductive parameters and other life history traits, as well as the quality of the habitat and extent and severity of stressors. Coral life history strategies vary across a continuum from k to r strategists, and include:

- 1) **broadcast spawners**, which are colonies that release sperm and eggs into the water for external fertilization generally during mass spawning events that occur once per year; these can have separate sexes or are hermaphroditic; these can have long distance dispersal and transport of larvae and are important recolonizers of degraded reefs.
- 2) **brooders** are colonies with internal fertilization and parental care; competent larvae are released, which settle relatively close to the parents. These tend to be smaller in size than broadcasters, are shorter lived and are more “weedy” often forming the dominant constituents (in terms of numbers of colonies) in areas undergoing early stages of recovery. Colonies usually have separate sexes.
- 3) taxa that propagate primarily via **asexual fragmentation**, which includes mostly branching corals.
- 4) taxa that reproduce using a **combination of sexual and asexual modes**. Many of the species of *Acropora* and *Pocillopora* rely on both modes of reproduction.

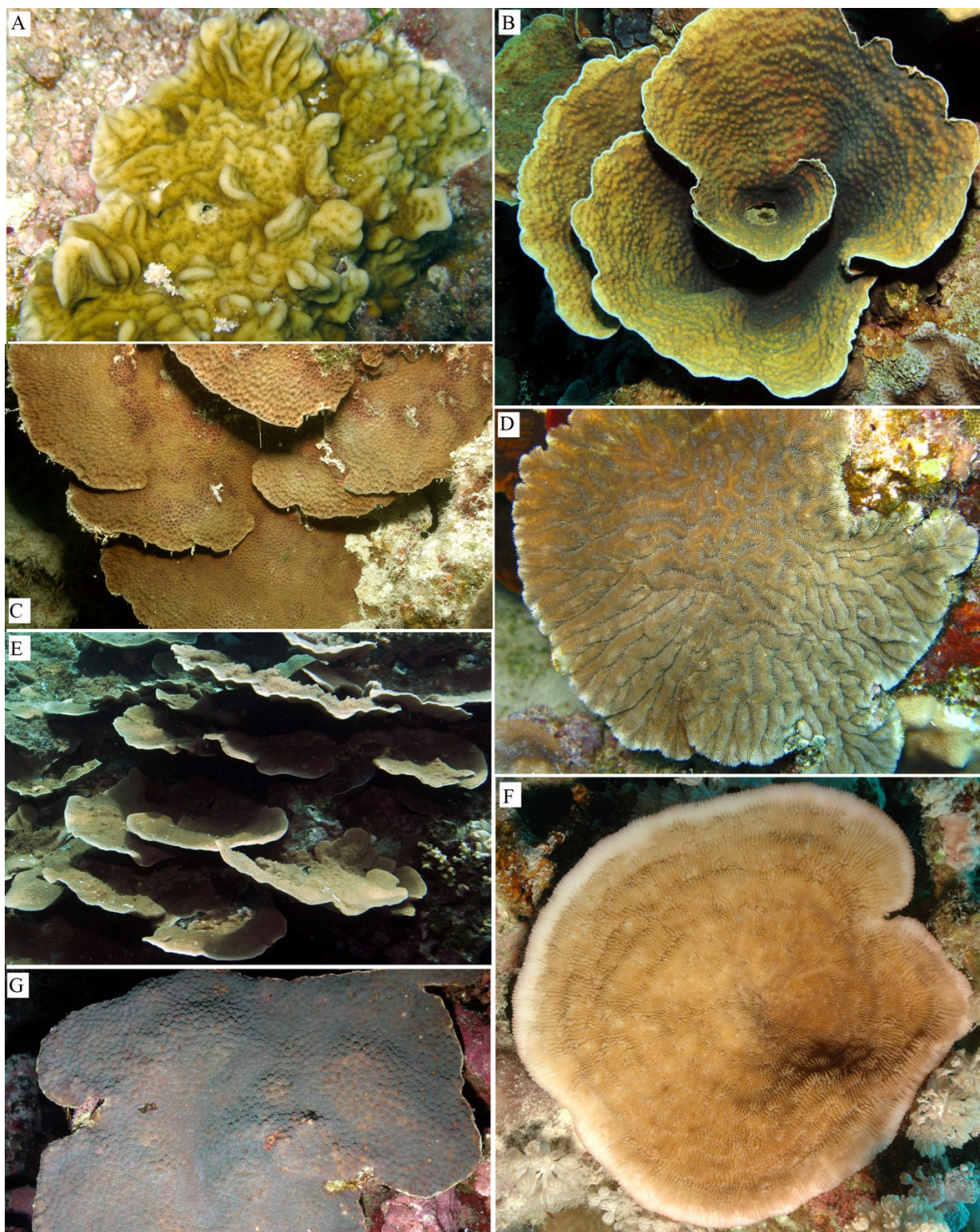
Corals also exhibit highly variable morphologies, both within and between species (Fig. 7.2). This includes massive boulders, plates, branching finger and tree-like structures, and crusts. The geographical location and environmental conditions at a site both play key roles in controlling the proportion of different growth forms present, as well as and diversity of coral functional guilds. While solitary corals do exist, most important reef builders are colonial (modular) organisms consisting of numerous interconnected animals (polyps), which may provide an adaptive advantage by allowing colonies to survive disturbance with partial mortality followed by regeneration once environmental conditions improve.





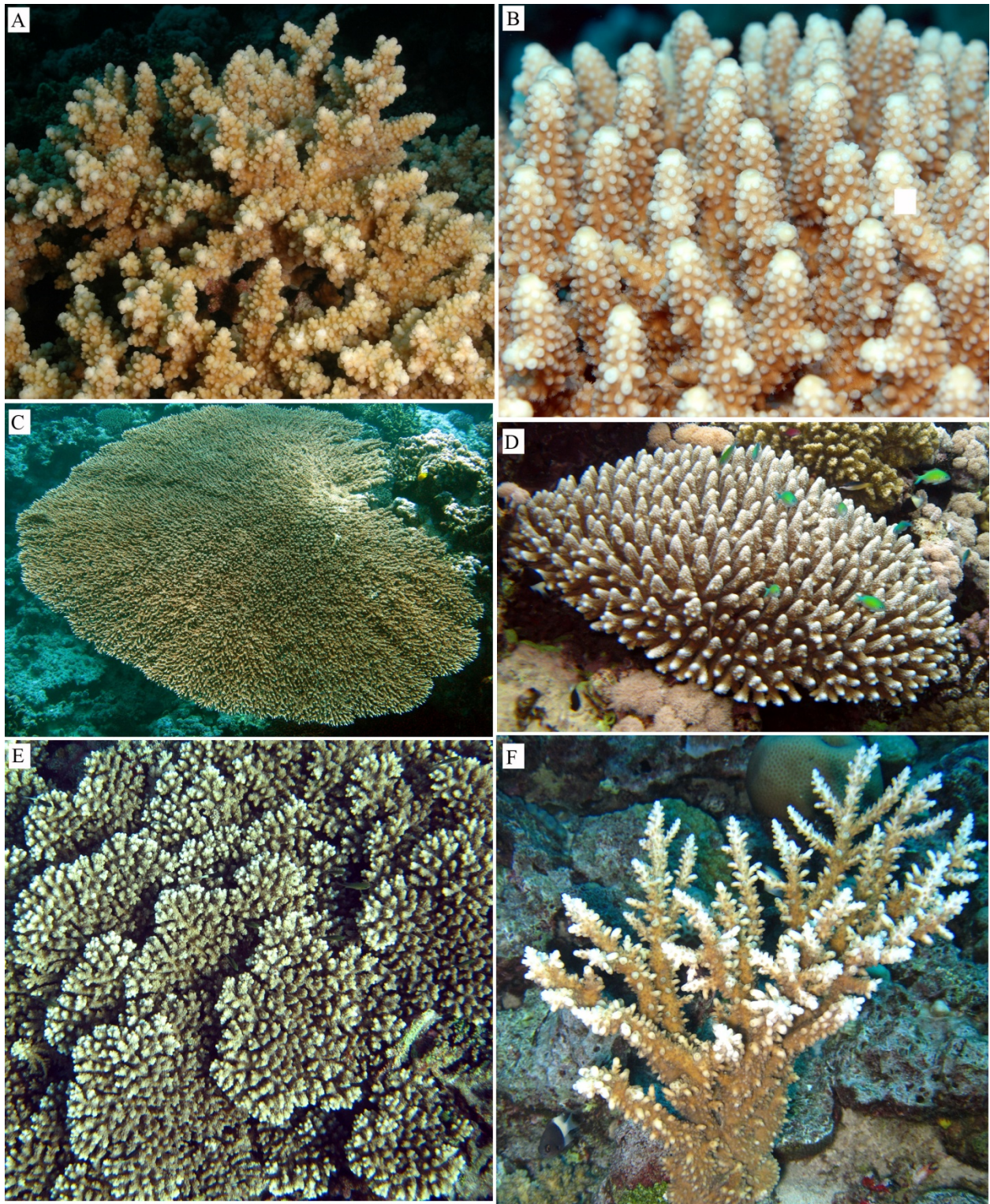
**Fig. 7.2a. Examples of growth forms of corals. A. *Cynarina*, a solitary coral. B. Massive growth form, plocoid corallites (*Porites*). C. Flabellate growth form (*Lobophyllia*) D. Massive growth form, meandroid corallites (*Platygyra*). E. Branching coral (*Stylophora*). E. Free living coral (*Ctenactis*). G. Branching coral, short stubby branches (*Pocillopora*).**





**Fig. 7.2b. Examples of plating corals. A. *Pavona* colony forms crusts with vertical extensions. B *Mycedium* forms lettuce-like foliose colonies. C. *Goniastrea* colony forming overlapping sheets on a vertical wall. D. *Mussimilia* colony forms meandroid plates. E. Some corals form shingle-like sheets that extend out from vertical walls. F. An attached fungiid coral that forms plates. G. Colony of *Echinopora* in deep water. This coral usually forms massive structures that flatten out at depth.**





**Fig. 7.2c. Examples of growth forms of *Acropora*. A. Bottlebrush (short branches); B. digitate (finger-like branches); c) tabular (table-like) colony with fused branches; d) digitate colony; e) tabular with short branches; f) erect branching growth form.**

### 7.3 Coral size structure

Knowledge of the size frequency distribution of corals provided an indication of the severity of past disturbances, resistance of the corals, how much recovery has occurred, and the likelihood that the reef will survive future disturbances. For instance, a reef dominated by large, massive *Porites* colonies with few juveniles likely has not experienced a recent large scale disturbance. This suggests it is a fairly stable community, but it may lack resilience to future disturbances because new corals are not settling or replacing older colonies. In contrast, a reef with few large corals and a high abundance of small colonies is either perturbed very frequently or it experienced a mass die-off from a previous disturbance, but it is showing rapid recovery. Further analysis of the type of corals (e.g. all small brooders vs. mixed populations of brooders and spawners) can help determine whether the reef is being impacted by chronic stressors or solely a single past acute stress. The best case scenario, a reef that exhibits very high resilience, would include a high diversity of corals and a wide range of sizes, including high numbers of recruits, juvenile corals and larger adult colonies.

Most corals (approx. 75% of all colonies) were small (1-30 cm diameter), while small and medium-sized corals (20-80 cm) occupied most of the available space on the reef. Isolated large colonies (>1 m diameter) of *Porites*, *Acropora*, *Diploastrea*, *Echinopora*, *Lobophyllia*, *Montipora*, *Favia*, *Hydnophora* and other species were present, but patchy in their distribution.

The reef framework throughout the region was constructed of massive *Porites* colonies, much of which was dead, although localized patches of up to 80% live cover, dominated by large (1-4 m diameter) colonies of *Porites*, were identified in shallow water (2-15 m depth). Massive *Porites* colonies were also numerically dominant in all sites and large corals were often subdivided into numerous smaller ramets via partial mortality.

Small (<20 cm) massive corals such as *Goniastrea* and *Echinopora* were also locally abundant, although signs of recent mortality from disease and COTS sea star predation were widespread, occurring both in instances when COTES were present and in locations where no COTS could be found or were at low abundances. On reefs that experienced large die-offs, either as a result of a bleaching impact or an outbreak of predators or disease, small massive colonies of *Echinopora* and remnants of *Goniastrea* were often the only survivors. In particular, many reefs within Al



Wajh lagoon had sustained high levels of mortality and the dominant remaining coral was *Echinopora*.

*Pocillopora* colonies were abundant in reef crest and shallow fore reef habitats of the northern and central Red Sea, but were less common in the south; these corals were typically small (<20 cm) with larger colonies sustaining progressive mortality from corallivores and disease.

Branching and table acroporids were most common on inshore, turbid reefs, and only rarely seen on offshore sites, with exception of digitate acroporids and tightly branched, low-lying colonies in reef crest and shallow fore reef habitats. On shallow midshelf and offshore sites with a high abundance of *Acropora*, these species were often being attacked by COTs sea star (*Acanthaster*).

In degraded areas with high amounts of dead coral, the most common surviving coral was *Diploastrea*, a species resistant to bleaching and predation by COTs sea stars. These corals were generally at a low abundance (1 colony per 10 square meters), but were often large in size (0.5-2 m diameter).

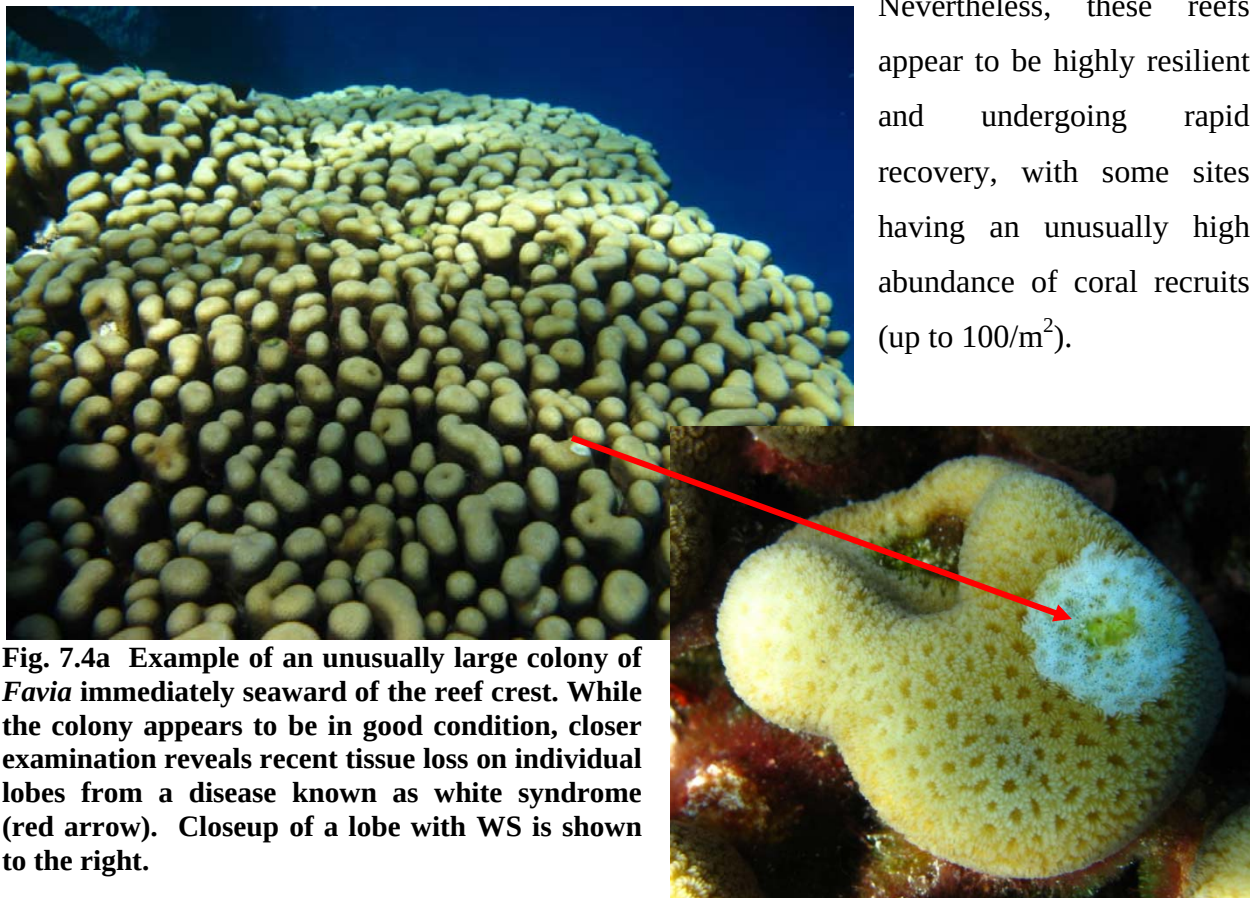
Coral assemblages were vastly different on offshore vertical walls. Stony corals either formed encrusting and plate-like colonies or small submassive colonies, such as *Stylophora marmorata*. Many of these walls had an abundance of soft corals, encrusting sponges and other non-coral invertebrates. This was particularly noteworthy around Farasan Banks, where offshore reefs often had lower live coral cover than inshore and midshelf areas. These areas were also characterized by a predominance of plating colonies of small to intermediate size.

Stony corals also were greatly reduced on deeper reefs (>20 m depth). For example, deep offshore reefs in the Farasan Banks often had high cover of organ pipe coral (*Tubipora musica*).

## 7.4 Coral Condition

Overall, coral communities off the coast of Saudi Arabia exhibited low levels of recent mortality, with exception of sites affected by recent outbreaks of crown of thorns (COTs) sea stars. Bleaching was rarely seen during the assessments, with exception of the Ras Qisbah surveys. There were no unusual temperature anomalies during the four year research program. Coral diseases were identified, including most of the common conditions reported for the Indo-Pacific, although an outbreak of disease was not seen during this study. High levels of predation by corallivores, especially *Drupella* snails and COTs sea stars were noted, but with exception of a few sites, predation scars were limited to isolated colonies. What was most apparent was that reefs throughout the region have experienced several past disturbances that were responsible for extensive coral losses, but these communities were typically showing signs of recovery. These past disturbances include possible bleaching events, disease outbreaks and infestations by corallivores, as evidenced by the presence of numerous dead standing corals, living corals dominated by small colonies, and entire reef tracts largely devoid of adult colonies.

Nevertheless, these reefs appear to be highly resilient and undergoing rapid recovery, with some sites having an unusually high abundance of coral recruits (up to 100/m<sup>2</sup>).



**Fig. 7.4a** Example of an unusually large colony of *Favia* immediately seaward of the reef crest. While the colony appears to be in good condition, closer examination reveals recent tissue loss on individual lobes from a disease known as white syndrome (red arrow). Closeup of a lobe with WS is shown to the right.



## 8. Fish assemblages

Red Sea coral reefs off the coast of Saudi Arabia support over 1400 species of reef fishes (Devantier et al. 2000a). Many of these fishes are both ecologically and commercially important, while some species are not currently harvested, they are important in maintaining the health and proper functioning of the reef. These fish species are integrally linked to their habitats, playing a key role in maintaining normal functioning and in preventing or mitigating synergistic impacts from human stressors and climate change. Fisheries have the potential to alter the composition and size structure of coral reef fishes, with unintentional consequences on reef health such as a phase shift from highly productive coral-dominated systems to low productivity algal reefs. Many species, such as groupers, snappers, sharks and certain herbivores were key targets of commercial and artisanal fisheries, and in several locations fish populations have been depleted due to increased fishing effort and the use of non-sustainable fishing gear. In particular, sharks were rarely seen, even in offshore reefs around Farasan Banks, except certain deeper reefs.

Fish assessments conducted by the Living Oceans Foundation emphasized the major functional groups that are thought to be indicators of reef resilience, including key herbivores, piscivores, scavengers, coral feeders, sessile invertebrate feeders, planktivores and detritivores (Appendix 4). Herbivores (e.g. parrotfish, surgeonfish, rabbitfish and unicornfish) are also allocated into functional groups, including excavators, scrapers, grazers and browsers, based on their role and importance in controlling phase shifts from coral to algae and in reversing this shift following a disturbance (Table 3). The top level predators (sharks, groupers, jacks) control abundances of lower trophic level fish and provide a good indication of fishing pressure, while second level predators such as snappers, sweetlips may prevent population explosions of invertebrates including *Acanthaster* (crown of thorns sea stars) and *Drupella* (coral eating snails) corallivores. Obligate and facultative coral feeders such as butterflyfish and filefish provide an indication of the health of the coral, and sessile invertebrate feeders (especially angelfish) are important indicators of the abundance of soft corals and sponges (which may monopolize bottom substrates and out compete corals if conditions allow). Certain planktivores (triggerfish) provide an indication of the condition of the water column and abundance of larvae critical to reseeding degraded reefs. Detritivores like goatfish are also included in our surveys as they are indicators

of eutrophication and conditions that may be unsuitable for corals. Because these species exert top down control on reef dynamics, knowledge of the numbers of fish species, abundance and density, and composition by functional and/or trophic groups can provide critical information on the ability of the coral reef to resist change and recover rapidly following large scale climatic perturbations. Herbivores are of particular importance to the recovery of reefs following mass die-offs of coral. Different groups of herbivores feed on different types of algae and they use a variety of feeding modes. Some species will only graze the fronds of algae, while others remove algae and some of the underlying substrate. Species with the largest, strongest jaws, including many of the parrotfish, are important sources of bioerosion and they produce much of the sediment found on reefs through their feeding behavior (Table 3).

In general, most reefs had a relatively high diversity of fishes, with representatives of most functional groups present. However, some species appeared to be depleted, including many of the top predators like sharks as well as mesopredators like groupers. This was apparent in both a reduced number of fishes within transects, and the presence of primarily juveniles and young adults of a small size, with few fish present that had achieved their maximum size. Throughout the region, the abundance of top predators, especially sharks and large groupers (>50 cm) was extremely low, although most reefs had at least one to two medium-sized groupers, higher numbers of small groupers and other large predators including barracuda. Most sharks were observed on offshore reefs, generally at the edge of the drop-off, in deeper water (20-40 m) around mesophotic coral reefs, and in blue water away from the reefs. Selected reefs had high numbers of second level predators, including a high dominance of commercially important snappers such as *Lutjanus bohar*, *L. fulviflamma*, and *L. kasmira*, although reefs with the largest populations of these species also had an abundance of fishing line and other lost fishing gear. A particularly important species, the humphead or Napoleon wrasse (*Cheilinus undulatus*), was present in many locations (especially Al Wajh and Farasan Banks), but every fish seen was a juvenile or subadult, typically no more than 30 cm in length and more frequently in the 20-30 cm size class. These fish are a valuable target for the export fishery (as live reef food fish) and their numbers have been depleted worldwide; as a result these species are listed as critically endangered on the IUCN Red List and are listed on Appendix II of the Convention on International Trade in Endangered Species (CITES). Obligate and facultative coral feeders, including butterflyfish, angelfish and filefish/pufferfish were common on reefs with moderate to

high cover, while they were absent from several of the more degraded sites. Certain planktivores, especially triggerfish and fusiliers were often abundant in offshore locations adjacent to a steep slope, which may be indicative of upwelling. Detritivores like goatfish were most common at the base of reef, where it meets sandy areas, and in channels between reefs. Herbivores, such as rabbitfish and surgeonfish were usually most common on the reef flats, especially in more southern locations where algal abundances were higher. In some cases, parrotfish were the largest-sized fish recorded in surveys.

**Table 3. Differentiation of the herbivorous fish into functional groups.**

| Functional group                                                                 | Taxonomic groups                                                                                                                                                                                                                                                                                                                                                                                 | Function and notes                                                                                                                                                          |
|----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Large excavators<br><b>Humpheaded parrotfish – large individuals (&gt;35 cm)</b> | <i>Bolbometopon</i> , <i>Chlorurus microrhinos</i> , <i>C. frontalis</i> and <i>Cetoscarus bicolor</i> . All humphead wrasse >35 cm.                                                                                                                                                                                                                                                             | Bioerosion. They take fewer, larger, deeper bites, remove more of the substratum with each bite, and play a key role in bioerosion.                                         |
| Small excavators<br><b>Humpheaded parrotfish – small individuals (&lt;35 cm)</b> | As above and other <i>Chlorurus</i> species ( <i>C. bleekeri</i> and <i>C. sordidus</i> ; All small humphead wrasse <35 cm)                                                                                                                                                                                                                                                                      | Bioerosion. Take more, smaller, shallower bites, and remove less of the substratum with each bite.                                                                          |
| Scrapers<br><b>Other parrotfish</b>                                              | <i>Scarus</i> and <i>Hipposcarus</i> .                                                                                                                                                                                                                                                                                                                                                           | Bioerosion, colonization surfaces. Remove algae, sediment and other material by closely cropping or scraping the substrate.                                                 |
| Grazers<br><b>Small rabbits, many surgeons</b>                                   | Small rabbitfish (<20 cm), all <i>Centropyge</i> , all <i>Zebrasoma</i> , most <i>Acanthurus</i> (excl. planktivores/ringtails).                                                                                                                                                                                                                                                                 | Algal control. Remove epilithic algal turf from the reef substratum, but do not scrape the surface, prevent coral overgrowth and shading by macroalgae.                     |
| Browsers<br><b>Unicorns, chub, batfish, large rabbits, Calotomus</b>             | Chub, batfish, large siganids (>20 cm), and parrotfish of genus <i>Calotomus</i> , <i>Leptoscarus</i> . Unicornfish - all sizes of <i>N. brachycentron</i> , <i>N. elegans</i> , <i>N. lituratus</i> , <i>N. tonganus</i> and <i>N. unicornis</i> , Unicornfish - (<20 cm) of <i>N. annulatus</i> , <i>N. brevirostris</i> , <i>N. maculatus</i> , <i>N. mcdadei</i> , and <i>N. vlamingii</i> . | Algal control. Feed on macroalgal fronds, reduce coral overgrowth and shading by macroalgae.                                                                                |
| Grazers/detritivores<br><b>Ringtail surgeons</b>                                 | Ringtail surgeonfish - <i>Acanthurus blochii</i> , <i>dussumieri</i> , <i>leucocheilus</i> , <i>maculiceps</i> , <i>nigricauda</i> , <i>olivaceus</i> , <i>pyroferus</i> , <i>A. tristis</i> and <i>A. xanthopterus</i> .                                                                                                                                                                        | Algal/sediment control. Feed on a combination of algal turf, sediment and some animal material similar role to grazers; remove macroalgae before it can become established. |

Because coral reef fishes exert top down control on reef dynamics, knowledge of the numbers of fish species, abundance and density, and composition by functional and/or trophic groups can provide critical information on the ability of the coral reef to resist change and recover rapidly following large scale climatic perturbations. Key fishery management targets should emphasize restrictions on gear type allowed in reef environments. For instance, fish traps and gill nets should be excluded from the fishery because these tend to have a small mesh size and they capture all functional groups of fishes, including those species that are not eaten. In contrast, hook and line has minimal impacts on the habitat, and only food fishes are caught. Measures should also be developed to restrict take of species that regulate community composition and structure of the reef, with emphasis on limits on harvest of herbivores like parrotfish, rabbitfish and certain invertebrate feeders. There also should be a ban on shark fishing for fins, as this is wasteful and sharks have a long lifespan and produce few offspring. In general, fishery management measures should emphasize the ecosystem role of these fishes, striving to protect those species that are vulnerable to fishing pressure and are most important in regulating the structure of the reef.



**Fig. 8.5.** Example of a top predator, a silky shark (*Carcharhinus falciformis*), seen in the Farasan Banks.



## 9. Threats

Threats affecting reefs in the Saudi Arabian Red Sea can be divided into human or anthropogenic stressors and natural stressors. Human stressors include indirect impacts associated with land-based activities as well as direct impacts from extraction of reef species (fishing), potential discharge of ballast water, and ship groundings. Natural stressors include biological agents of destruction, such as coral diseases, coral predators, coral bleaching and storm damage. Both of these are worsened by climate change, and interactions among multiple stressors can also have synergistic effects.

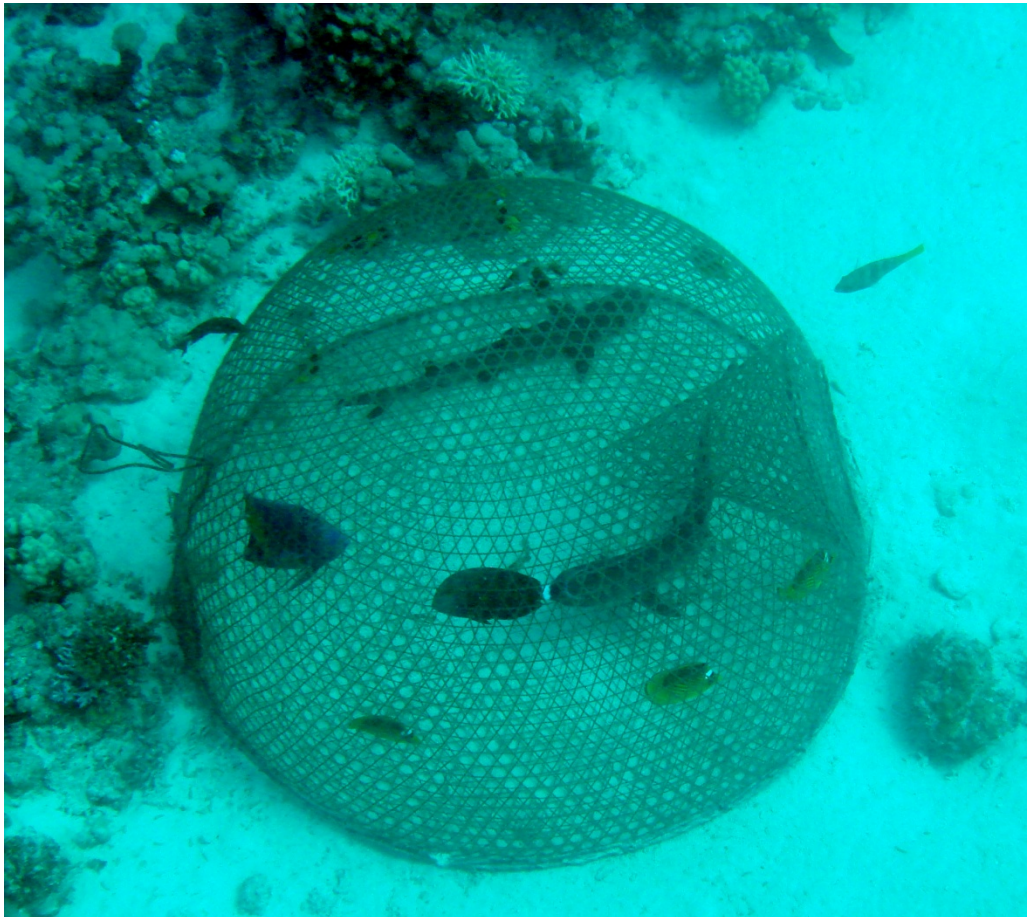
### 9.1. Human impacts

Stressors to reefs examined along the Saudi Arabian Red Sea coastline varied spatially, with greatest levels of human threats at sites near large cities such as Jeddah and Yanbu. These sites were affected by impacts associated with coastal development, untreated sewage and industrial discharge, dredging, infilling, shipping and transport and associated habitat impacts from groundings and anchors, desalinization plants and other land-based stressors. Many of the nearshore sites exhibited moderate to high levels of turbidity (especially in lagoonal sites) and corals were restricted to shallow water (e.g. <10 m depth). In contrast, most of the complex, offshore reefs examined off Ras Qisbah, Al Wajh, Farasan Islands and Farasan Banks appeared to be affected minimally by land-based threats. Solid waste on island beaches and in the water column was also low, except at a few sites.



**Fig. 9.1a. Fishing boat with dozens of fish traps in the Farasan Banks.**

Moderate levels of fishing pressure were noted in all locations and there were indications that fishing pressure is increasing. Mostly small fishing boats were observed, with fishermen using handlines and gill nets, although some traps were observed in Al Wajh and Farasan Banks, and trap fishing appears to be becoming more common among non-native fishermen. Large amounts of fishing line was entangled in corals at many sites, and abandoned gill nets, seine nets and derelict fish traps were found. Recreational use of the reefs and islands appears to be currently low, but will undoubtedly increase as the Farasan Banks, Yanbu and Al Wajh become better known as a premier dive site.



**Fig. 9.1b. A fish trap in the Farasan Banks. Two small sharks, angelfish, surgeonfish and butterflyfish were trapped.**

## **9.2 Natural stressors:**

Many of the sites examined appear to have been impacted by several large scale disturbances that have resulted in extensive coral mortality. In particular, there are reports of extensive bleaching associated with temperature stress in 1998 (Devantier et al. 200b), with high levels of mortality identified in some central and northern sites. The potential for temperature-related bleaching perturbations also existed in 2001, 2002, and 2005. In many cases, corals may bleach (turn white or pale) due to a loss of symbiotic zooxanthellae or algal pigments, but they can exhibit complete recovery if conditions improve relatively quickly (e.g. water temperatures decline). However, if temperature anomalies are unusually high and/or prolonged for several weeks to months, corals may experience partial to total mortality. In 1998, many reefs in the Indo-Pacific (especially Indian Ocean) exhibited total bleaching to 20-30 m depth, followed by mass mortalities that often exceeded 80%. Reports from Saudi Arabia suggest fewer losses (Devantier et al. 200b; Kotb et al. 2004, 2008), although quantitative surveys were limited. Bleached corals were rare during all surveys conducted from 2006-2009; isolated colonies were observed with partial to total bleaching but no large scale bleaching events were recorded.

## **9.3 Coral Diseases**

### **9.3.1 Descriptions of diseases**

Coral diseases were first described from Saudi Arabia in 1985. Until work conducted by the Living Oceans Foundation, there were no subsequent records of disease from this region, but it is likely that they were present. During the 2006-2009 research missions, a total of 10 named diseases were identified and at least one additional undescribed disease was observed. These were relatively uncommon at the times of the surveys, with exception of the undescribed condition affecting *Porites* colonies. A summary of the general features, species affected and similar conditions is presented below and in Table 4, and photographic plates illustrating colonies identified with disease during this mission are shown in Figs 9.3a-c.

### **9.3.2 White syndromes (WS)**

White syndromes are distinguished by the presence of a diffuse, white lesion that develops into a linear (or annular) band or an irregular patch on a coral colony. The lesion consists of an area of recently exposed coral skeleton adjacent to apparently healthy tissue. In some cases, a narrow

band of bleached tissue may separate the denuded skeleton and normal appearing tissue. Live tissue typically forms an abrupt margin at the lesion border and colonies usually lack a zone of transition between live coral tissue and freshly denuded skeleton, although some tissue sloughing may be apparent. Lesion boundaries are free of visible microorganisms, pigmented bands or other colonizing organisms. Colonies that have been affected by a white syndrome for weeks to months often display extensive areas of tissue loss. Exposed skeleton first denuded by the disease, distal to the actively progressing front of the lesion, may be colonized by algae or other microorganisms and often colonies exhibit a progression from stark white skeleton to green or brownish skeletal surfaces with fine filamentous algae, followed by later stages of colonization by macroalgae, crustose coralline algae or other organisms.

White Syndromes characterized by diffuse patterns of tissue loss have been reported as white plague-like disease in the Red Sea, atramentous necrosis on the GBR, and white band disease. White syndromes can be confused with predation by COTs sea stars.

### **9.3.3 Ulcerative white spots (UWS)**

UWS includes lesions were first described on *Porites* as Porites ulcerative white spot (PUWS) and more recently similar white spots (UWS) on other taxa. The disease is characterized by one or more small circular to irregular areas of bleached or bare white skeleton, generally less than 5 cm diameter, progressing to multifocal patterns of tissue loss. Lesions typically start as discrete, bleached, round foci, 3 to 5 mm in diameter, affecting 3-5 polyps. Affected regions may still be alive, but over time bleached tissue may progress to full tissue ulcerations devoid of living tissue. Occasionally, the lesions coalesce and can cause whole colony mortality. In other cases full colony recovery may occur. Signs that resemble ulcerative white spots may be caused by repeated fish bites.

### **9.3.4 Black band disease (BBD)**

Black band disease is characterized by a black, purple or reddish, linear to annular band separating healthy coral tissue from a zone of recently-exposed white skeleton. The band width varies from about 0.1 mm to 5 cm or more in extreme cases. The length of the band can vary from a few cm to several meters, depending on the side of the colony. Often, the band encircles the entire perimeter of the coral in hemispherical colonies. The band overlays recently-killed



tissue, and can be dislodged. Often, filaments are visible extending from the band into adjacent corallites.

BBD may initiate in a central previously denuded algal colonized lesion, or at the perimeter of the colony. Sites of physical injury, abrasion and algal/invertebrate overgrowth may serve as an entry point for the BBD. In severe infections, there may be more than one lesion per colony. Infections usually start on an upper or side surface of a coral colony as a small dark pigmented patch 1-2 cm in diameter. Infections do not initiate within the colony surface in areas that appear healthy; if the band initiates within the colony surface, it starts adjacent to a previously denuded or abraded area on the corallum.

The patch generally forms a ring, the circumference of which rapidly increases as the band migrates horizontally across the coral and denudes tissue in its path. Linear tissue loss progresses at an average rate of 3 mm/day, but the band is capable of advancing up to 1 cm/day. Entire colonies of a small size may experience total mortality within a few days to weeks. Larger colonies typically lose portions of their tissue, with the disease advance declining or stopping at the onset of lower seasonal temperatures. Colonies may be reinfected in subsequent seasons. In older infections and rapidly progressing advanced stages of the disease, a zone of stark white exposed skeleton may lie between the progressing band and older skeleton that has been colonized by algae.

### **9.3.5 Brown band disease (BrB)**

Brown band disease (BrB) primarily affects acroporids, particularly thicket-forming species such as *Acropora formosa*, *A. aspera*, *A. acuminata* and *A. intermedia*. BrB also affects pocilloporids and faviids, but less frequently.

BrB consists of dense aggregations of mobile ciliates located between living tissue and exposed coral skeleton. These appear to directly consume coral tissue; endosymbiotic zooxanthellae (*Symbiodinium*) are generally visible within the ciliates and give the band its characteristic brownish color.

BrB manifests as a golden-brown band, 0.1-1 cm wide, with a slight jelly-like consistency. As the disease progresses, a band of white skeleton is visible behind the band which is rapidly

colonized by algae (usually within one week). Often, a narrow band of white skeleton is also visible at the advancing front of the disease, separating the ciliates and healthy coral tissue. In branching species, the band typically circumscribes the branch. The disease usually begins at the base of a branch, rapidly progressing upward. There is usually only a single band per branch. Multiple branches may be affected on individual colonies. On tabular and massive species, the band generally begins at the colony margin, and progresses upward and inward.

### **9.3.6 Skeletal Eroding Band (SEB)**

Skeletal eroding band (SEB) is characterized by diffuse areas of tissue loss that may form a band or line at the interface with living tissue. Tissue loss is associated with ciliates that consume tissue and expose the underlying skeleton. The ciliate typically become embedded in the skeleton and they contribute to erosion of the skeleton. As the tissue loss advances, previously denuded and eroded skeleton is covered by the external casings of the ciliates (vacated loricae of *Halofolliculina*) that give the disease its salt and pepper appearance. Living tissue is typically separated from algal colonized skeleton by a non-uniform (1-10 cm thick), black to dark-green, undulating, annular border.

At low densities, ciliates may appear as sparsely scattered, dark dots on skeleton recently denuded of tissue, producing a characteristic speckled appearance. At high densities, ciliates form a thick dark band that grades into areas of sparsely scattered, vacated loricae.

The locations of lesions associated with SEB vary among coral species and also as lesions progress across colonies. Most infections originate basally, progressing to the branch tips in branching colonies, while they are often located centrally in hemispherical, sub-massive or encrusting colonies. SEB can also appear at the margin of any previously denuded lesion, and they are often associated with white syndromes, especially during the later stages of an infection.

Without magnification, dense bands of *Halofolliculina* ciliates can appear similar to black band disease. However, SEB infections tend to be more speckled in appearance. In contrast, BBD lesions are characterized by discrete black bands composed primarily of cyanobacterial filaments that overly live tissue and can be readily dislodged. BBD lesions also lack the eroded calices often seen in SEB infections.

SEB has been recorded on 82 species of scleractinian corals, in 26 genera and 12 families, as well as the hydrozoan coral, *Millepora*. The family Pocilloporidae and Acroporidae are the most susceptible scleractinian families to SEB.

#### **9.3.7 Pink Line disease (PLD)**

Pink line disease (PLD) is a condition only reported to affect corals in the genus *Porites*. This condition can appear vastly different among each affected coral, but the general characteristic is for a pink to purplish coloration of living tissue. The pigmented tissue can form a linear, annular, circular or irregular band, irregular blotches, or circular patches separating recently killed skeleton and normal tissue. In some cases, it may begin as a small ring and progress outward. It is important to note that many factors can cause pink to purple pigmentation in *Porites*, including fish bites, fin scrapes, encrusting barnacles and other irritations.

#### **9.3.8 Arabian yellow band disease (AYBD)**

Arabian yellow band disease (AYBD) manifests as a bright yellow band of one to several cm in diameter at the interface of healthy and dead coral. The band migrates across the coral in a linear to annular pattern, producing a margin of decaying tissue adjacent to healthy tissue. The yellow band is raised above the surrounding tissue and appears often to have a thin mucous envelope. As the band progresses, dead skeleton may retain a yellow pigmentation, or it becomes greenly discolored in the genus *Porites* or, in *Acropora*, is usually pure white. Unlike BBD, no filaments or microbial band are visible.

#### **9.3.9 Pacific yellow band disease (PYBD)**

Pacific yellow band disease (PYBD) first appears as a pale yellow blotch within the colony perimeter or as a narrow band at the colony margin. The pale yellow areas are living coral tissue located adjacent to normal, fully pigmented brown or greenish tissue. As the band/blotch progresses it typically forms a circular or annular ring separating normal tissue from algal-colonized skeleton. Progression is generally slow, and often white, recently denuded skeleton is absent or limited to small irregular patches consisting of a few polyps.

Pacific yellow band disease (PYBD) is only known to affect *Diploastrea heliophora*, *Fungia* spp. and *Herpolitha* spp. In *Fungia* spp., diseased tissue appeared as one or more irregular blotches

dispersed over the corallum, often forming an expanding circle, but not the circular rings seen in faviids. In advanced stages, the yellow lesions in *Fungia* disappear as host tissue is degraded, and a pink coloration becomes evident in the skeleton

#### **9.3.10 Dark spots disease (DSD)**

Dark spots disease (DSD) is characterized by focal to multifocal lesions located within the colony surface and generally surrounded by normal appearing tissue. These may be distinct brown to purple, round to amorphous to oblong areas of discoloration, with smooth to gently undulating edges. The dark spots consist of live coral tissue.

DSD Lesions range in size from about 1-5 cm but they may coalesce over time forming larger lesions. In some cases, the center of these discolored areas may die, with chronic tissue loss occurring over prolonged periods and older denuded areas being overgrown by turf algae. In more advanced cases of DSD, there may be some erosion of the skeleton, leaving a central indentation colonized by turf algae and bordered by an irregular distinct band of dark discoloration.

#### **9.3.11 Growth anomalies (GAs)**

Growth anomalies (GAs) of corals typically consist of circumscribed areas of tissue and skeleton that have grown at a faster rate than the surrounding tissue and skeleton. Affected areas have morphological features visible underwater that differ from normal. This includes changes in the shape and size of skeletal elements and polyps, discolored (lighter) tissue, and complete loss of polyps.

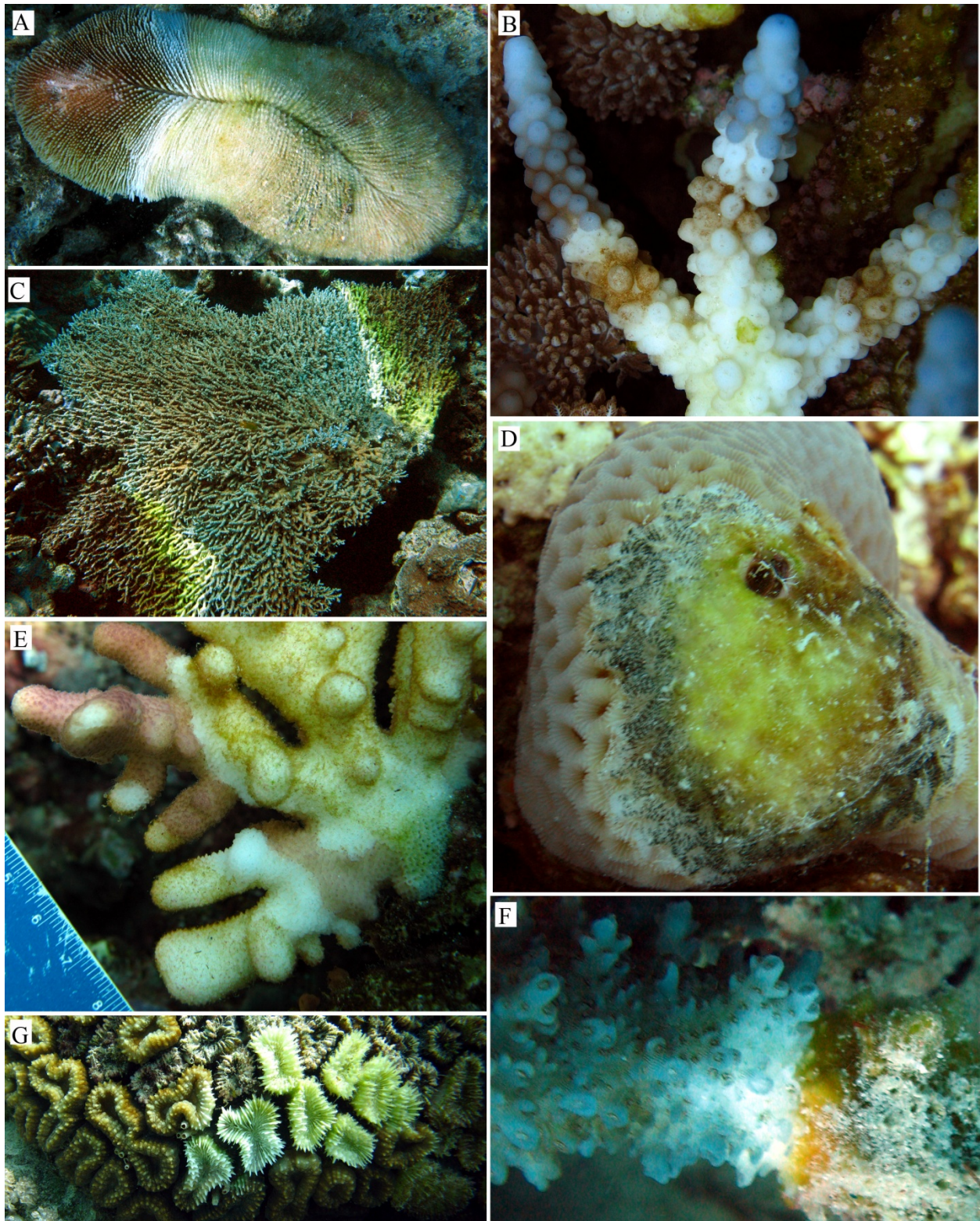
GAs are composed of coral tissue and supporting skeleton, but they differ markedly in morphology from the surrounding tissue and skeleton. Some characteristic features include aberrant corallite shape and coenosteal structures, presence and development of abnormally large polyps and skeletal elements, discolored tissue, and often more rapid growth than that of the surrounding polyps. Acroporids often exhibit whitened protuberant masses of gastrovascular canals characterized by reduced to absent calices and polyps and loss of normal polyp structure. These growths have been termed hyperplasia. In branching corals, GAs can appear anywhere on the colony, while plating corals typically have GAs only on the upper surfaces. GAs in *Acropora*



from the Indo-Pacific are divided into 7 distinct morphological types: nodular, crateriform, exophytic, fimbriate, vermiform, annular, and bosselated.

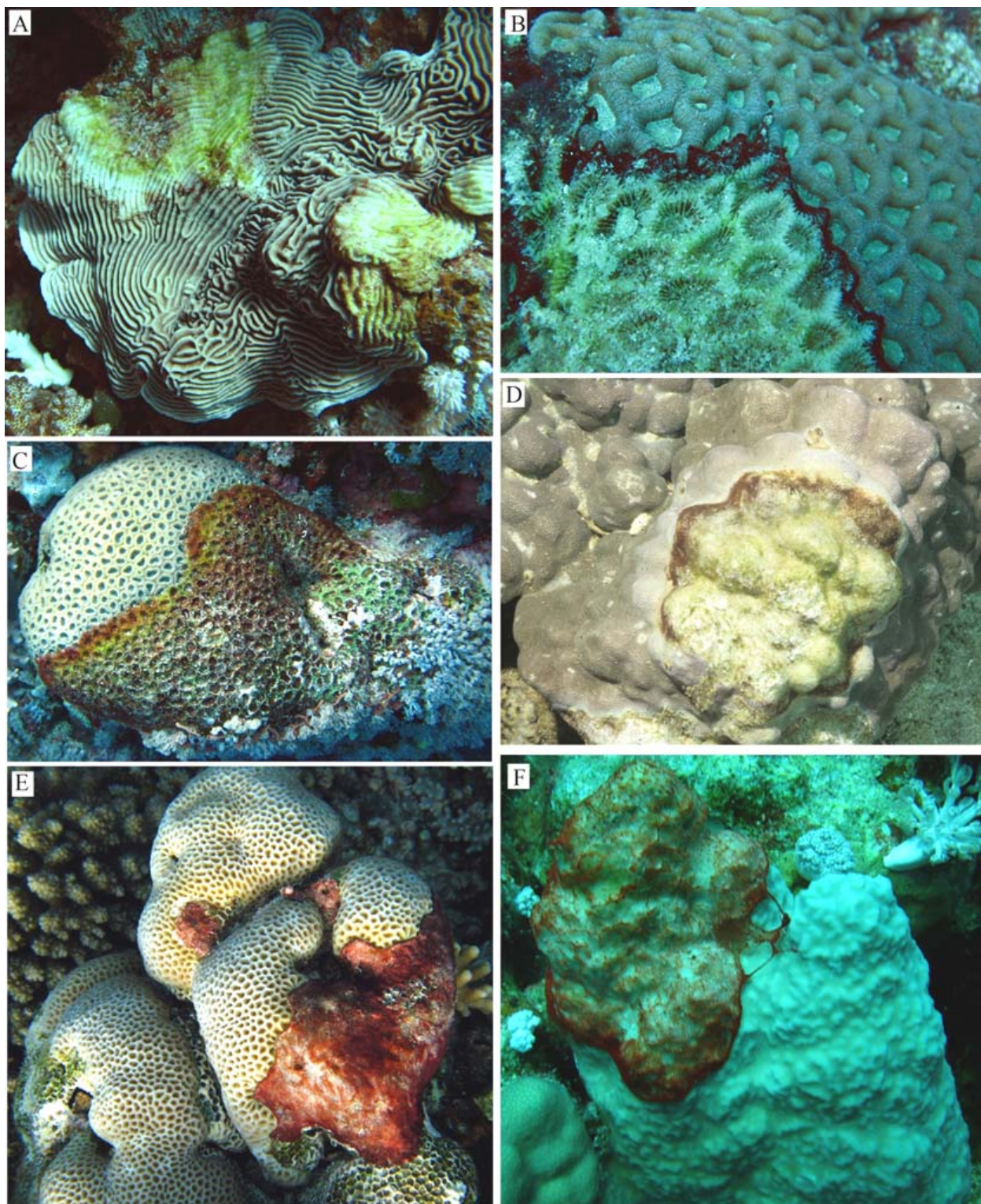
### **9.3.12 Coral disease prevalence in the Red Sea**

Coral diseases were observed throughout the region at low levels. Two corals diseases, black band disease (BBD) and white band disease (WBD) were first described from reefs near Jeddah, Saudi Arabia in 1985 by Dr. Arnfried Antonius. Since this time, WBD (also called white syndrome) and BBD have been reported off Egypt, Djibouti, Jordan, and Eritrea. These conditions as well as several newly emergent diseases were identified during these surveys off Saudi Arabia. White syndromes were observed most frequently overall, primarily affecting six genera throughout the region: *Acropora*, *Echinopora*, *Goniastrea*, *Diploastrea*, *Stylophora*, and *Pocillopora*. Pink line disease was also relatively common, affecting massive colonies of *Porites* throughout the region. Other diseases observed during these studies include brown band disease (BrB) on *Acropora*, skeleton eroding band (SEB) on *Goniastrea*, growth anomalies (tumors) mostly on *Acropora*, dark spots disease (DSD) on *Goniastrea* and ulcerative white spots (UWS) on *Porites*, *Fungia*, and *Ctenactis*. The prevalence of all diseases was low (<1%). In addition, several undescribed diseases were observed. One of these was widespread on massive *Porites* in the Farasan Banks and the other was causing significant amounts of tissue loss to *Pocillopora* colonies.



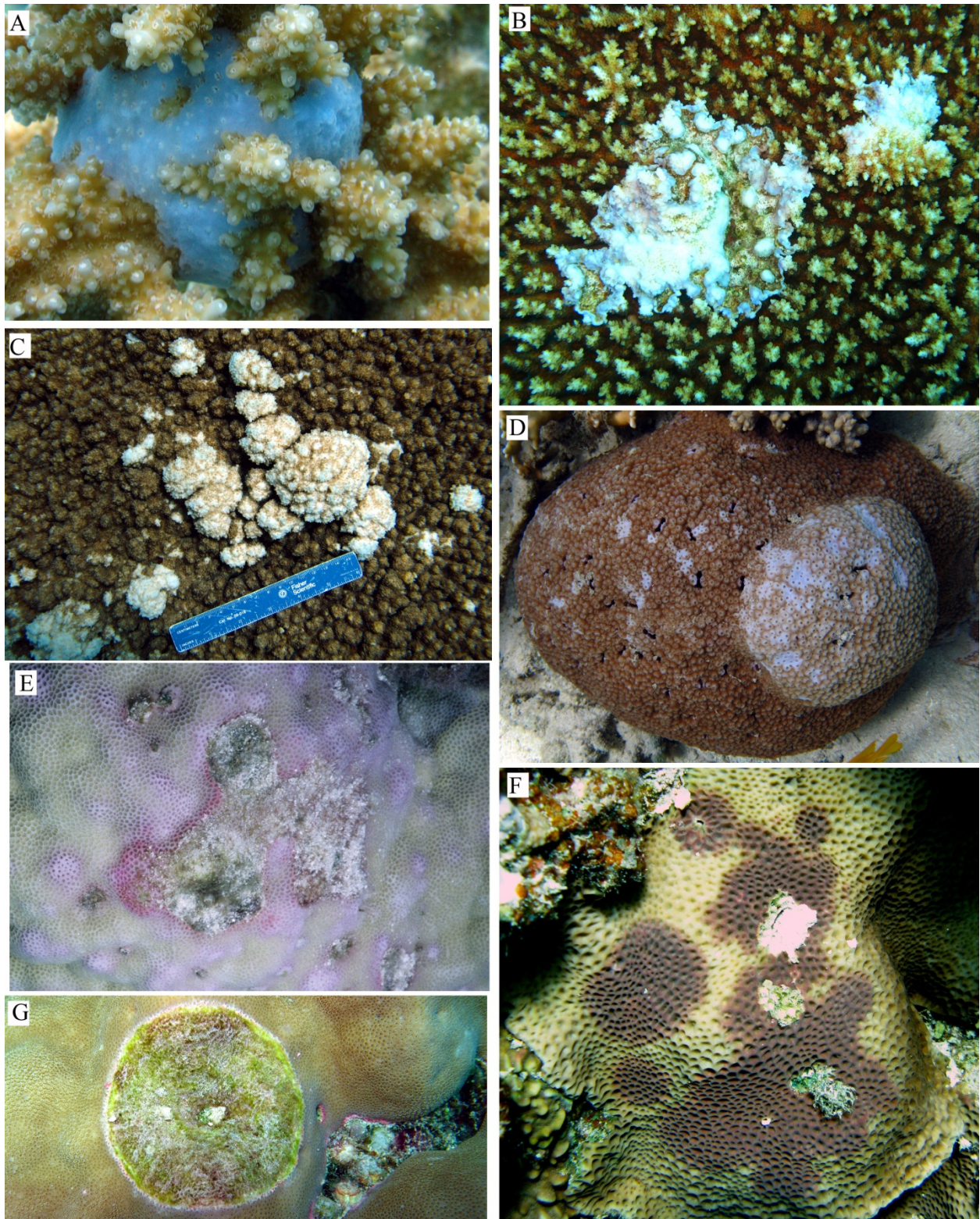
**Fig. 9.3a. Examples of coral diseases observed off Saudi Arabia. A, C, E, G: white syndromes on *Ctenactis* (A), *Acropora* (C), *Stylophora* (E) and *Lobophyllia* (G). B. Brown band disease on *Acropora*. D. Skeletal eroding band on *Goniastrea*. F. Arabian yellow band disease on *Acropora*.**





**Fig. 9.3b. Additional coral diseases observed in the Red Sea. A, B. Black band disease on *Pachyseris* (A) and *Favia* (B). Red band disease on *Favia* (C) and *Porites* (D). Cyanobacterial mats on *Goniastrea* (E) and *Montipora* (F).**





**Fig. 9.3c. Coral diseases observed in the Red Sea (continued). A-C. Examples of growth anomalies on *Acropora*. D. Growth anomaly on *Astreopora*. E. Pink line disease on *Porites*. F. Dark spots disease on *Goniastrea*. G. New unidentified disease on *Porites* (G).**

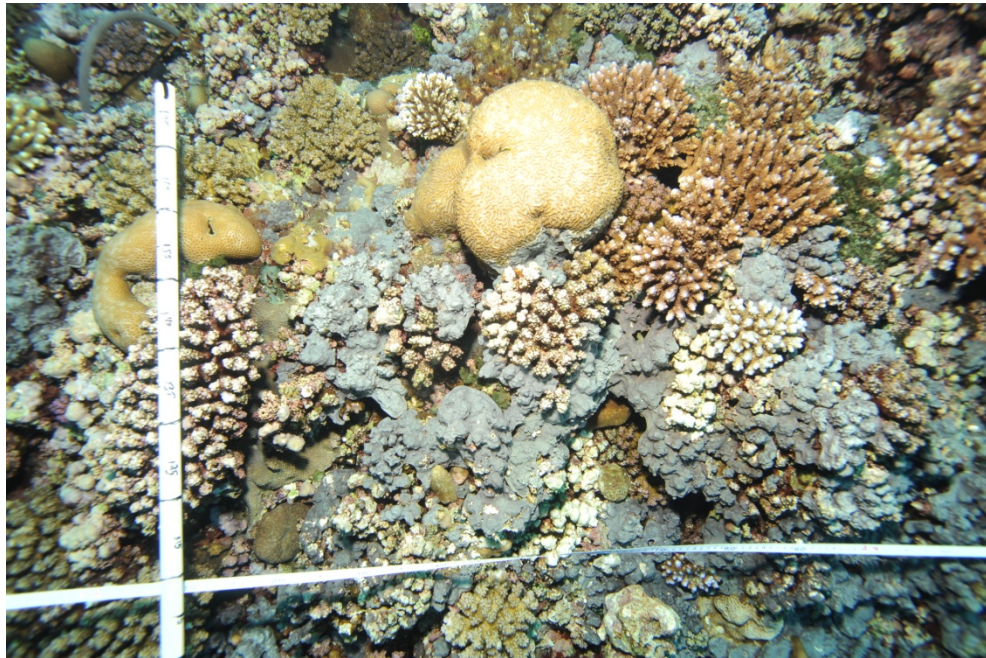
**Table 4. Major diseases of Indo-Pacific and Red Sea scleractinian corals.**

| Syndrome                                | Location                                                                                                                                                               | Host species                                                                                                                                                                                                                                                                                                                                  | Prevalence/impact                                                                                                   |
|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| Black band disease (BBD)                | Australia, Egypt, Fiji, India, Jordan, Papua New Guinea, Philippines, Saudi Arabia, Tonga, South Africa, CNMI, Palau, Indonesia                                        | 19 genera, 49 species; <i>Pocillopora</i> , <i>Acropora</i> and faviids most frequently infected                                                                                                                                                                                                                                              | Generally <1%; outbreaks of up to 50% in restricted areas; mean spread of 3 mm/day; mostly causes partial mortality |
| White syndrome (WS)                     | Egypt, Australia, Solitary Islands, Saudi Arabia                                                                                                                       | 38 species <i>Turbinaria</i> , <i>Acropora</i> , <i>Goniastrea</i> , <i>Porites</i> , <i>Pocillopora</i> , <i>Stylophora</i>                                                                                                                                                                                                                  | Increased 20X in Australia between 1998-2003; Up to 2-4 cm/day with 3-20% coral mortality during outbreaks          |
| Ulcerative white spot disease (PUWS)    | Philippines, East Africa, Indonesia, Guam, Palau, Saudi Arabia                                                                                                         | <i>Porites</i> : 7 species; <i>Echinopora</i> , <i>Goniastrea</i> , <i>Heliopora</i> , <i>Favia</i> , <i>Montipora</i>                                                                                                                                                                                                                        | Up to 82% of susceptible corals; increases in summer; Slow spread, lesions 2-5 mm in diameter                       |
| Vibronic Bleaching                      | Mediterranean, Israel, Tanzania                                                                                                                                        | <i>Oculina patagonica</i> ; <i>Pocillopora</i>                                                                                                                                                                                                                                                                                                | Vibrios pathogenic at high temperatures; bleaching and tissue sloughing if elevated temperatures persist            |
| Atramentous necrosis                    | Florence Bay and Bright Point, Australia                                                                                                                               | <i>Montipora</i> <i>Acropora</i> <i>Echinopora</i> , <i>Turbinaria</i> , <i>Merulina</i>                                                                                                                                                                                                                                                      | Unknown                                                                                                             |
| Growth anomalies (Gas)                  | CNMI, Australia, Hawaii, Guam, Palau, Eniwetok, French Polynesia, New Caledonia, Maldives, China, Micronesia, Marshall Islands, Japan, Oman, Philippines, Saudi Arabia | <i>Acropora</i> , <i>Pocillopora</i> , <i>Pavona</i> , <i>Fungia</i> , <i>Madrepora</i> , <i>Montipora</i> , <i>Platygyra</i>                                                                                                                                                                                                                 | Generally <1%, but lesions increase in number on affected corals                                                    |
| Pink Line Syndrome (PLS)                | Papua New Guinea, Sri Lanka, Kavaratti Island, Indian Ocean, Saudi Arabia                                                                                              | <i>Porites</i>                                                                                                                                                                                                                                                                                                                                | Increased from 20% in 1996 to 80% in 1999 in one location                                                           |
| Fungal syndrome (FuD)                   | East African Coast                                                                                                                                                     | <i>Astreopora</i> , <i>Montipora</i> , <i>Acropora</i> , <i>Pocillopora</i> , <i>Echinopora</i> , <i>Porites</i> , <i>Platygyra</i> , <i>Goniopora</i> , <i>Cyphastrea</i> , <i>Goniastrea</i> , <i>Hydnophora</i> ,                                                                                                                          | Unknown; single event in 2002 caused extensive colony mortality                                                     |
| <i>Plagiosporus trematode</i> infection | Hawaii                                                                                                                                                                 | <i>Porites compressa</i> , <i>P. lobata</i>                                                                                                                                                                                                                                                                                                   | Not reported to kill corals; Does not advance; colony may have multiple infections                                  |
| Skeleton eroding band (SEB)             | Australia Egypt, Jordan, PNG, Mauritius, Australia, Saudi Arabia                                                                                                       | <i>Acropora</i> , <i>Stylophora</i> , <i>Pavona</i> , <i>Seriatopora</i> , <i>Hydnophora</i> , <i>Galaxea</i> ; <i>Pocillopora</i> , <i>Favites</i> , <i>Mycodium</i> , <i>Montipora</i> , <i>Echinopora</i> , <i>Lobophyllia</i> , <i>Goniastrea</i> , <i>Platygyra</i> , <i>Fungia</i> , <i>Favia</i> , <i>Porites</i> , <i>Goniopora</i> , | 0.01% up to 77%. 0.5-3 mm/day; In Australia increased 20X in summer; 1mm/week to 1mm/day                            |
| Yellow band disease (YBD)               | United Arab Emirates; Arabian Gulf; Iran                                                                                                                               | 4 genera, 12 species                                                                                                                                                                                                                                                                                                                          | Prevalence unknown; spread: 9.4 mm/week in winter; 19.7 mm/wk in summer                                             |
| Brown band disease (BrBD)               | Australia, Saudi Arabia                                                                                                                                                | <i>Acropora</i> , <i>Pocillopora</i> , <i>Echinopora</i> , 16 spp.                                                                                                                                                                                                                                                                            | Generally rare; 0.3% in Australia                                                                                   |
| Dark spots disease (DSD)                | Hawaii, American Samoa, Saudi Arabia                                                                                                                                   | <i>Goniastrea</i>                                                                                                                                                                                                                                                                                                                             | Generally uncommon                                                                                                  |



## 9.4 Competitive Interactions

There were also numerous competitive interactions between reef building corals and nuisance species of algae (e.g. *Lobophora*), cyanobacteria, sponges, and soft corals, but coral tissue loss from these factors was patchy and low overall at this time with exception of a few isolated reefs. The only exception to this is a gray encrusting sponge that carpeted many reefs in the Farasan Banks and Farasan Islands (Fig. 9.4a).



**Fig. 9.4a. Example of a rapidly spreading encrusting sponge that is carpeting large areas of the reef and is capable of overgrowing and smothering most coral species. Photo is from the Farasan Banks.**

Coral eaters (known as corallivores) observed during our assessments include corallivorous molluscs (*Drupella* and *Coralliophila* snails), corallivorous echinoderms (*Acanthaster* crown of thorns sea stars and cushion stars, *Culcita* spp.), and several parrotfishes and other fish (especially the bumphead parrotfish, *Bolbometapon*). *Drupella* were observed on nearly every dive, although only isolated corals (mostly *Acropora* and *Pocillopora*) were heavily infested. *Coralliophila* were also very common, although they tended to be associated with massive corals typically occurring in crevices and depressions on the colony surface, at the perimeter of living tissue. Massive *Porites* colonies were a preferred host for *Coralliophila*.

COTs sea stars (*Acanthaster planci*) were the most significant coral predators observed on these reefs. They are found throughout the Indo-Pacific region, from the Red Sea, across the Indian Ocean and through to the Pacific. These starfish look sinister - they are reddish-grey and blue in color and are covered in 4-5 cm long spines (which give a nasty wound). They are voracious predators and are specially adapted to feed on coral tissue. COTs sea star predation is very visible as it leaves behind a bright white scar which is the coral skeleton. An individual adult crown-of-thorns sea star consumes coral at an average rate of 160 cm<sup>2</sup> per day and they are estimated to consume between 5-6 m<sup>2</sup> of coral tissue per year.

COTs sea stars have the potential to cause near total coral loss to entire reef tracts in the Red Sea. This was first observed in the 1970s, with an increase in the number of outbreaks of COTs sea stars reported over the last five years from Egypt, Djibouti, Jordan, Sudan, Yemen, western Somalia and Saudi Arabia. During our Red Sea surveys, stark white, recently eaten coral colonies could be found on nearly every reef examined off Farasan Islands (2006), Yanbu, Al Wajh Bank (2008) and the Farasan Banks (2009), although the proportion of colonies with COTs sea star grazing scars was generally low (0.1-2%). The only exception was one site in the Farasan Islands (reefs of Abu Shuqar Island), one in Al Wajh lagoon, and three sites in the Farasan Banks, where 5-90% of the colonies were partially or completely eaten, and hundreds of COTs sea stars were observed actively feeding (max = 396 COTs/100 m<sup>2</sup> of reef).



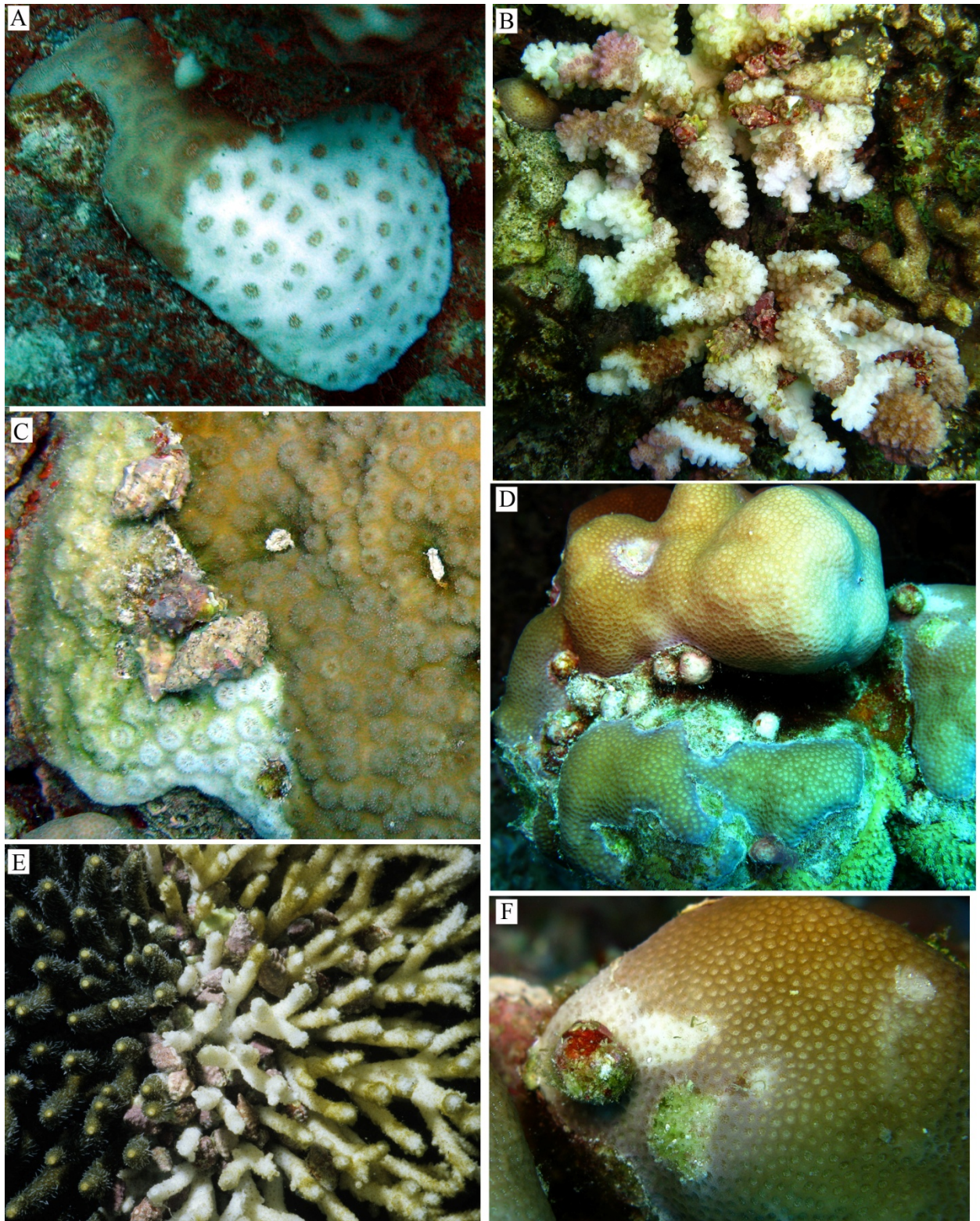
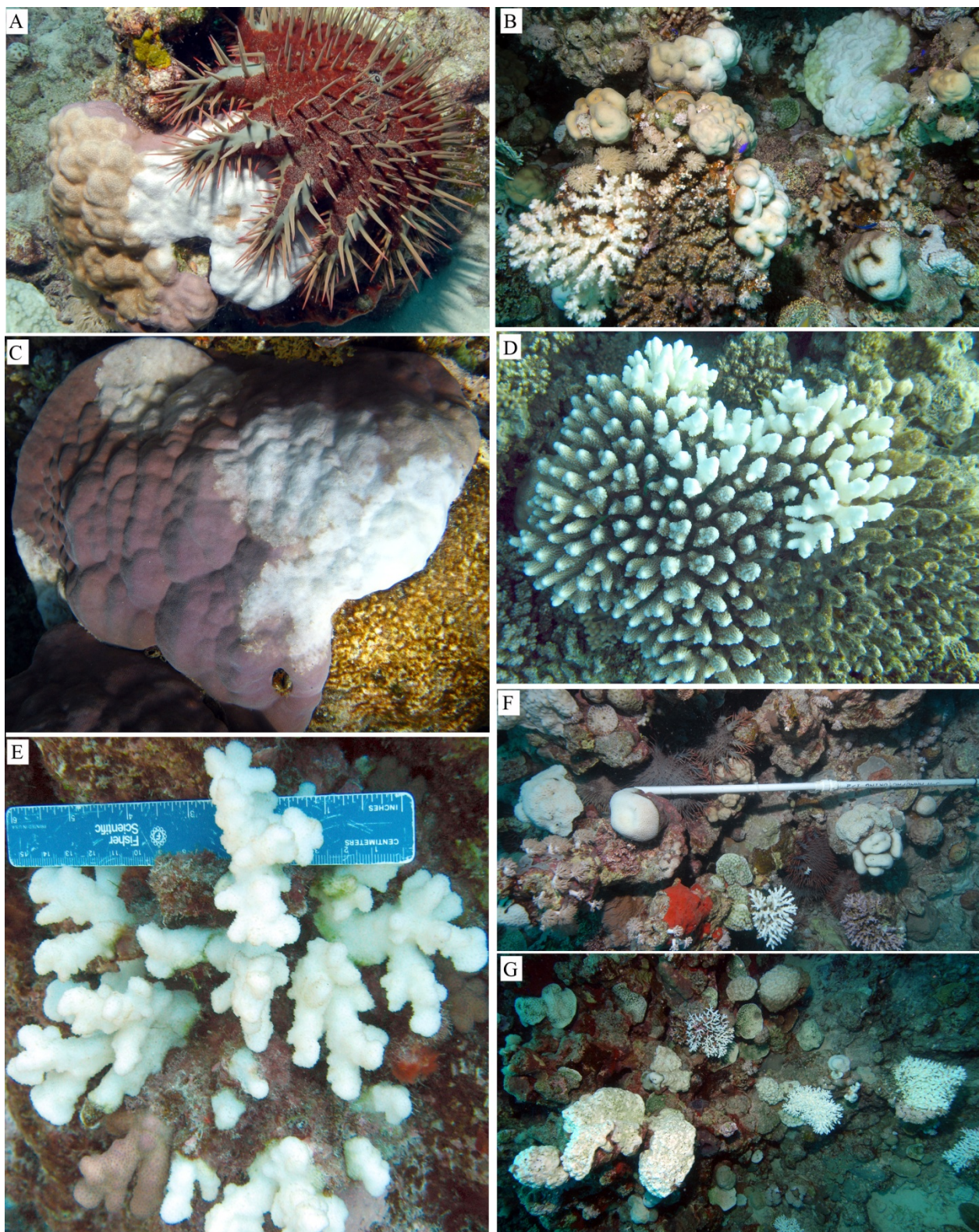


Fig. 9.4b. Examples of invertebrate corallivores. A. A feeding scar on *Echinopora* created by a *Culcita* sea star. B, C, E. *Drupella* snail predation on *Pocillopora* (B), *Echinopora* (C) and *Acropora* (E). A group of *Coralliophila violacea* on *Porites* (D) and a closeup of a single animal and its feeding scar on *Porites* (F).





**Fig. 9.4c.** Predation on corals by crown of thorns (COTs) sea stars (*Acanthaster planci*). See following page for legend.

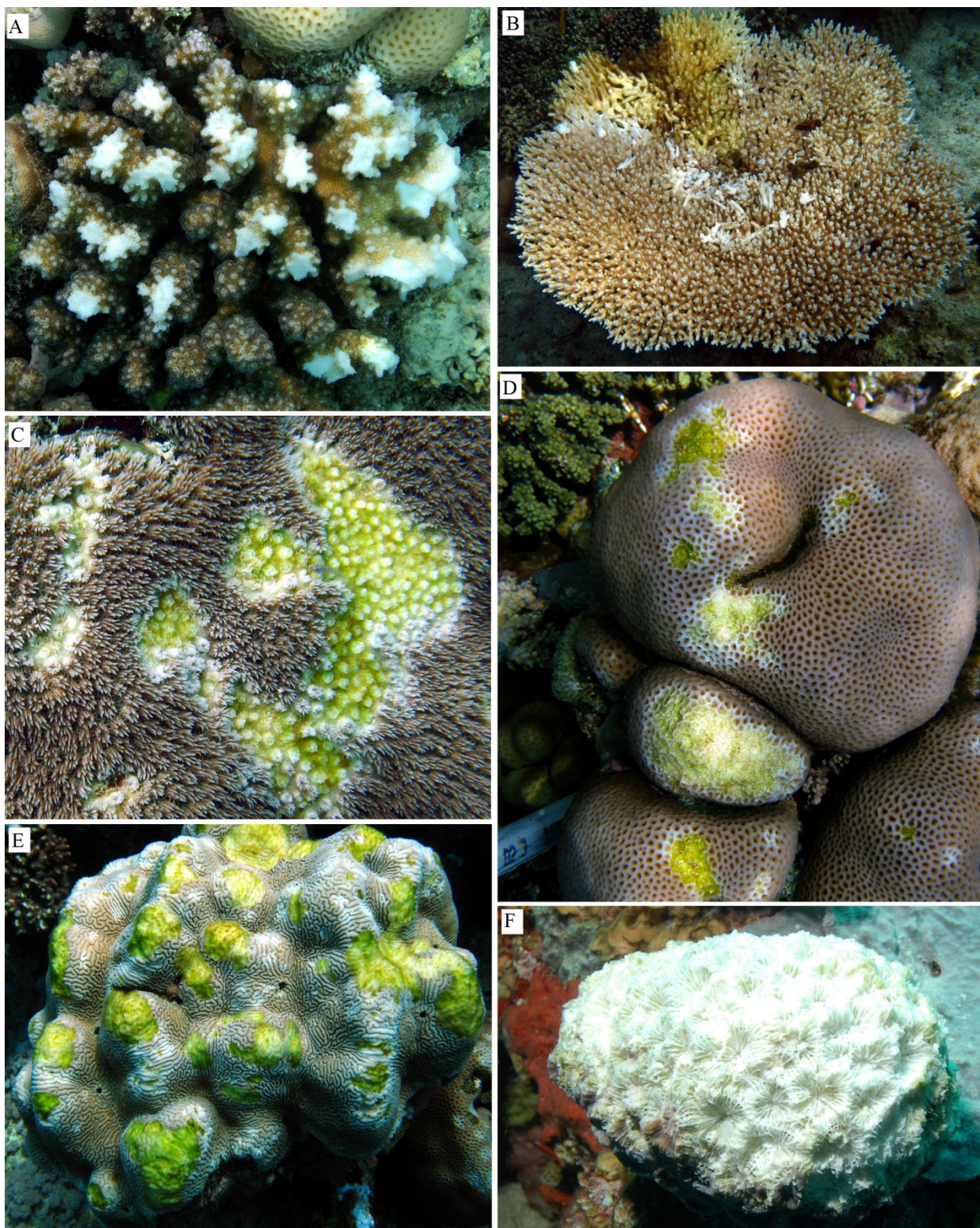


Figure 9.4. Legends for preceding page and subsequent pages.

Fig. 9.4c. Predation on corals by *Acanthaster* (crown of thorns) sea stars. A. COTs sea star on a *Porites lobata* colony. B. Reef scene showing numerous recently consumed corals. COTs sea stars have eaten *Acropora*, *Porites*, *Goniastrea* and *Echinopora* corals. C. Typical COTs sea star feeding on *Porites*. Three separate lesions are visible. D. Repeat predation events by COTs sea star on *Pocillopora*. A COTs sea star ate the tissue in the lower right 1-2 weeks prior to the photo (skeleton is algal colonized) and then returned to eat the upper portion of the colony (white exposed skeleton). Tissue remains at the bases of the branches, where the COTs sea star cannot reach. E. COTs sea star predation on *Stylophora*. The colony is nearly dead (white exposed skeleton), although one branch (lower left) remains live. F and G. Example of mass predation during a COTs sea star outbreak. White corals are dead. Scale bar = 1 m.

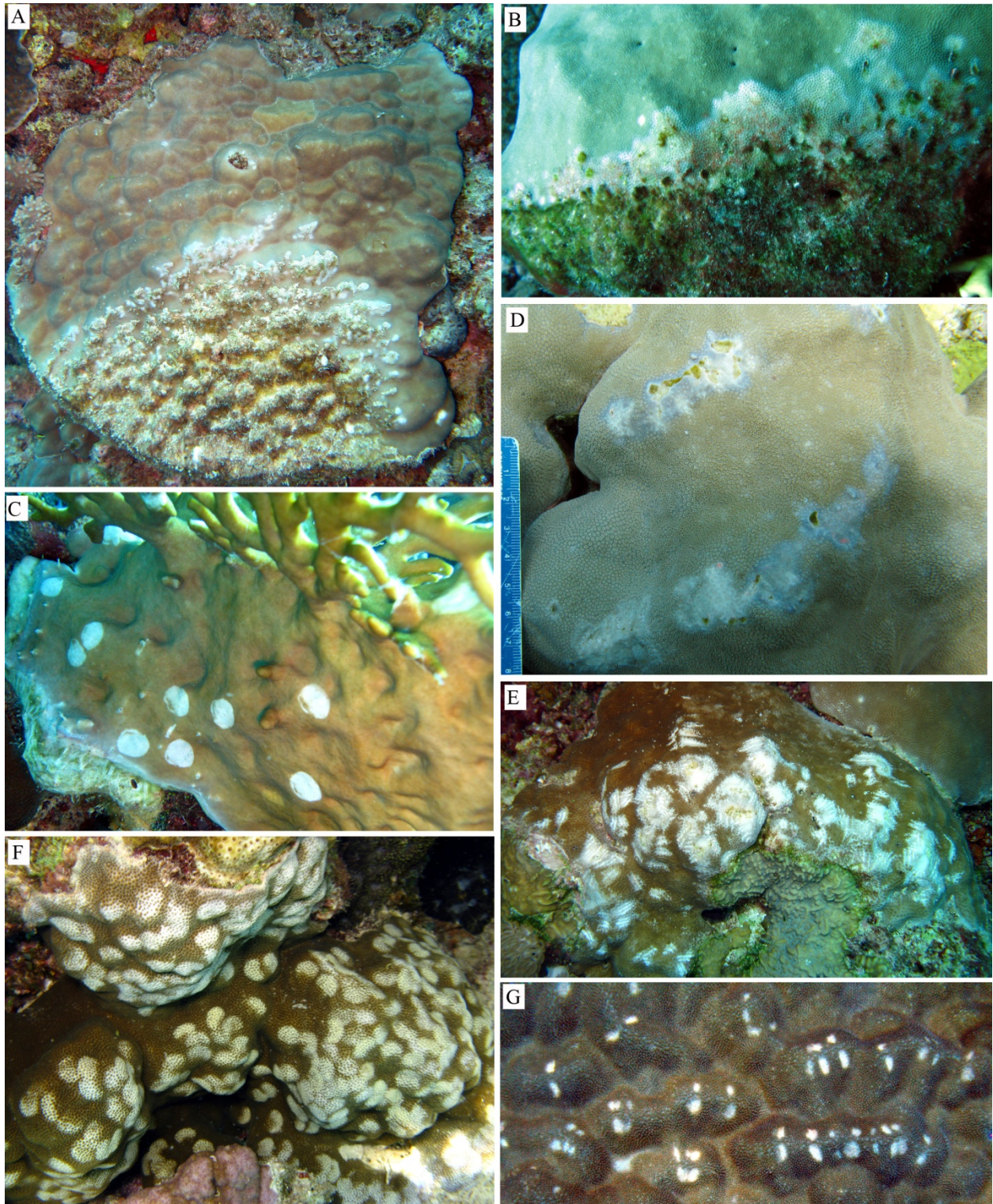
Fig. 9.4d. Fish predation on corals. A. *Pocillopora* colony missing its branch tips. A bumphead parrotfish (*Bolbometapon muricatum*) bit the branch tips off and white, exposed skeleton is visible. This type of damage is common in the Red Sea within shallow reef flat communities. C. Typical predation damage by bumphead parrotfish (*Bolbometapon muricatum*) on a table acroporid. The fish use the bump on their head to smash the coral, breaking the branches. C. Focused biting by parrotfish on *Galaxea*. Lesions that have a green coloration have been colonized by filamentous algae. D. Focused biting by parrotfish on *Goniastrea*. Lesions were created through repeated biting 7-10 days earlier and the skeleton is now colonized by filamentous algae. E. Focused biting on *Leptoria* by parrotfish. The fish remove the tissue and upper layers of the skeleton. F. Focused biting on a *Favia* colony. Parrotfish have removed tissue and skeleton from the entire upper surface of the colony; a few remaining live polyps exist at the base of the colony in areas not accessible to the fish.

Fig. 9.4e. Signs of fish bites on stony corals. A and B. Damselfish algal lawns on massive *Porites* colonies. Damselfish repeatedly bite at live tissue to open up space to allow them to farm algae. The lawn will increase in size over time, eventually overwhelming the colony. B. Close-up of a damselfish algae lawn. Areas that have been recently bitten, but not yet colonized by algae are visible (white lesions). C. Spot biting by a wrasse on *Millepora* (fire coral). Wrasse often create round lesions devoid of tissue; these will heal over time. D. Lesions created by parrotfish on *Porites*. The lesions are healing. E. Lesions on *Porites* involving removal of tissue and upper layers of the skeleton created by parrotfish. Scrape marks from the jaws are visible. F. Multiple round lesions on *Porites* created by repeated fish bites. G. Characteristic spot biting by parrotfish on a massive colony of *Porites*. Lesions are in pairs, representing the upper and lower jaws.



**Fig. 9.4d. Fish predation on corals.**





**Fig. 9.4e. Fish predation on corals (continued).**

## 10. Resilience indicators

### 10.1 Biological attributes of resilience

In addition to quantifying the species diversity, cover, size structure and levels of recruitment of important reef building corals, we also assessed the condition of corals, placing emphasis on the prevalence of disease and amount of mortality. This methodology permits us to estimate the severity of past disturbances and to predict future trends. Our studies identified a number of reefs that appeared highly degraded, with low coral cover and few remaining live colonies. Apparently, there have been several large scale disturbances on these reefs in the recent past that resulted in mass mortalities of reef building corals. However, the damage was highly variable, with some reefs being affected at all depths on both leeward and windward sides, while others exhibited patchy losses of coral. While there are reports of several previous mass bleaching events, patterns of coral mortality we observed were not always what would be expected if bleaching was the causative factor. In some cases, both deep and shallow sites were affected, while in other locations only deeper reefs were impacted suggesting that bleaching was not the cause of degradation. In many cases only *Millepora* and *Diploastrea* were the dominant corals remaining on the reefs; two species that are susceptible to bleaching, but are not preferred food sources of COTs sea stars.

Even though a number of degraded sites had very few remaining adult corals, most sites appeared to be highly resilient as indicated by 1) high numbers of coral recruits; 2) very little recent mortality; and 3) a low amount of macroalgae. Representatives of most of the key functional groups of fishes were present, especially herbivorous surgeonfish, rabbitfish and parrotfish which are important in controlling algae. Pest species were generally uncommon, with exception of a few cases of overgrowth by clionid sponges and other encrusting sponges and a high cover of *Xenia*. The high number of COTs sea stars in several locations is of concern, as this was noted on a number of the reefs that had the highest remaining cover of live acroporids, and it may be a sign that the predatory fishes that feed on their larvae have been depleted. Human disturbances on the environment may also cause an increase of COTs sea star populations. Substrate quality and reef morphology, including the topographic complexity, sediment composition and depth, and the amount of rubble are also important resilience indicators. Substrate composition is a useful metric to determine the amount of space available



for the settlement of new corals and the likelihood of their survival. In general, most reefs had relatively high rugosity (which provides lots of spaces to shelter key reef fishes and motile invertebrates), several canopy layers (which helps shade corals), and low amounts of loose rubble (which makes the substrate unstable and reduces the settlement of corals).

## **10.2 Oceanographic and environmental parameters**

There are numerous environmental and oceanographic parameters that control the occurrence and distribution of reef species and either enhance or degrade their ability to resist other stressors and continue to persist on Saudi Arabian coral reefs (Table 5). On the scale of individual reefs, water temperatures can be regulated, at least partially by currents, exposure to waves, proximity of that reef to deep water, size, depth and structure of associated reef flat communities and other factors, especially during periods of thermal stress, further enhancing coral survival. Other parameters of importance include tides, seasonal variation in temperature and salinity, and proximity to the coast.

### **10.2.1 Tides**

Tides in the Red Sea ranges are small and vary seasonally; this is a major determining factor for shallow-water biotopes. Tides are oscillatory, semi-diurnal with an average spring range of 0.5 m, and a mean sea level up to 1.0 m higher in winter. A 6-hour time difference exists between tide times in the southern and northern areas (Morcos 1970). There is a central node to tidal oscillation near Jeddah and tide increases north to Aqaba (range 1.7 m) and south to Perim (range 1.0 m). Storm surges and barometric pressure variations may affect water level.

### **10.2.2 Water exchange**

The Red Sea represents a sill basin with high surface density water resulting from an excess of evaporation over precipitation or runoff inputs (Tchernia 1980). The Red Sea exchanges water with the Indian Ocean across the Strait of Bab-el-Mandab sill (110 m depth). Convection currents ensure renewal of deep water, which is uniform in characteristics below the sill level. Water loss by evaporation is compensated for by influx of water across the sill. Less dense inflowing water remains at the surface and denser deeper water of the basin flows out at depth into the adjacent ocean. Marked seasonal changes in the exchange and circulation patterns of

water are determined primarily by prevailing monsoon winds and secondarily by temporal variations in density and evaporation (Ross 1983). The northwest monsoon dominates from October to May, sustaining N winds in the northern Red Sea, while winds in the south are mainly from the SSE. At the Strait of Bab-el-Mandab, winds and surface waters move in the same direction with a surface layer (to 80 m depth) inflowing from the Gulf of Aden to the Red Sea (Grasshoff 1975). A strong winter inflow occurs in response to increased wind stress generated by higher wind speeds. In the northern Red Sea (19°-29° N), the surface waters flow N to NE against the wind direction, increase in density due to salinity increase and cool by evaporative processes, the sink and move south to the Gulf of Aden as a warm, high-salinity, subsurface current (Tchernia 1980). Grasshoff's simple model describes this situation, but does not impart the complexity of summer circulation patterns (Poisson et al. 1984). In summer (June to September), surface waters flow south along the entire Red Sea paralleling the prevailing NNW winds which are driven by the southeast monsoon. Surface water inflow at the Strait of Bab-el-Mandab is opposed by the wind direction (Siedler 1969). Inflow of water from the Gulf of Aden occurs in intermediate layers while surface waters flow out of the Red Sea (Neumann and McGill 1961). Associated with the change in monsoon winds, upwelling occurs in northern areas of the Red Sea (Patzert 1974). Water flowing out of the Red Sea is predominantly intermediate water and not deep water. Renewal estimates are six years for the upper 150 m of water and 200 years for the entire Red Sea, including the deep water mass (Ross 1983).

### **10.2.3 Water Temperature**

Sea surface temperatures broadly correlate with air temperatures (Ross 1983), increasing from north (winter 21 °C; summer 26 °C) to south (winter 28 °C; summer 32 °C) until cooled by the water inflowing from the Gulf of Aden (Morcos 1970).

### **10.2.4 Salinity**

Surface salinity in the Red Sea is the highest of any ocean water, increasing from south (37 ‰) to north (42 ‰). The southern and central Red Sea is characterized by a strong halocline, generally absent from the northern areas. Water below the near-surface thermocline (100-200 m depth) is essentially isothermal (21.5-22.0 °C) and isohaline (40‰) as a result of the northern convection process and restricted exchange with the Indian Ocean (Siedler 1969; Morcos 1970).

**Table 5. Variation in environmental conditions along the Saudi Arabian Red Sea coastline.**

| REGION          | General oceanographic and environmental conditions                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ras Qisbah      | Water temperatures are most variable in the north, ranging from approx. 17 °C in February to 27 °C in August, with greater extremes in shallow water near the coast. From January to April, currents run north, but the direction reverses from June to September. In winter wind flows from the northwest, with Mediterranean weather penetrating into the northern Red Sea; the northwest Monsoon season does not affect this region. In summer winds flow from north to south. The tide is semidiurnal, with high water and low water occurring almost simultaneously all along the northern Red Sea. Tidal ranges are approximately 0.6 m. Salinity is highest in the northern regions (up to 40 ppt).                                                                                                                                                                                                     |
| Al Wajh         | Winds in winter may come from both southwest and northeast, converging in the central Red Sea. In summer winds flow from north to south. Tidal change is slightly greater than Yanbu, but less than Ras Qisbah, with both diurnal variation and a seasonal increase in winter. Rainfall is typically about 16 mm/yr.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| Yanbu           | Air temperatures range from a low of about 9 °C in January to a high of 42 °C in June. Winds in winter may come from both southwest and northeast, converging in the central Red Sea. In summer winds flow from north to south. Tidal change in the central Red Sea is much less than in the southern or northern, and it may show almost no daily differences. However, there is an abrupt change in sea level between summer and winter, with winter sea level being approximately 0.5 m higher. Rainfall is typically about 16 mm/yr.                                                                                                                                                                                                                                                                                                                                                                       |
| Farasan Banks   | In summer winds flow from north to south. Winds also blow offshore, during the southwest monsoon season, pushing warm surface waters offshore, which are replaced by deeper, colder nutrient rich waters through upwelling. Tides are similar, but slightly less than the Farasan Islands. The daily variation is superimposed onto a seasonal tide of about 0.5 m greater during winter. Rainfall is higher than northern regions, generally about 63 mm/yr.                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Farasan Islands | Air temperatures range from 21 °C (March) to about 38 °C (September) while sea water temperatures vary from a maximum of about 33 °C to a minimum of 26 °C. Winds are strongest in this region, blowing from the southwest in winter and pushing nutrient rich waters from the Indian Ocean into the region. In summer winds blow from the north to northwest. Winds also blow offshore, during the southwest monsoon season, pushing warm surface waters offshore, which are replaced by deeper, colder nutrient rich waters through upwelling. Tidal range is greatest in the south, with up to about 0.9 m difference between low and high water. Salinity is lowest in the south (about 40 ppt), and is closest to the salinity of the Indian Ocean, although salinities increase from June to September to 45 ppt due to evaporation. Rainfall is higher than northern regions, generally about 63 mm/yr. |

### 10.3 Physical attributes

The Red Sea is bounded by mountains throughout much of its length, which are separated from the coast by a narrow coastal plain. Mountains are tallest in southern Saudi Arabia, reaching a maximum of 3700 m. Daily winds have a profound effect on reef occurrence and structure, with reef structures growing into prevailing waves. For most of the Red Sea, narrow fringing reefs can be found along the coast, extending tens of meters from the shore. In several locations, alluvial deposits have accumulated near old Wadi systems, forming fans that extend several km offshore with fringing reefs found on the seaward edges and backreef lagoons extending parallel to shoreline. Offshore in the northern Red Sea is a large bank (Al Wajh) with numerous islands, a barrier reef and deep water lagoon and an extensive series of submerged limestone platforms near Yanbu often referred to as “Little Barrier Reef”. South of Jeddah (beginning around 20 °N latitude near Al Lith) fringing reefs become reduced in size and the continental shelf becomes much broader. This is associated with an increase in muddy substrates and mangroves, pushing reefs offshore. In some cases, true coral reefs are rare, with reef structures consisting almost entirely of build-ups of calcareous red algae on sublittoral sand.

The range of environmental conditions, latitude and geological formations are the primary factors controlling the varied coral habitats located in the region, with changes in coral assemblages associated with changes in depth, exposure and levels of sedimentation. The most pertinent physical attributes controlling reef development include the relative width of the platform, whether it is linked or not to the mainland, the degree of circulation within a platform, the orientation of habitat features and relative wind exposure, the depositional environment, the depth of the habitat patch, and the latitude. Furthermore, aspects of reef slope, facing direction of the reef, presence of cliffs and above-water features, occurrence of canopy corals, and specific zone/depth can cause localized variations in coral community structure. For instance, coral diversity on reef flat communities is low, and it increases to a maximum between 5-30 m depth, diminishing in deeper water. Many sheltered reefs can have particularly high cover of *Goniopora*, *Galaxea*, *Acropora* or *Porites*, while reef slopes and vertical walls in exposed areas tend to have more plating corals like *Echinopora*, *Pachyseris*, *Mycedium* and *Oxypora*.



**Table 6. Reef types observed in the Red Sea off Saudi Arabia.**

| Reef type                     | Description                                                                                                                                                                                                                                                                                                                                                                               |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Fringing Reefs                | Most common “classic” reef type seen in the Red Sea, these structures run parallel to shore. Most are narrow, located a few tens of meters from shore, up to about 1 km in the south, in areas with a broad alluvial plain (near old Wadis) here alluvial deposits. Seaward or lateral growth is restricted due to deep water and an absence of shallow substrate within the photic zone. |
| Ridge Reefs                   | Characterized by longitudinal ridges lying along the axis of the Red Sea and running in a NE/SW direction. Reefs result from faulting associated with the progressive opening of the Red Sea and upward movement of underlying salt deposits.                                                                                                                                             |
| Barrier Reef                  | Yanbu Barrier Reef. Extends about 500 km, located between Al Wajh Bank and Jeddah. Consists of a chain of reefs running parallel to the coast, 5-20 km offshore and 1-7 km wide, separated by gaps and channels usually over 100 m deep. Present day reefs formed on a limestone platform between 30-50 m deep.                                                                           |
| Spur and Groove systems       | Reef crest structures with projections (spurs) pointing into the waves, separated by deep channels. Formed through accretion of calcareous algae.                                                                                                                                                                                                                                         |
| Algal Reefs                   | Farasan Islands. Located in the southern Red Sea, in low energy environments. Coarse sand extends several km seaward, being relatively shallow in nearshore areas (2-4 m deep) with steeply sloping sides at the seaward extent. These habitats are colonized by <i>Sargassum</i> and sparse corals                                                                                       |
| High patch reefs              | Farasan Banks. Four high pinnacle forming Dohra, Marmar, El Jedir and Malathu. The slopes of these are similar to ridge reefs, ending at similar depths of several hundred meters. However, they are shorter in length and are not associated with faults, only uplift of salt domes.                                                                                                     |
| Platform reefs                | Large patch reefs, often found in lagoons that form on the shelf and spread out in all directions.                                                                                                                                                                                                                                                                                        |
| Atoll-like reefs/tower reefs  | Farasan Banks. Reefs arising from deep water, generally located offshore that form a ring like structure with a central lagoon, a narrow reef flat and a steep sloping leeward and windward reef slope. These are not true atolls, being formed by accretion of coral on top of uplifted salt domes rather than the subsidence of an island.                                              |
| Circular/elongate patch reefs | Al Wajh. Small, flat topped reefs that may be circular to elongate, up-to about 1 km in length with all sides sloping away into slightly deeper water. They tend to occur in relatively shallow water, especially in lagoonal habitats.                                                                                                                                                   |
| Reticulate patch reefs        | Tiran, Al Wajh. Interconnected networks of reef matrix separated by sand, and forming intricate reticulate patterns; particularly well developed in shallow waters (<10 m depth).                                                                                                                                                                                                         |
| Pinnacles                     | Tiran, Al Wajh. Individual corals and coral ‘bommies’ surrounded by sand.                                                                                                                                                                                                                                                                                                                 |

#### 10.4. Coral reef fisheries

**The following information is summarized from:** Bruckner, A.W., H. Alnazary and M. Faisal 2011. Paradigm shift for fisheries management to enhance recovery, resilience, and sustainability of coral reef ecosystems in the Red Sea. In: Sustainable Fisheries: Multi-Level Approaches to a Global Problem. American Fisheries Society. pp. 85-111

Red Sea coral reefs have supported artisanal fishery harvests for thousands of years (NCWCD 1995), and most of these fisheries were considered sustainable at least partially due to the low density of populations living along the coasts (Behairy et al. 1992). In the last few decades, increased human settlement in coastal areas and the resultant increase in artisanal and commercial fishing activities to support local consumption, and to supply a growing international trade in coral reef species and products, have led to depletion of many commercially valuable species. Threats from overfishing and destructive fishing practices have direct and indirect impacts to trophic structure and ecological function.

Red Sea fisheries are diverse due to the broad variety of species available for exploitation (Sheppard et al. 1992). The productivity of fisheries varies widely throughout the region, but is generally highest wherever there are high levels of nutrient input. Areas with seasonal upwelling of nutrient-rich cool water, such as that found in the southern Red Sea, results in high water column productivity, high yields of pelagic fishes, and productive demersal crustacean and mollusc fisheries. Broad, shallow shelf areas also support most of the reef fish fisheries. Although coral reefs are highly productive ecosystems, commercial exploitation was historically limited due to their topography, which prevents access of large boats and the use of trawls, seines, and large nets. Most reef fisheries are artisanal, yet there has been a move towards greater commercialization, especially in Saudi Arabia, and the introduction of new, destructive gear types.

The main methods used to catch reef-associated fishes are hook and line, traps, trammel nets, gill nets, and spears; throw nets are also used to collect bait fish and bottom set long-lines may be employed. Catch composition varies by fishing method and season, with considerable effort directed at large predators that migrate to mass spawning sites. Despite the large variety of species landed, a small number make up the bulk of the catch. For instance, three of the 13 species of parrotfish (family Scaridae) in the Red Sea dominate landings because they feed over

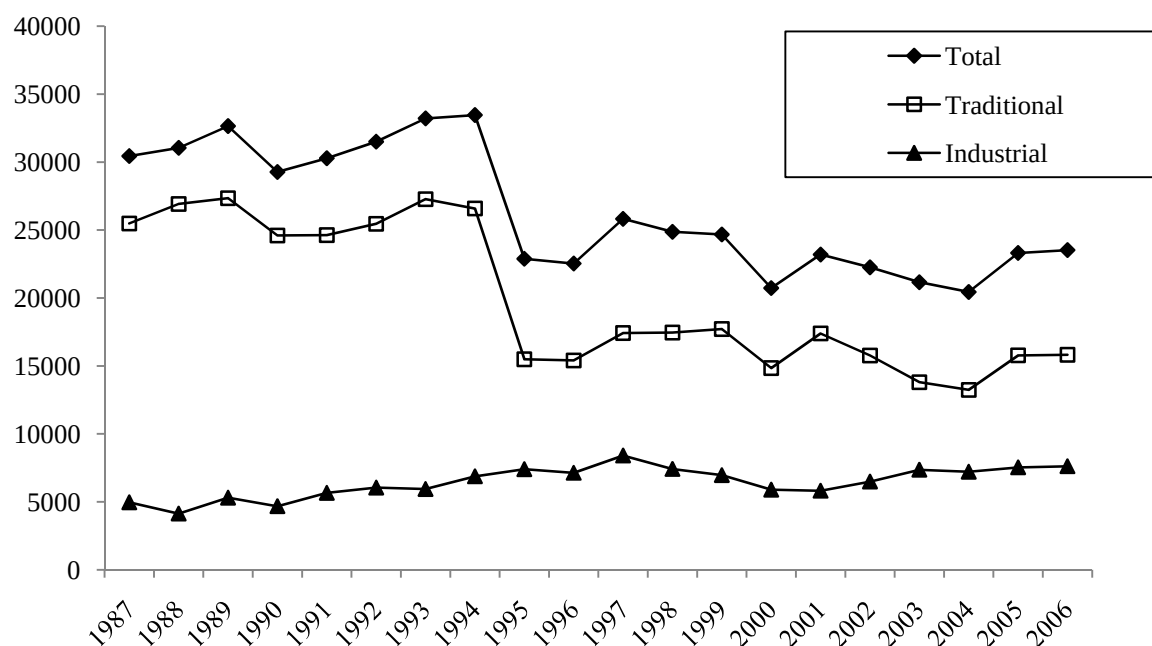
sandy bottoms adjacent to coral reefs, and are easily caught in trammel nets and small gillnets. Reef associated predators from Egypt are dominated by four species of grouper (Serranidae) and two species of emperor (Lethrinidae) (Sheppard et al. 2003). Reef fisheries throughout the Red Sea historically targeted predatory piscivores, although total productivity of these stocks is relatively low (e.g. 0.4 ton/km<sup>2</sup> per year; Kedidi 1984). More than 25 years ago the fishery was already thought to be fully exploited and production could not be increased above these levels. Nevertheless, as piscivores have been depleted, increased effort has been directed towards species lower down the food chain such as herbivores and planktivores (Sheppard et al. 2003).

#### **10.41 Types of fisheries**

There was a substantial increase in the size of both industrial and traditional fishery sectors since the 1980s; landings dropped significantly in 1995 from that reported during the previous decade, but have been relatively stable since 2003 (Fig. 10.41a; Sheppard et al. 2003). Between 1988-2006, industrial vessels increased from 30 to more than 160, while smaller boats used for traditional and investor fisheries increased from about 3,100 - 10,000 (Fig. 10.41b; Marine Fisheries Department 2006). The investment fishery is controlled by a small number of Saudi investors (<45), with about 10% (1,764) of the registered fishermen being Saudi Arabia nationals and 90% (>16,000) consisting of foreign fishery workers. Foreign fishermen are primarily from Bangladesh (49%), India (18%), Egypt (15%), Philippines (11%), and Yemen (3%), with 3% total from Sri Lanka, Turkey, and Burma. Most fishermen are 20-40 yr in age; 8% are 60 years or older. ‘

As of 2006, artisanal and investor fisheries accounted for 68% of the landings reported from the Saudi Arabian Red Sea, with 32% by the industrial fishery sector. The industrial fisheries include line fishing, gill netting, fish trapping and demersal fish and shrimp trawling, while investor fisheries use similar gear types except for trawling gear. The investor fishing sector consisted of Saudi nationals and foreigners employed by local businesses (“investors”) that provide boats and equipment to the crew, typically 2-4 men that lived on the boat fishing in the same areas as artisanal fishermen. These fishermen sell fish to the markets in large cities such as Jeddah, Yanbu, and Madinah, where fish prices are considerably higher. Industrial fishing is undertaken by a single company, the Saudi Fisheries Company; this company primarily operates

out of Jizan, south of the Farasan Banks (143 vessels), with only six vessels targeting reefs and associated habitats in the central and northern sectors. Traditional fishing in the Red Sea is mostly undertaken by self employed independent fishermen who use handlines and gill nets (89% of total landings for 2006), with pot traps accounting for 10% of the landings.



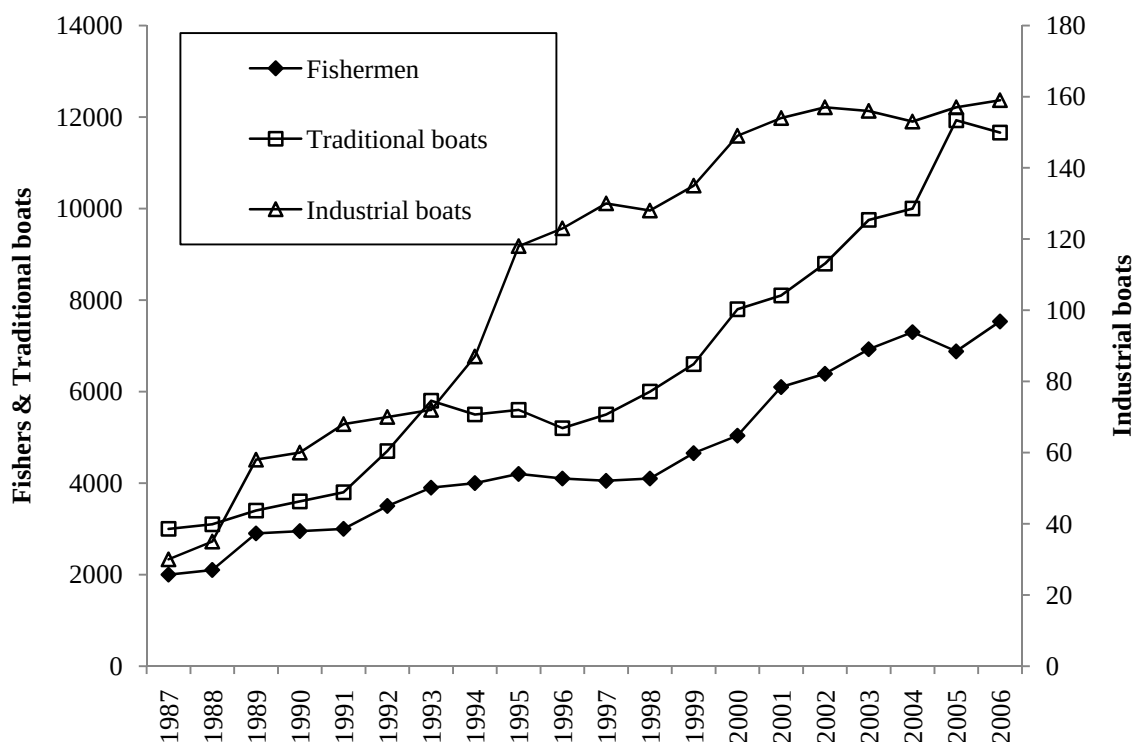
**Fig. 10.41a. Change in landings in the Saudi Arabian Red Sea over the last 20 years**

#### **10.42 Fisheries landings**

Fishing pressure is greatest in central and southern waters from Jeddah to the Farasan Islands, and in remote locations which are not patrolled as frequently. The coastline bordering the Red Sea represents about 79% of the total Saudi Arabian coast, yet fish production is about 35% of the total production, compared to 65% from the Arabian Gulf. Marine fisheries catch in 2006 was 65,472 metric tons (tons), with 23,435 tons landed in the Red Sea and 42,037 tons from the Arabian Gulf. While total catches of marine fish have substantially increased over the last 15 years in the Arabian Gulf (from about 12,000 tons in 1990), landings from the Red Sea have remained fairly constant since 1995, fluctuating between about 20,000-24,000 tons. In contrast, landings in the Red Sea from 1987-1994 ranged from 30,000 and 33,000 tons per year (Fig. 10.41b). Fishing effort (numbers of boats and fishermen and amount of effort) has also



increased significantly over the last two decades while landings of individual stocks continue to vary by and species. For example, landings over region the last four years increased annually in the northern (from 2,580 to 4,018 tons) and central sectors (2,800-4,635 tons), while they declined in the southern sectors (7,419-6,419 tons).



**Fig. 10.41b. Changes in fishing effort in the Saudi Arabian Red Sea over the last 20 years**

#### 10.43 Threats to fisheries and fishery resources

An increase in fishery production from the Red Sea over the last 30 years, and an expansion in the use of destructive fishing are key threats affecting the sustainability of reef resources. These threats are increasing in severity mainly due to increased commercial fishing pressure, more frequent trawling, fish traps, and other destructive methods, poaching in no-take zones, increased fishing pressure at spawning and nursery sites, and growing pressure on sharks, sea cucumbers and other species in high international demand (Kotb 2008). In several countries, traditional fishermen are abandoning fishing for more lucrative opportunities such as tourism, and local knowledge of the ecology of reefs is being irreversibly lost. Local nationals are being replaced

by migratory fishermen and visiting fishers from other countries who lack knowledge about the resource. These non-nationals have also introduced unsustainable and destructive gear types, including purse-seine nets, traps and dynamite fishing, which is contributing to habitat damage and bycatch, including harvest of a high diversity of undersized (juvenile) fishes due to a small mesh size. These traps are being used by investor fisheries in the same areas fished by artisanal fishers; they catch the same species as those targeted by artisanal fishers as well as non-target species important to the health and ecology of reefs, such as angelfishes, butterflyfish and surgeonfish.

Nearly a decade ago, artisanal fishers interviewed by Gladstone (2002) reported declines in catches, sizes of fish, and income from fishing, and both more time and larger areas were required to catch the same number of fish as in the past. Rapid urban, industrial and commercial development of Saudi Arabia has led to population growth, development of coastal areas, and increased exploitation of marine resources through commercial fishing (Gladstone et al. 1999). The government has also provided interest free loans, engines and new materials for boat making for the fishery sector in an attempt to expand and further develop the traditional fishing sector, yet management of the resources has not kept pace with fisheries growth. In many of the locations throughout the Red Sea, signs of depleted fishery resources have been reported, especially on reefs with declining coral cover. Inadequate data on the status of stocks and the biology of the fished species limits the ability to design and implement sustainable management approaches, and many countries lack adequate regulatory structures. Loss and degradation of habitat, especially the removal of mangroves and grassbeds, is reducing the amount of coastal areas available as nursery areas, with further deleterious effects on fisheries production. Unless new management interventions are adopted, these factors are a potential threat to the resource sustainability, conservation status and cultural values.

The major fisheries species caught, in order of importance for 2006 by all fisheries sectors were: mackerel (Scombridae, 13.8%), groupers (Serranidae, 13.4%), emperors (Lethrinidae, 13.4%), scads, jacks and trevallies (Carangidae, 11.6%), kingfish (8%), barracuda (Sphyraenidae, 6%), shrimp (4%), snapper (Lutjanidae, 3.5%), tuna (Scombridae, 3.4%), and squid and cuttlefish (2.5%). The industrial fishery primarily targets Indian mackerel, shrimp, squids and cuttlefish, jacks and trevallies, emperors, threadfin bream, barracuda, crab, mojarras and sea catfish

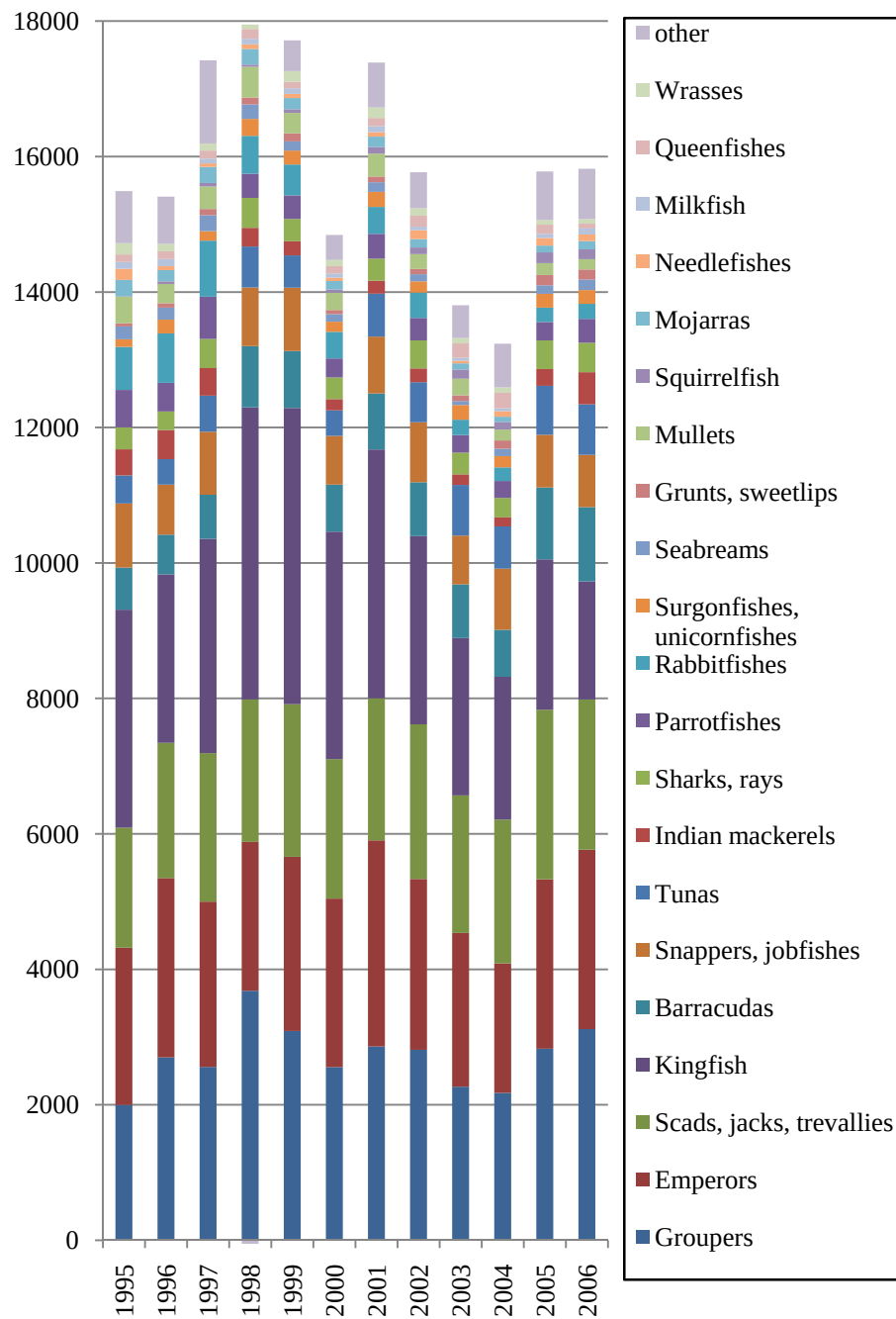
respectively, with most effort directed at open water fishes (Table 10.41). In contrast, traditional fisheries operate in shallow coastal lagoons and reefal habitats, with landings in 2006 dominated by grouper (3,117 tons; 20%), emperors (2,650 tons), jacks and trevallies (2,200 tons), kingfish (1,745 tons), barracuda (1,095 tons), snappers (773 tons), and 28 other functional groups including herbivores (unicornfish, parrotfish, surgeonfish, rabbitfish; 775 tons) and top predators (sharks, 434 tons) (Table 10.41).

The numbers of species landed over the last decade has increased, while certain major species have varied in abundance between years (Fig. 10.43a). In particular, comparisons between mean landings in the 1990s (1996-1999) vs. the 2000s (2000-2006) illustrate large declines in kingfish (35%), parrotfish (52%), rabbitfishes (121%), mackerel (51%), sea bream (64%), mojarras (84%), milkfish (39%) and wrasses (28%). Increases were observed in barracuda (16%), tuna (24%), grunts (19%), squirrelfish (68%) and queenfish (11%). In addition to food fishes, ornamental reef fish for the aquarium trade were also collected in southern regions with seven aquarium fish exporters operating out of Jeddah; this industry was banned in 2004. Shark fisheries were also banned in 2008.

**Table 10.41 Total landings for traditional fisheries in the Red Sea off Saudi Arabia for 2006 in metric tons reported for major groups of species in order of importance. Tab = Tabouk, Mad= Madeenah, Mak= Makkah.**

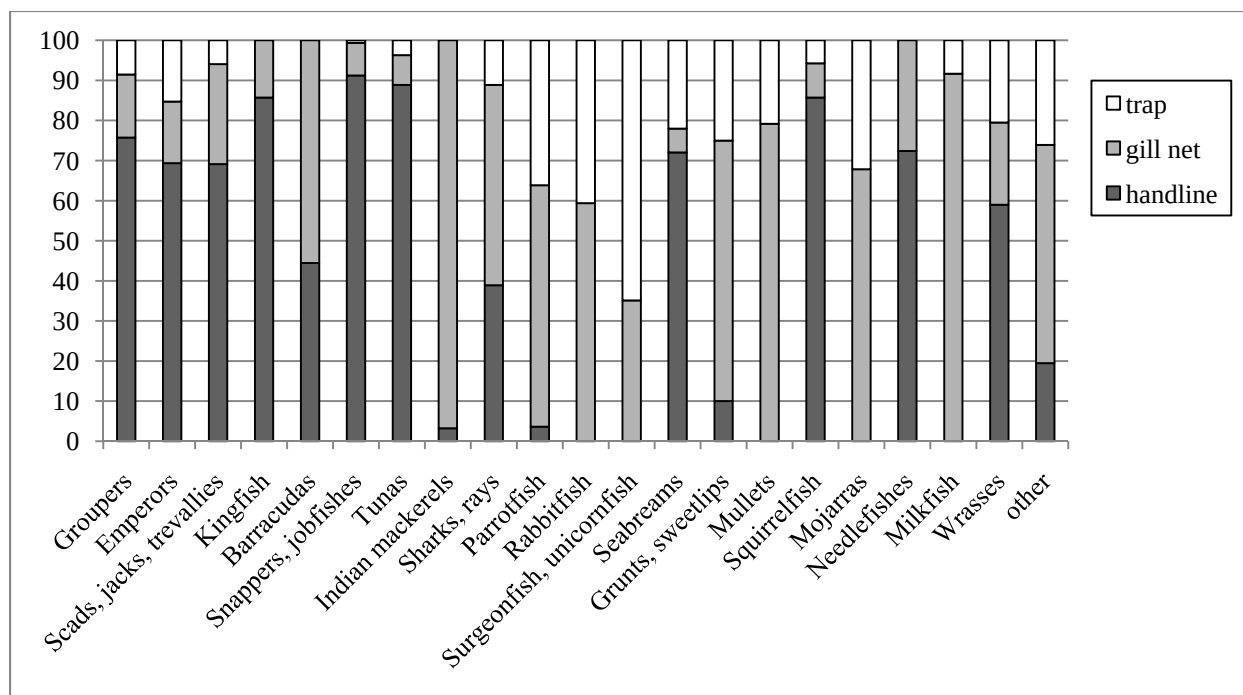
|                              | <b>Total</b> | <b>Tab</b>  | <b>Mad</b> | <b>Mak</b>  | <b>Aseer</b> | <b>Jizan</b> |
|------------------------------|--------------|-------------|------------|-------------|--------------|--------------|
| Groupers                     | 3117         | 711         | 228        | 1135        | 112          | 931          |
| Emperors                     | 2650         | 886         | 284        | 515         | 91           | 874          |
| Scads, jacks, trevallies     | 2217         | 373         | 119        | 652         | 324          | 749          |
| Kingfish                     | 1745         | 59          | 19         | 205         | 135          | 1327         |
| Barracudas                   | 1095         | 41          | 13         | 291         | 16           | 734          |
| Snappers, jobfishes          | 773          | 154         | 49         | 350         | 14           | 206          |
| Tunas                        | 744          | 52          | 17         | 353         | 17           | 305          |
| Indian mackerel              | 475          | 34          | 11         | 47          | 0            | 383          |
| Sharks, rays                 | 434          | 22          | 7          | 112         | 4            | 289          |
| Parrotfishes                 | 354          | 119         | 38         | 156         | 0            | 41           |
| Rabbitfishes                 | 223          | 78          | 25         | 100         | 0            | 20           |
| Surgeonfishes, unicornfishes | 202          | 79          | 25         | 96          | 2            | 0            |
| Seabreams                    | 155          | 110         | 35         | 9           | 1            | 0            |
| Grunts, sweetlips            | 150          | 10          | 3          | 58          | 5            | 74           |
| Mulletts                     | 150          | 36          | 12         | 57          | 0            | 45           |
| Squirrelfish                 | 146          | 19          | 6          | 121         | 0            | 0            |
| Mojarras                     | 121          | 27          | 9          | 67          | 0            | 18           |
| Needlefishes                 | 98           | 30          | 10         | 57          | 1            | 0            |
| Milkfish                     | 89           | 7           | 2          | 78          | 0            | 2            |
| Queenfishes                  | 70           | 0           | 0          | 18          | 0            | 52           |
| Wrasses                      | 69           | 26          | 8          | 34          | 1            | 0            |
| Sea catfishes                | 53           | 0           | 0          | 0           | 0            | 53           |
| Cobia                        | 50           | 0           | 0          | 4           | 0            | 46           |
| Angle fishes                 | 28           | 0           | 0          | 0           | 28           | 0            |
| Sardines                     | 20           | 12          | 4          | 4           | 0            | 0            |
| Snubnose chub                | 19           | 14          | 5          | 0           | 0            | 0            |
| Goatfishes                   | 14           | 10          | 3          | 1           | 0            | 0            |
| Triggerfishes                | 9            | 6           | 2          | 0           | 1            | 0            |
| Rainbow Runner               | 5            | 4           | 1          | 0           | 0            | 0            |
| Flat fishes                  | 4            | 0           | 0          | 4           | 0            | 0            |
| Crabs                        | 3            | 0           | 0          | 0           | 0            | 3            |
| Batfishes                    | 1            | 0           | 0          | 1           | 0            | 0            |
| Squids and cuttlefish        | 1            | 0           | 0          | 1           | 0            | 0            |
| <b>TOTAL</b>                 | <b>15819</b> | <b>3044</b> | <b>974</b> | <b>4635</b> | <b>751</b>   | <b>6415</b>  |





**Fig. 10.43a** Changes in landings between 1995-2006 for the 21 dominant groups of fish and all other species (pooled as other) by traditional fisheries off the Red Sea coast of Saudi Arabia.

Catch composition is highly dependent on fishing method. The two major types of gears used by traditional fishers are hand lines and gill nets, which account for about 89% of all landings in 2006. Predatory species, such as groupers (Serranidae), snappers (Lutjanidae), emperors (Lethrinidae) and bream (Sparidae) are targeted mainly by hook and line fishing. Traps were not used historically by artisanal fishermen, but their use is increasing. Approximately 10% of all landings were from traps in 2006, compared with only 6% in 2005 and 3.8% in 1996. In areas north of Jeddah, such as the Wajh Bank area, fish traps now dominate the artisanal fisheries and there is also an expansion in southern areas around the Farasan Banks. Traps, trammel nets and gill nets are less selective, catching a wide variety of species and functional groups. Several species, such as most parrotfish, rabbitfish, surgeonfish, unicornfish and other herbivores are rarely caught using handlines (Fig. 10.43b). Overall, more than 240 species of fish are reported to be landed using traps and nets (about 25% of all species reported from the region), although a smaller number of species make up the bulk of the catch by weight. For instance, three species of the family Scaridae (*Hipposcarus harid*, *Scarus ghobban* and *S. psittacus*) that comprise the bulk of the landings caught in trammel and gill nets when the fish feed over sand bottoms adjacent to reefs. Other gear types of minor importance include small trawl nets, cast nets for bait and wall nets (with relatively large openings) used to catch large herbivorous fish that cannot be caught with handlines. These nets were also used to catch transient reef predators, such as trevally (*Caranx* spp.) and dogfin tuna (*Gymnosarda* spp.) by chumming or baiting an area close to the reef, then enclosing it with the net so the fish are caught between the reef and the net with nowhere to escape. Spearfishing is illegal, although it is reported to be used occasionally on SCUBA to target large parrotfish (Scaridae), surgeonfishes (Acanthuridae) and groupers (Serranidae).



**Fig. 10.43b Differences in the relative proportion of the major groups of fish caught in coral reef environments off the Red Sea coast of Saudi Arabia by traditional fisheries using three different gear types.**

There are multiple problems associated with coral reef fisheries related to gear types, fishing effort, and fisheries targets. Predatory fish are vulnerable to most fishing gears and they usually disappear first under conditions of unsustainable fishing pressure. Fishermen often remove fish before they reach their most productive size, resulting in growth overfishing, partially due to the use of gear types that have mesh sizes which are too small, such as fish pots and gill nets. Intense exploitation of a particular reef, especially where there are few external sources of larvae to replenish the reef, may drive numbers to levels that are inadequate to maintain viable population (e.g. recruitment overfishing). As the top predators are depleted, fishing shifts to lower trophic levels to maintain high production. While this may arise because a greater proportion of the primary production is incorporated into fish biomass at these levels (Sheppard et al. 2003), unsustainable removal can cause a progressive shift in the balance of species on the reef, resulting in ecosystem overfishing. This is likely to distort the natural balance of energy flow from the bottom to the top of the food chain. Some fishing techniques, such as dynamite and cyanide fishing and the placement of fish traps on live coral damage the complex environment fish need to survive.

## **11. Role of geology and historic reef structures in modern day reef communities**

**The following section was summarized from:** Purkis, S., G. Rowlands, B. Riegl, and P. Renaud. 2010. The paradox of tropical karst morphology in the coral reefs of the arid Middle East. *Geology* 38:227-230.

### **11.1 Background**

The shallow waters of both the Arabian Gulf and Red Sea display reticulated networks capped by cement-bound carbonate debris. Similar morphology has also been reported for Belize (Macintyre et al. 2000), Kiritimati (Woodroffe and McLean 1998), Pearl and Hermes Atoll (Rooney et al. 2008), the Cocos/Keeling Islands (Searle 1994), the Maldives (Purdy and Bertram 1993), the Tuamotu archipelago (Guilcher 1988), and the Great Barrier Reef (Hopley et al. 2007), yet there are distinct differences between these locations. First, unlike the hyper-arid Red Sea and Gulf, these sites receive >1 m of rainfall per year. In the Red Sea, the reticulated structures support a veneer of live coral, whereas in the Gulf, where modern coral growth is at best incipient, accretion is predominantly by coralline algae (Purkis and Riegl 2005; Sheppard et al. 1992). In both settings the patterned seafloor displays two characteristic formations. ‘Type-1’ depressions are circular ponds of several 100 m diameter attaining depths up to 40 m. These are rimmed on all sides or coalesce to form networks of canals. ‘Type-2’ depressions have lesser relief, are smaller in aperture, and form a complex maze of reticulated sills that surround polygonal sediment-filled depressions (ponds).

Purkis et al. (2009) concludes that the reticulated morphology created by the Type-2 depressions is due to antecedent topography forming a template for later reef growth. Their findings suggest that such a complex pattern could not develop from any reef-limiting factor such as temperature, salinity, or sedimentation. These cannot be anticipated to vary in such a complicated or geometrically regular manner, suggesting substrate-controlled modern coral framework veneers over the sills (Purdy 1974). Furthermore, the pattern morphometry is statistically consistent between Red Sea and Gulf, despite different exposure, depth, salinity, temperature regimes, and dynamics and composition of reef-builders (Purkis and Riegl 2005; Sheppard et al. 1992). The morphology can be explained by karstic dissolution of carbonate rocks by mildly acidic rainwater, a process generating a terrain pattern of enclosed depressions bounded by steep-



walled sills (Fleurant et al. 2008). This could have occurred in the Red Sea during a sea-level low-stand, as chemical erosion is restricted to episodes when the surface is sub-aerially exposed.

## **11.2 Paleoclimate and sea level**

Reconstruction of Late-Pleistocene to Holocene sea-level and climate reveals mechanisms generating reticulated seafloors. Reef terraces <25 m below present sea-level were exposed from ~110,000-9,000 years B.P. (before present) causing scars of ~100,000 years meteoric alteration and dissolution. Reconstructions of Saharan climate for this period reveals a brief (~8,000 years) wet-phase for both the Red Sea and Gulf during the transition from the penultimate glacial to the last interglacial period, followed by the onset of 100,000 years of extreme aridity (McKenzie 1993; Preusser et al. 2002), before a recent return to wet conditions of ~5,000 years duration in the early Holocene (Parker et al. 2006). At the same time that sea-level approximated its present position (3000-6000 years ago), the climate of the Red Sea and Gulf shifted toward extremely hot and dry (Arz et al. 2003). These hyper-arid conditions persist today with annual average rainfall <10 cm in the Gulf and half that in the Red Sea (Sheppard et al. 1992).

It is reasonable to assume a similar sea-level history of the Red Sea and Gulf following the LGM, both tracking the rise of the Indian Ocean. To chart the Holocene inundation of Arabia, we consider the transgression from the perspective of two sea-level curves – an earliest possible flooding (Camoin et al. 2004) and a latest (Lambeck 1996). At the onset of the Holocene pluvial period in Arabia, the most recent abrupt switch to a cooler and wetter climate in the arid Middle East at 10,000 years B.P. (Parker et al. 2006), sea-level stood between ~35 m (Lambeck 1996) or even ~45 m below present (Camoin et al. 2004). Irrespective of the sea-level used to reconstruct the transgression, seafloors displaying Type-2 morphology lay exposed 10,000 years B.P. At this time the climate entered a pluvial period, peaking ~9,000 years B.P. and persisting until at least 6,000 years B.P. (Lézine et al. 1998; McClure 1976; Neff et al. 2001; Parker et al. 2006). This was caused by the migration of the Indian Ocean Monsoon (IOM) (Davies 2006; Gasse et al. 1990; Lézine et al. 1998), extending the limit of the monsoon rainfall belt far north of its modern location, the southern shoreline of Arabia (Davies 2006; deMenocal et al. 2000; Fleitmann et al. 2003; Neff et al. 2001; Parker et al. 2006). The IOM shift may not have been sufficient to induce monsoonal rains in the northern reaches of the Red Sea (Ras Qisbah) where evidence for equally wet conditions exists but the onset of westerly winter rainfall originating in

the Mediterranean is implicated (Arz et al. 2003). Chemical erosion of exposed limestone terraces can be expected to have proceeded slowly during the 100,000 years of aridity that separated the last and present interglacial. Dissolution would have initiated quickly after the onset of the Holocene wet-phase and been well under way by its peak 9,000 years B.P.

Evidence of Type-2 depressions having mid-Holocene age derives from the ~25 m maximum depth below present sea-level at which they are observed. In the Red Sea and Gulf, a pronounced increase in the prevalence of Type-2 morphology shallower than 10 m is observed, peaking at ~5 m. If Type-2 patterning were to owe its origin to meteoric alteration that occurred prior to the mid-Holocene (i.e., during the 100,000 years interglacial before the most recent transgression), it would also be expected at water depths >25 m. This is not the case, as the ~25 m depth limit can be constrained with high confidence from the visual analysis of 25,000 km<sup>2</sup> of QuickBird imagery, coupled with exhaustive ground-truthing. Terraces situated 5 m below present sea-level (which display the highest prevalence of Type-2 patterning) would have been subjected to meteoric erosion until at least 7,000 years B.P. and perhaps as long as 5,000 years B.P.. This would allow between 3,000-5,000 years of exposure to the Holocene monsoon climate.

### **11.3 Landform modeling**

To numerically simulate the effects of sub-aerial exposure on a limestone terrace we employ the CHILD landform model (v.8.12) (Kaufmann and Braun 2001) which is capable of simulating karst formation in soluble landscapes (Tucker et al. 2001) and can be modified to apply well-known calcite dissolution kinetics to calculate mass loss as water flow across/under a terrain surface (Fleurant et al. 2008)

For the simulation, a landscape consisting of 10,000 nodes was subjected to 1 m of rainfall per year for 10,000 years. The initial model surface was roughened with  $\pm 0.5$  m random topographic variation, deemed realistic heterogeneity for an Arabian reef terrace. Precipitation was concentrated in storms of 5-hour duration, occurring every 30 days. Present day rainfall in the Arabian Gulf averages 10 cm per year and even less in the Red Sea (Sheppard et al. 1992). The model parameters were however set to mimic the conditions at the northern limit of the IOM today. This honors the premise that during the mid-Holocence the IOM extended northwards over Arabia. Rainfall was therefore set one order of magnitude greater than present. This value

equals the present yearly average for the Arabian margin of the Indian Ocean (Fleitmann et al. 2003), the current northerly limit of the IOM, and is in agreement with the predicted rate of precipitation for the region during the Holocene wet-phase (Lézine et al. 1998). The proportion of moisture lost to evaporation was neglected and the rate of tectonic uplift assumed zero. Accompanying Supplementary Material develops a validation of the model, showing that with precipitation rates as low as 0.7 m/yr and with realistic tectonic shifts, our conclusions on geomorphic evolution are unchanged.

Simulations demonstrate that 2,000 years of exposure is sufficient to form reticulated pond-and-sill patterning, even with the moderately low rainfall of 1 m/yr. Unlike the initial topography used in the model, this patterning is not random, but has evolved to display the ordered morphology observed in the QuickBird data. Based on this correspondence, we conclude rainfall in the region during the Holocene wet-phase likely did not exceed 1 m/yr. Furthermore, the simulated 0.06 m/1,000 yr rate of denudation is in concert with comparable literature studies of karst in reefal limestones (Marshall and Davies 1984; Spencer 1985). The model also demonstrates that Type-1 sinkholes require considerably more time to develop. By 8,000 years of simulation, Type-1 formations are present but their relief is limited to <5 m as compared to tens of meters observed in the field. These structures therefore must have developed over much longer periods of sub-aerial denudation, likely initiating during the penultimate pluvial period 120,000 years B.P. Type-2 reticulates must have formed in the last pluvial period since if they were older, any exposure exceeding 8,000 years with even moderate rainfall would force a shift to Type-1 morphology. Type-2 reticulated karst is therefore a transient condition, persisting only for a few thousand years, and prior to the development of Type-1 morphology.

The model indicates that at the point of submergence by the transgression, the vertical relief of the Type-2 karst would have been 1 m or less. Upon flooding, this low-relief patterning survived the erosive processes of submergence by serving as a template for reef initiation. Coral growth preferentially focused on topographic highs (i.e., sills) while being inhibited in the lows (ponds) by an abundance of unconsolidated sediment. Hence, reef growth accentuates underlying karst topography (Macintyre et al. 2000; Purdy et al. 2003; Searle 1994). To reconcile the differences for the simulated karst with the several meters of vertical relief observed in the field, a rate of accretion atop the sills of ~1.5 m/1,000 yr is required. This is in broad agreement with the pace

of Holocene reef accretion which averages 3–6 m/1,000 yr in the Indo-Pacific, depending on water depth and rate of sea-level rise (Montaggioni 2005). The comparatively slow rate of 1.5 m/1,000 yr is explained both by the low accretion potential of the foliaceous and encrusting coral communities typical to the area, and the inevitable decline in reef vigor ~5,000 years B.P. imposed by a reduction in accommodation space through the stabilization of sea-level at this time. Since reticulated karst is evident in the northern limits of the Red Sea (Ras Qisbah), the area must have been subjected to a Holocene humid interval, despite likely being beyond the reach of the IOM. The presence of patterning reaffirms a Mediterranean pluvial influence on the northernmost Red Sea (Arz et al. 2003).

In conclusion, the complex maze of reticulated sills surrounding polygonal sediment-filled ponds on the shallow seabed of the Arabian Gulf and Red Sea are indicative of a brief period of sub-aerial chemical erosion followed by submergence and initiation of reef growth. There is strong evidence that the timing of this short episode of karst weathering occurred during the Holocene pluvial period in Arabia. We demonstrate that aspects of the reef morphology in the region are controlled by antecedent topography formed as recently as the mid-Holocene.



## 12. REFERENCES

- Al-Mansi A. M, A. Z. Sambas and K.F. Al- Shmary. 2005. The Status of the Marine Mammals in Farasan Islands. NCWCD Report, Riyadh, July 1994.
- Al-Merghani, M., J. D. Miller, N. J. Pilcher, and A. Al-Mansi. 2000. The green and hawksbill in the Kingdom of Saudi Arabia Synopsis of nesting study 1986-1997. *Fauna of Saudi Arabia*, 18:369-384.
- Al-Yami, H.M. and A.B. Roupheal. 2000. Patterns of coral mortality across the Farasan Shelf, Saudi Arabia. In: H. Tatwany, ed. *Proceedings of the International Workshop on the Extent and Impact of Coral Bleaching in the Arabian Region*. National Commission for Wildlife Conservation and Development, Riyadh.
- Al-Wetaid, A. 2003. Status of Red Sea mangrove in Kingdom of Saudi Arabia (Draft Report). PERSGA, Jeddah (in Arabic).
- Antonius, A. 1985. Coral diseases in the Indo Pacific: a first record. *P.S.Z.N.I. Mar. Ecol.* 6: 197-218.
- Aronson, R. B., I. G. MacIntyre, C. M. Wapnick, and M. W. O'Neill. 2004. Phase shifts, alternative states, and the unprecedented convergence of two reef systems. *Ecology* 85:1876–1891.
- Baker, A. C., P. W. Glynn, and B. Riegl. 2008. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal, and Shelf Science* 80: 435-471.
- Behairy, A.K.A., C.R.C. Sheppard, and M.K. El-Sayed. 1992. A review of the geology of coral reefs in the Red Sea. *UNEP Regional Seas Reports and Studies No. 152*, 39 pp.
- Bell, J.D. and D.A. Pollard. 1989. Ecology of fish assemblages and fisheries associated with seagrasses. In A.W.D. Larkum, A.J. McComb, and S.A. Shepherd (eds.), *Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian Region*. Aquatic Plant Studies 2. Elsevier, Amsterdam, pp. 565-609
- Bemert G, and R.F.G. Ormond. 1981. Red sea coral reefs, London, Kegan Paul International.
- Braithwaite, C.J.R. 1987. Geology and Paleogeography of the Red Sea region. In: Head S.M. (ed) *Red Sea – Key Environments*, Pergamon, 22-45

- Bruckner, A.W., H. Alnazary and M. Faisal 2011. Paradigm shift for fisheries management to enhance recovery, resilience, and sustainability of coral reef ecosystems in the Red Sea. In: Sustainable Fisheries: Multi-Level Approaches to a Global Problem. American Fisheries Society. pp. 85-111
- Chazot, G., M.A. Menzies and J. Baker. 1998. Pre-, syn-, and post-rift volcanism of the southwestern margin of the Arabian plate. Purser, B.H., and D.W.J. Bosence (eds.) Sedimentation and Tectonics in Rift Basins. Red Sea – Gulf of Aden. Chapman & Hall, pp.50-56.
- Child, G. and J. Grainger. 1990. A System Plan for Protected Areas for Wildlife Conservation and Sustainable Rural Development in Saudi Arabia. National Commission for Wildlife Conservation and Development – World Conservation Union, Gland, Switzerland.
- Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.
- Davison L, I. Davison, M. Al-Kadasi, S. Al-Khirbash, A.K. Al-Subbary, J. Baker, S. Blakey, D. Bosence, C. Dart, R. Heaton, K. McClay, M. Menzies, G. Nichols, L. Owen and A. Yelland. 1994. Geological evolution of the southeastern Red Sea Rift margin, Republic of Yemen. *GSA Bulletin* 106; no. 11; p. 1474-1493;
- Debelius, H. 1998. Red Sea reef guide. IKAN, Frankfurt, Germany.
- Den Hartog, C. 1970. The Seagrasses of the World. North-Holland, Amsterdam, 275 pp.
- DeVantier, L., E. Tourak, K. Al-Shaikh, and G. De'ath. 2000a. Coral communities of the central-northern Saudi Arabian Red Sea. *Fauna of Arabia* 18:23-66.
- DeVantier, L., E. Tourak, and K. Al-Shaikh. 2000b. Coral bleaching in the central-northern Saudi Arabian Red Sea, August-September 1998. In H. Tatwany, ed. Proceedings of the International Workshop on the Extent and Impact of Coral Bleaching in the Arabian Region . National Commission for Wildlife Conservation and Development, Riyadh, Saudi Arabia.
- Dicks, B. 1987. Pollution. Pages 383-404, In: A. Edwards and S.M. Head, eds. Key environments: the Red Sea. Pergamon Press, Oxford, United Kingdom.
- Edwards, A.J. and S.M. Head. 1987. *Red Sea (Key Environments)*. 441pp. Pergamon Press in collaboration with IUCN. Oxford.
- Fonseca, M.S. and J.S. Fisher. 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Mar. Ecol. Prog. Ser.* **29**: 15-22.

Girdler R.W., and T.C. Southren 1984. Structure and evolution of the Red Sea. *Nature* 330, 716-721

Gladstone, W. 1994. The Farasan Islands Marine Protected Area: biological resources, conservation values, human uses and impacts. National Commission for Wildlife Conservation and Development, Riyadh, Saudi Arabia.

Gladstone, W. 1996. Unique annual aggregation of longnose parrotfish (*Hipposcassus harid*) at Farasan Island (Saudi Arabia, Red Sea). *Copeia* 2:483-485.

Gladstone, W. 2000. The ecological and social basis for management of a Red Sea marine-protected area. *Ocean and Coastal Management* 43:1015-1032.

Gladstone, W. 2002. Fisheries of the Farasan Islands (Red Sea). *Naga*, World Fisheries Center 25(3&4):3034.

Gladstone, W., N. Tawfiq, D. Nasr, I. Andersen, C. Cheung, H. Drammeh, F. Krupp, and S. Lintner 1999. Sustainable use of renewable resources and conservation in the Red Sea and Gulf of Aden: Issues, needs and strategic actions. *Ocean and Coastal Management* 42:671-697.

Guilcher, A. 1988. A heretofore neglected type of coral reef: the ridge reef: morphology and origin. *Proceedings of the 6th International Coral Reef Symposium, Australia, 1988, Vol. 3.* 399-402.

Harvell, D., E. Jordán -Dahlgren, S. Merkel, E. Rosenberg, L.J. Raymundo, G. Smith, E. Weil, and B.L. Willis. 2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. *Oceanography* 20 172-195.

Head, S.M. 1987. Introduction. In Head, S.M (ed.) *Red Sea – Key Environments*. Pergamon, 1-20.

Hughes, T. P. 1989. Community structure and diversity of coral reefs - the role of history. *Ecology* 70:275–279.

Hughes, T. P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science* 265:1547–1551.

JICA/NCWCD, 2000. The Study on coastal/marine habitat and biological inventories in the northern part of the Red Sea coast in the Kingdom of Saudi Arabia .JICA/NCWCD report, Riyadh, March 2002.

Kedidi, S.M. 1984. Description of the artisanal fishery at Tuwwal, Saudi Arabia. Catches, efforts and catches per unit effort survey conducted during 1981-1982. UNDP/FAO RAB/81/002/16. 17 pp.

Khalil, S.M. and K.R. McClay. 2002. Extensional fault-related folding in the northern Red Sea. *J. Structural Geology* 24:743-762

Klumpp, D.W., R.K. Howard, and D.A. Pollard. 1989. Trophodynamics and nutritional ecology of seagrass communities. *In* A.W.D. Larkum, A.J. McComb, and S.A. Shepherd (eds.), *Biology of Seagrasses. A Treatise on the Biology of Seagrasses with Special Reference to the Australian region*. Aquatic Plant Studies 2. Elsevier, Amsterdam, pp. 394-45

Knowlton, N. 1992. Thresholds and multiple stable states in coral reef community dynamics. *American Zoology* 32:674–682.

Kotb, M., M. AbdulAziz, Z. Al-Agwan, K. Al Shaikh, H. Al-Yami, A. Banajah, L. DeVantier, M. Eisinger, M. Eltayeb, M. Hassan, G. Heiss, S. Howe, J. Kemp, R. Klaus, F. Krupp, N. Mohamed, T. Roupheal, J. Turner, and U. Zajonz. 2004. Chapter 4: Status of coral reefs in the Red Sea and Gulf of Aden. Pages 137–154, *In*: Wilkinson, C.R. editor. *Status of Coral Reefs of the World: 2004*. Vol. 1: Australian Institute of Marine Science publ., Cairns, Australia

Kotb, M.M, M. H. Hanafy, H. Rirache, S. Matsumura, A. A. Al-Sofyani, A. G. Ahmed, G. Bawazir, and F. A. Al-Horani. 2008. Status of coral reefs in the Red Sea and Gulf of Aden region. Pages 67-78. *in* WC. Wilkinson, editor. *Status of coral reefs of the world: 2008*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia.

Lang, J.C. 2003. Status of coral reefs in the Western Atlantic: results of initial surveys, Atlantic and Gulf Rapid Reef Assessment (AGGRA) Program. *Atoll Research Bulletin* 496:1-630.

Makris J., and C.H. Henke 1992 Pullapart evolution of the Red Sea. *J Petroleum Geol* 15: 127-134.

Mandura, A.S., S.M. Saifullah, and A.K. Khafaji. 1987. Mangrove ecosystem of southern Red Sea coast of Saudi Arabia. *Proceedings of Saudi Biology Society*. 10: 165-193.

Marine Fisheries Department. 2008. Fisheries statistics of Saudi Arabia 2006. Ministry of Agriculture and Water, Kingdom of Saudi Arabia, Jeddah.

McClanahan, T.R., M. Ateweberhan, N. A. J. Graham, S. K. Wilson, C. R. Sebastian, M. M. M. Guillaume, and J. H. Bruggemann. 2007. Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction. *Marine Ecology Progress Series* 337:1–13.

Miller, J. D. 1989. Marine turtle: an assessment of the conservation status of marine turtle in the Kingdom of Saudi Arabia. Vol. 1 MEPA Coastal and Marine Management Series Technical Report 9, 209 pp.



Morcos, S. A. 1970. Physical and chemical oceanography of the Red Sea. *Oceanogr. Mar. Biol. Ann. Rev.* 8: 73-202.

Mustafa, Z., Z. Nawab, R. Horn and F. Le Lann 1980. Role of physical oceanography and environmental studies. *Proceedings of Symposium on Coastal and Marine Environment of the Red Sea, Gulf of Aden and Tropical Western Indian Ocean*,. Vol. 3, 7-31. University of Khatoum Khartoum, Sudan.

NCWCD. 1995. The Farasan Islands – Conservation and the Development of Ecotourism in the Southern Red Sea. National Commission for Wildlife Conservation and Development, Riyadh and King Abdulaziz University, Jeddah, Saudi Arabia.

Neumann, A. C. and D. A. McGill 1961. Circulation of the Red Sea in early summer. *Deep-Sea Res.* 8:223-35.

Nystrom, N., N. A. J. Graham, J. Lokrantz, and A.V. Norstrom. 2008. Capturing the cornerstones of coral reef resilience: linking theory to practice. *Coral Reefs* 27:795-809.

Obura, D.O., and G. Grimsdith. 2009. Resilience Assessment of coral reefs – manual. IUCN working group on Climate Change and Coral Reefs. IUCN, Gland, Switzerland.

Ormond, R.F.G., A. Dawson-Sheppard, A. Price and R.G. Pitts. 1984a. Report on the distribution of habitats and species in the Saudi Arabian Red Sea. International Union for Conservation of Nature / Meteorological and Environmental Protection Administration / PERSGA, Kingdom of Saudi Arabia. 123 pp.

Ormond, R.F.G., A. Dawson-Sheppard, A. Price and R.G. Pitts. 1984b. Report on the distribution of habitats and species in the Saudi Arabian Red Sea. 2. International Union for Conservation of Nature / Meteorological and Environmental Protection Administration / PERSGA, Kingdom of Saudi Arabia. 151 pp.

Ormond, R.F.G., A. Dawson-Sheppard, A. Price and R.G. Pitts. 1984c. Management of Red Sea coastal resources: recommendations for protected areas International Union for Conservation of Nature / Meteorological and Environmental Protection Administration / PERSGA, Kingdom of Saudi Arabia. 113 pp.

Orszag-Sperber, F., B.H. Purser, M. Rioual, and J.-C. Plaziat. 1998. Post-Miocene sedimentation and rift dynamics in the southern Gulf of Suez and northern Red Sea. Purser, B.H., and D.W.J. Bosence (eds.) *Sedimentation and Tectonics in Rift Basins. Red Sea – Gulf of Aden*. Chapman & Hall, pp.427-444

- Patzert, W. C. 1974. Wind induced reversal in Red Sea circulation. *Deep-Sea Res.* 21:109-21.
- PERGSA. 2003. Regional action plan for the conservation of coral reefs in the Red Sea and Gulf of Aden. PERGSA Technical Report Series 3:1-50.
- Perrin, C., J.-C. Plaziat, and B.R. Rosen. 1998. Miocene coral reefs and reef corals of the south-western Gulf of Suez and north-western Red Sea: distribution, diversity, and regional environmental control. Purser, B.H., and D.W.J. Bosence (eds.) *Sedimentation and Tectonics in Rift Basins. Red Sea – Gulf of Aden.* Chapman & Hall, pp.296-320
- Pilcher, N. and A. Alsuhaibany 2000. Regional Status of Coral Reefs in the Red Sea and the Gulf of Aden. In : *Status of Coral Reefs of the World : 2000.* AIMS, Townsville
- Preen, T. 1989. The status and conservation of Dugong in the Arabain Region. MEPA. Report No. 10. Vol. 1 MEPA Coastal and Marine Management Series Technical Report 9, 209 pp.
- Price, A.R.G., P.A.H. Medley, R.J. McDowall, A.R. Dawson Shepherd, P.J. Hogarth, and R.F.G. Ormond. 1987. Aspects of mangal ecology along the Red Sea coast of Saudi Arabia. *Journal of Natural History* 21: 449–64.
- Price, A.R.G., G. Jobbins, A. Dawson Shepherd, and R.F.G. Ormond. 1998. An integrated environmental assessment of the Red Sea coast of Saudi Arabia. *Environmental Conservation* 25: 65-76.
- Purkis, S.J. 2005. A 'reef-up' approach to classifying coral habitats from IKONOS imagery. *IEEE Transactions on Geoscience and Remote Sensing* 43: 1375-1390.
- Purkis S.J. and R. Pasterkamp 2004. Integrating in situ reef-top reflectance spectra with Landsat TM imagery to aid shallow-tropical benthic habitat mapping. *Coral Reefs* 23 (1): 5-20.
- Purkis, S., G. Rowlands, B. Riegl, and P. Renaud. 2010. The paradox of tropical karst morphology in the coral reefs of the arid Middle East. *Geology* 38:227-230.
- Purser, B.H., and D.W.J. Bosence. 1998. Organization and scientific contributions in sedimentation and tectonics of rift basins: Red Sea-Gulf of Aden. Purser, B.H., and D.W.J. Bosence (eds.) *Sedimentation and Tectonics in Rift Basins. Red Sea – Gulf of Aden.* Chapman & Hall, pp.3-8
- Riegl, B. and W.M. Piller 1997. Distribution and environmental control of coral assemblages in Northern Safaga Bay (Red Sea, Egypt). *Facies* 36; 141-162.
- Riegl, B. and B. Velimirov. 1994. The structure of coral communities at Hurghada in the Red Sea. *Marine Ecology* 15, 213-231.

- Rihm R, and C.H. Henke. 1998. Geophysical studies on early tectonic controls on Red Sea rifting, opening and sedimentation. In: Purser, B.H., and D.W.J. Bosence (eds.) Sedimentation and Tectonics in Rift Basins. Red Sea – Gulf of Aden. Chapman & Hall, pp.27-48
- Roberts, C.M. 1986. Aspects of Coral Reef Fish Community Structure in the Saudi Arabian Red Sea and on the Great Barrier Reef. D. Phil. Thesis University of York, U.K.
- Roberts, C.M. and Ormond, R.F.G. 1987. Habitat complexity and coral reef fish diversity and abundance on Red Sea fringing reefs. Marine Ecology Progress Series 41, 1-8.
- Rotjan, R.D. and S.M. Lewis. 2008. The impact of coral predators on tropical reefs. Marine Ecology Progress Series 367:73-91.
- Roupheal, A.B. and H. Al-Yami. 2000a. Spatial abundances of marine organisms in the Farasan Islands Marine Protected Area, Saudi Arabia. Proceedings of the international symposium on the extent and impacts of coral bleaching in the Arabian region. Riyadh, Kingdom of Saudi Arabia.
- Roupheal, A.B. and H. Al-Yami. 2000b. Temporal variation in abundances of marine organisms, Farasan Islands Marine Protected Area, Saudi Arabia. Report 4, National Commission for Wildlife Conservation and Development. Jeddah, Saudi Arabia.
- Sheppard, C.R.C. 1985. Reefs and coral assemblages of Saudi Arabia, 2. Fringing reefs of the southern region, Jeddah to Jizan. *Fauna of Saudi Arabia* 7: 37–58.
- Sheppard, C.R.C. and A.L.S. Sheppard, 1985. Reefs and coral assemblages of Saudi Arabia 1. The central Red Sea at Yanbu al Sinaiyah. *Fauna of Saudi Arabia* 7: 17-36.
- Sheppard, C.R.C. and A.L.S. Sheppard. 1991. Corals and coral communities of Arabia. *Fauna of Saudi Arabia* 12: 3-170.
- Sheppard, C., A. Price, and C. X. Roberts. 1992. Marine ecology of the Arabian Region. Patterns and processes in extreme tropical environments. Academic Press, New York.
- Siedler, G. 1969. General circulation of water masses in the Red Sea. In Hot brines and recent heavy metal deposits in the Red Sea, ed. E. T. Degens and D. A. Ross, 131-37. Springer Verlag, New York.
- Siraj. A. 1984. Climate of Saudi Arabia: Climatological features of Saudi Arabia. *Fauna of Saudi Arabia*. 6: 32-52.
- Smith, L., J. Gilmour, and A. Heyward. 2008. Resilience of coral communities on an isolated system of reefs following catastrophic mass-bleaching. *Coral Reefs* 27:197–205.

Spalding, M. D., C. Ravilious, and E. P. Green. 2001. World atlas of coral reefs. University of California Press, Berkeley, California.

Stumpf R.P., K. Holderied, and M. Sinclair. 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnology. Oceanography*. 48 (1, part 2): 547–556.

Veron, J.E.N. 1993. Corals of Australia and the Indo-Pacific. University of Hawaii Press.

Veron, J.E.N. and M. Stafford Smith. 2000. Corals of the world. Australian Institute of Marine Science.

Weikert, H. 1987. Plankton and pelagic environment. In: Key Environment The Red Sea. Ed. A. J. Edwards and S. M. Head. Pergamon Press. pp. 90-111.

Wilkinson, C. 2008. Status of Coral Reefs of the World: 2008. Townsville, Australia: Global Coral Reef Monitoring Network and Reef and Rainforest Research Center.

Zieman, J.C. and R.G. Wetzel. 1980. Productivity in seagrasses: methods and rates. *In* R.C. Phillips and C.P. McRoy (eds.), *Handbook of Seagrass Biology*. Garland STPM, New York, pp. 87-116.



## **Appendix 1. Partners**

### **Farasan Islands. Survey Dates: May 3- May 24, 2006**

#### **Affiliated Organizations**

1. The Saudi Arabian National Commission for Wildlife Conservation and Development (NCWCD), Kingdom of Saudi Arabia
2. The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), Kingdom of Saudi Arabia
3. Lantra, the UK Sector Skills Council for the Environmental and Land-based Sector,
4. The Trident Trust,
5. The University of Cambridge, Cambridge Coastal Research Unit and Unit for Landscape Modeling, United Kingdom
6. NOVA Southeastern University, National Coral Reef Institute (NCRI), Florida USA
7. College of Ocean and Fishery Sciences, the University of Washington, Washington, USA
8. Spanish Oceanographic Institute, Madrid, Spain
9. University of Hawaii, Hawaii, USA
10. Hyperspectral Data International, Inc. (HDI) – Halifax, Nova Scotia, Canada
11. BirchHill GeoSolutions, Canada

### **Ras Qisbah. Survey Dates: September 1-September 11 2007**

#### **Affiliated Organizations**

1. The Saudi Arabian National Commission for Wildlife Conservation and Development (NCWCD), Kingdom of Saudi Arabia
2. The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), Kingdom of Saudi Arabia
3. NOVA Southeastern University, National Coral Reef Institute (NCRI), Florida USA
4. The University of Cambridge, Cambridge Coastal Research Unit and Unit for Landscape Modeling, United Kingdom
5. The International Union for Conservation of Nature (IUCN), Geneva, Switzerland
6. Coastal Ocean Research and Development in the Indian Ocean (CORDIO)

### **Yanbu/Al Wajh Survey dates: May 7-May 24, 2008**

#### **Affiliated Organizations**

1. The National Commission for Wildlife Conservation and Development (NCWCD), Kingdom of Saudi Arabia
2. The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), Kingdom of Saudi Arabia
3. National Coral Reef Institute (NCRI),
4. Coastal Ocean Research and Development in the Indian Ocean (CORDIO),
5. The International Union for Conservation of Nature (IUCN), Geneva, Switzerland
6. NOVA Southeastern University, National Coral Reef Institute (NCRI), Florida USA
7. The University of Cambridge, Cambridge Coastal Research Unit and Unit for Landscape Modeling

### **Farasan Banks Survey dates: April 3-April 27, 2008**

#### **Affiliated Organizations**

1. The National Commission for Wildlife Conservation and Development (NCWCD), Kingdom of Saudi Arabia
2. The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), Kingdom of Saudi Arabia
3. Ministry of Agriculture, Marine Fisheries Department (MFD), Kingdom of Saudi Arabia
4. The International Union for Conservation of Nature (IUCN), Geneva, Switzerland
5. NOVA Southeastern University, National Coral Reef Institute (NCRI), Florida USA
6. Blue Ventures, United Kingdom

**Appendix 2. List of scientists conducting research during the four year Red Sea Expedition.**

| Researcher              | Farasan Islands | Ras Qisbah | Yanbu/Al Wajh | Farasan Banks |
|-------------------------|-----------------|------------|---------------|---------------|
| Captain Philip Renaud   | X               | X          | X             | X             |
| Dr. Annelise Hagan      | X               | X          | X             |               |
| Dr. Andrew Bruckner     |                 |            | X             | X             |
| Dr. Sam Purkis          | X               | X          | X             | X             |
| Mr. Gwilym Rowlands     |                 | X          | X             | X             |
| Dr. Bernhard Reigl      | X               |            | X             | X             |
| Dr. David Obura         |                 | X          | X             |               |
| Dr. Ameer Abdulla       |                 | X          | X             | X             |
| Ms. Sarah Hamylton      |                 | X          | X             |               |
| Dr. Tony Raphael        |                 |            |               | X             |
| Mr. Alastair Harris     |                 |            |               | X             |
| Mr Omar Al-Khushaim     | X               | X          | X             | X             |
| Mr. Khalid Al-Shaikh    | X               | X          | X             | X             |
| Dr. Ahmed Al Mansi      | X               |            | X             | X             |
| Mr. Hatem Al-Yami       | X               | X          |               |               |
| Mr. Hussein Alnazry     |                 |            |               | X             |
| Mr. Anas Sambas         | X               |            |               |               |
| Mr Abdullah Alsuhaibany | X               |            |               |               |
| Mr. Ray Buckley         | X               |            |               |               |
| Mr. Glenn Page          |                 |            |               | X             |
| Mr. D.J. Rollers        |                 |            | X             |               |
| Ms. Frederique Kandel   | X               |            |               |               |
| Ms. Beth Lacey          | X               |            |               |               |
| Dr. Ben Stobart         | X               |            |               |               |
| Mr. Martin Callow       | X               |            |               |               |
| Mr. Alastair Kennel     | X               |            |               |               |
| Mr. Peter Scoones       | X               |            |               |               |
| Mr. Nicholas Claxton    | X               |            |               |               |
| Mr Herbert Ripley       | X               |            |               |               |
| Mr Jeff Parks           | X               |            |               |               |

### **Appendix 3** Research platform

#### **Motor Yacht *Golden Shadow***

The founder makes significant assets available to the Living Oceans Foundation at no expense to the Foundation. Accordingly, the Foundation can access remote marine sites to conduct scientific research via periodic employment of a 219 ft logistics support vessel. The Motor Yacht *Golden Shadow* has dedicated laboratory facilities, a diving recompression chamber and an embarked amphibious aircraft (*Golden Eye*) that has been used extensively for aerial multi-spectral surveys of coral reef ecosystems. One of the most important capabilities of the *Golden Shadow* is its stern elevator platform. This system is used to launch and recover the *Golden Eye*, as well as its various tenders, and can handle loads up to 12 tons. To ensure the safety of visiting

divers, the *Golden Shadow* also has a recompression chamber capable of accommodating one casualty and one medic. Fully qualified medical staff members are present during all dive operations.

**Photograph of the stern of the *Golden Shadow* and smaller tenders used for SCUBA operations**



#### **The *Golden Eye***

The *Golden Eye* is a Cessna Caravan 208 Amphibious Aircraft embarked aboard the *Golden Shadow*. The aircraft has long endurance and can carry up to a maximum of 11 passengers and two pilots. It also carries the sophisticated hyperspectral sensor for conducting remote sensing operations over shallow water coral reef ecosystems.