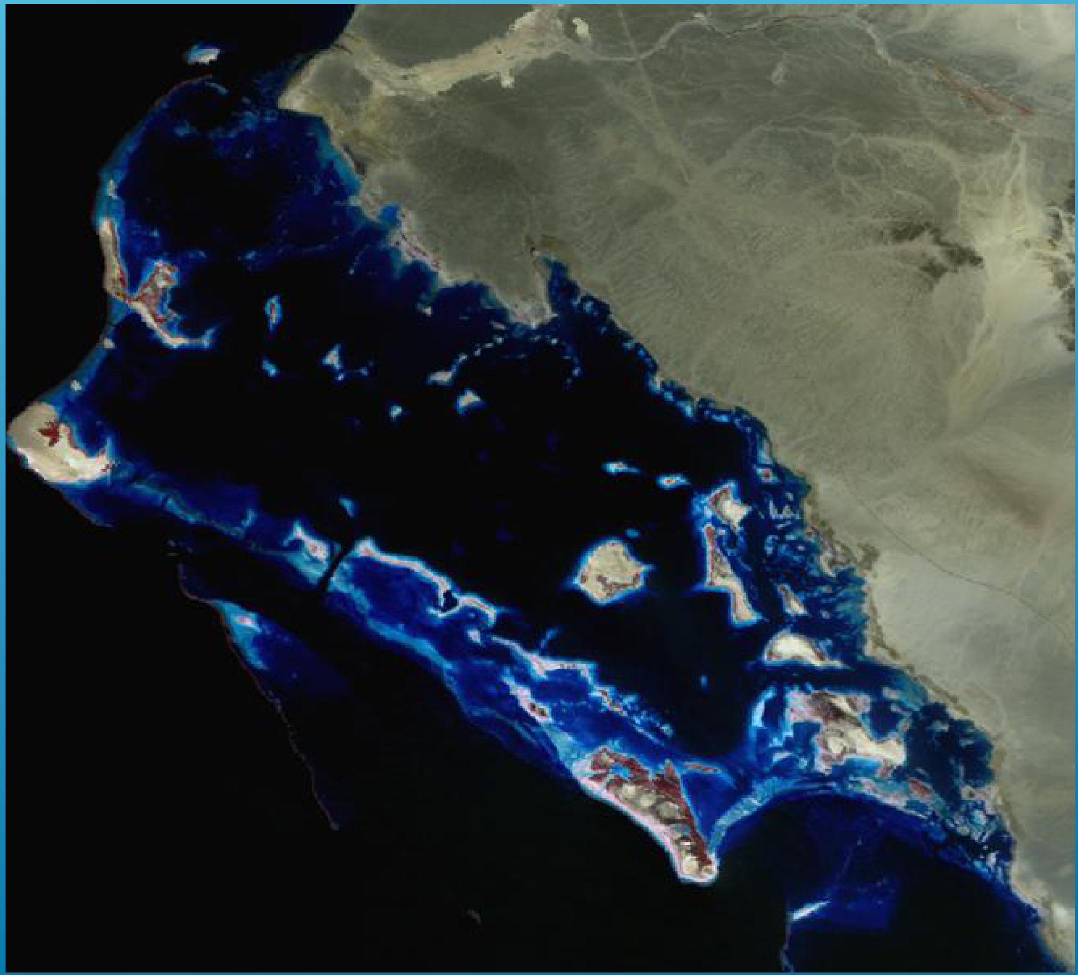
Coral Reef Atlas of Red Sea & Gulf of Aden



Space Applications Centre (ISRO), Ahmedabad
Govt. of India

Coral Reef Atlas of Red Sea & Gulf of Aden

Space Applications Centre

Indian Space Research Organisation

Govt. of India

Ahmedabad – 380 015

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सत्यमेव जयते

FOREWORD

Space Applications Centre (SAC) of Indian Space Research Organisation (ISRO) is engaged in designing and developing diverse satellite payloads and build space based applications for societal benefits. SAC has been in the forefront for realizing various kinds of Earth Observation (EO) payloads in both optical and microwave domains along with potential developments in their data applications. Indian Remote Sensing satellite suit of Resourcesat-1, -2 and -2A support, mapping and monitoring of various natural resources of our planet through unique three-tier imaging system by providing moderate to high resolution satellite images for improved natural resource management.

SAC has undertaken a challenging task of creating baseline data of Indian Ocean coral reefs, a fast depleting natural resource of our planet. Coral reef ecosystems are critically important resources to human population whose livelihood and economy depends on them. It is important to monitor the health of this critical ecosystem in an era of anthropocene when climate change in the form of warming and acidifying oceans, marine pollution and local anthropogenic pressures continuously test the resilience of the reefs.

Coral reefs of the Central Indian Ocean including India and neighbouring countries have been mapped using Resourcesat-1 data and have been published by SAC in 2010. The geospatial inventory of Indian coral reefs at 1:25000 scale is available in the public domain through our geoportal called VEDAS.

In continuity to this mission, SAC has created a baseline data on the coral reef habitats of the Red Sea and Gulf of Aden: the marginal northern seas of the Indian Ocean. This atlas documents the coral reef habitats of eight countries of Red Sea and Gulf of Aden coasts using Resourcesat-1 Advanced Wide Field Sensor (AWiFS) data of 2004-2009 timeframe.

The coral reefs of Egypt, Sudan, Eritrea, Jordan, Saudi Arabia, Yemen, Djibouti and Northern Somalia have been depicted at 1:25000 scale. This kind of satellite data based, systematic, detailed reef maps at country level are first-of-its kind and showcase the potential of AWiFS sensor in detection of moderate to large reef structures, their typology, reef-scale geomorphology and ecological categories. The geospatial, digital database summarized the surficial area of the coral reefs at country level from satellite data for the first time for this biogeographic region.

*I appreciate the effort of the project team in bringing out **"Coral Reef Atlas of Red Sea & Gulf of Aden" and document the baseline status of Red Sea and Gulf of Aden reefs as viewed by Resourcesat-1.** Hope this atlas has a meaningful utility to reef researchers, managers and planners and anyone who is interested to know about Red Sea and Gulf of Aden coral reefs.*

Tapan Misra
(तपन मिश्रा)
(Tapan Misra)

Date: May 3, 2018
Place: Ahmedabad

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PREFACE

Coral reefs and associated near-shore marine ecosystems like mangroves and seagrass beds represent world's most biodiverse ecosystems. They are home to significant proportion of known biological species on the earth. Coral reefs have high ecological and economic resource value to the coastal population of tropical nations. The vitality of this keystone ecosystem is presently at risk from global climate change as well as anthropogenic pressures.

Space-borne satellite remote sensing technology is the only means to map and monitor global coral reefs in a cost and time effective manner as compared to field-based observations. Optical remote sensing helps in characterizing coral reef types, mapping intra-reef geomorphological zones and ecological communities within a unit reef. Monitoring reef scale changes have become possible with a rich global legacy of satellite based remote sensing of coral reefs spanning over a period of little more than four decades.

Coral reef habitat maps and geospatial inventories are effective means of resource documentation, planning and management. Space Applications Centre (SAC) of Indian Space Research Organization (ISRO) has a rich legacy of satellite remote sensing and preparation of such geospatial inventories of various natural resources including coral reefs. In 2010, SAC, ISRO has published a coral reef atlas of the Central Indian Ocean covering the coastlines of India and neighbouring countries of Sri Lanka, Bangladesh, Maldives and British Indian Ocean Territory based on Resourcesat-1 satellite data. In continuation of our endeavour to map the coral reefs of Indian Ocean with Resourcesat-1 satellite, SAC, ISRO has made a sincere effort to create baseline data on Red Sea and Gulf of Aden coral reef habitats using Resourcesat-1 Advanced Wide Field Sensor (AWiFS) data pertaining to 2004-09 time frame.

Red Sea and Gulf of Aden are marginal seas of the Indian Ocean and represent a globally significant marine ecosystem. They include some of the northerly reef communities and are well renowned for their species richness including many endemic species. These coral reef habitats are depicted in 110 coral reef habitat maps covering the coastlines of eight countries.

This atlas will be a significant addition to the state of current knowledge on Red Sea and Gulf of Aden coral reefs, on their typology, reef-scale geomorphology, broad ecological categories and status of health based on an Indian satellite data. This database will also work as a systematic baseline for long term monitoring of the Red Sea and Gulf of Aden coral reef habitats. This atlas will be useful to reef researchers, reef managers and planners working in Red Sea and Gulf of Aden coral reefs.

I appreciate the efforts of the project team in completion of this voluminous task and bringing out this atlas. We will be very happy to receive feedback from the users of this atlas regarding the utility of this volume.

Date: May 3, 2018
Place: Ahmedabad

Raj Kumar
डॉ. राज कुमार (Dr. Raj Kumar)

Prelude

Coral reef ecosystems present a natural wonder on the planet earth. Reefs are marine landforms with biological origin and occupies the oligotrophic waters of the tropical seas. Coral reefs are essential habitats for a wide range of marine flora and fauna and harbour high biodiversity, to the extent of becoming marine equivalent of tropical rainforests. This keystone ecosystem is characterized by high biodiversity and productivity along with a superlative sensitivity towards environmental changes. As a near-shore ecosystem, coral reefs are ecologically and economically important to the coastal and hinterland population of the tropical maritime nations whose life, livelihood and higher interests depend on this eco-resource.

Since the past four decades, space-borne, satellite remote sensing is playing a key role in harnessing a plethora information of some of the remote areas on the earth along with continuous observation and monitoring of natural resources. Many of the coral reefs are remote, so far remain uncharted in existing hydrographic and shipping charts. Accordingly, there exists a knowledge gap about their geographic location, extent and other reef characteristics.

Space Applications Centre (SAC), ISRO has undertaken a challenging task of creating a baseline data of the Indian Ocean coral reefs using Indian Remote Sensing Satellite Resourcesat-1 operational since 2003. In 2010, SAC has published an atlas depicting the coral reefs of the Central Indian Ocean covering five countries: India, Sri Lanka, Bangladesh, Maldives and British Indian Ocean Territory based on Resourcesat-1 data of 2004-2007 timeframe.

This atlas is an addition to our endeavor to map the coral reef habitats of Red Sea and Gulf of Aden, the northern marginal seas of the Indian Ocean. This atlas charts a total of 110 coral reef habitat maps based on Resourcesat-1 Advanced Wide Field Sensor (AWiFS) data of 2004-09 timeframe. The coral reef habitat maps give information on the reef typology, reef geomorphology and the ecological communities discernible through satellite data. Coral reefs of eight countries sharing the territorial waters of Red Sea and Gulf of Aden have been mapped and discussed in detail along with information on country-level reef area and their overall health.

This geospatial inventory has been systematically created at 1:25000 scale for individual reef subsets for each of the eight country's coastlines and off-shore areas. This atlas comprehensively discusses individual reef geomorphology as viewed by the AWiFS sensor, mentions about the ecological communities of the reef, provides reef area statistics at map and country level and comment upon their overall health along with information on their threats. The country level reef area statistics is a new, revised estimate at 1:25000 scale based on satellite data.

I appreciate the effort of the project team to bring out this atlas. This kind of detailed coral reef atlas is a first-of-its kind and is expected to serve as a baseline data for anyone studying or managing the reefs of Red Sea and Gulf of Aden. It will be heartening to receive feedback and suggestions on this atlas from the user community for improvising our coral reef targeted work in future.

B.K.Bhattacharya

(Dr. Bimal K. Bhattacharya)

Document Control and Data Sheet

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8 Originating Unit	Agriculture & Land-Ecosystems Division (AED/BPSG/EPSA) Space Applications Centre (ISRO), Ahmedabad - 380015
9 Abstract	A geospatial inventory of coral reef habitats of Red Sea and Gulf of Aden has been created based on Resourcesat-1 AWiFS data of 2004-2009 period. The four-level classification system for mapping Indian Ocean coral reefs have been applied to map the coral reef habitats of Red Sea and Gulf of Aden. Coral reef habitats of Red Sea and Gulf of Aden have been mapped for one-time with AWiFS data. Each coral reef habitat map represents the reef–typology, intra-reef geomorphological zones and sub-zones and the benthic zones in form of digital annotations within the reef habitat boundary. The Red Sea and Gulf of Aden coral reef atlas comprises of 110 reef habitat maps covering the coastlines of 8 countries. Fringing reefs and its sub-types dominate both Red Sea and Gulf of Aden reef structures. Barrier reef, one true atoll and pseudo-atoll structures have also been found in Red Sea. In an overall analysis, the coral reefs of Red Sea and Gulf of Aden are in near-pristine condition barring the localized impacts of urban and industrial centers located on the coast. Coral reef habitats of Red Sea and Gulf of Aden occupy total area of 15020.66 and 621.11 sq km, respectively.
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We are thankful to Dr. Sushma Panigraphy, former Group Director, Agriculture, Biological Sciences and Hydrology Group (ABHG), SAC for her guidance and co-ordination of this project.

We thank Dr. Ajai, former Group Director, Marine & Earth Sciences Group (MESG), SAC for his guidance, co-ordination and fruitful discussions on this project. We express thanks to Dr. Anjali Bahuguna, former Scientist, SAC for initiating this project.

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Project Team

CONTENTS

Abbreviations & Acronyms

AOI	Area of Interest
AWiFS	Advanced Wide Field Sensor
BIOT	British Indian Ocean Territory
CIO	Central Indian Ocean
COTS	Crown-of-Thorns Starfish
ECT	Equatorial Crossing Time
EEAA	Egyptian Environmental Affairs Agency
EEPP	Egyptian Environmental Policy Programs
FCC	False Colour Composite
IRS-P6	Indian Remote Sensing Satellite-P6
ISRO	Indian Space Research Organisation
LGSOWG	Landsat Ground Station Operators Working Group
LISS	Linear Imaging Self-Scanning Sensors
LiDAR	Light Detection and Ranging
LUT	Look Up Table
MCRMP	Millennium Coral Reef Mapping Programme
MPA	Marine Protected Area
MRPA	Managed Resource Protected Area

NASA	National Areonautics and Space Agency
NCWCD	National Commission for Wildlife Conservation and Development
PA	Protected Area
PCo	Protected Coast
PERSGA	The Regional Organization for the Conservation of the Environment of the Red Sea & Gulf of Aden
RMSE	Root Mean Square Error
RSGA	Red Sea and Gulf of Aden
SAC	Space Applications Centre
SAR	Synthetic Aperture Radar
SCUBA	Self Contained Underwater Breathing Apparatus
SS	Super Structure
SST	Sea Surface Temperature
UNEP	United Nations Environment Programme
UTM	Universal Transverse Mercator
WCMC	World Conservation Monitoring Centre

Chapter 1

Introduction

Tracing the tropical coastlines where the blue sea turns into cyan or turquoise as distinctly visible from space, there starts the story of a living coast. These coasts are known as coral reefs and have a biological origin on earth unlike any other sedimentary or rocky coasts. A walk or a dive into these emerald waters, the magic of coral reef magnifies – a colourful living ecosystem under the water! Corals and some calcifying algae are the main architects of reefs. These tiny marine organisms are members of Cnidaria phylum in the animal kingdom: the same group as that of jelly fish and sea anemones. A single coral appears in a centimeter scale, tube like body structure known as polyp. Each polyp is attached to a cup-like calcium carbonate skeleton outside their body. Many corals together give shape to their colonies. Coral colonies appear in different colours and shapes. Over thousands of years, coral colonies together assume a massive, three-dimensional, wave-resistant structure on the sea-floor which grows upward and give rise to a unique landform: the reef. Coral reefs constitute one-third of the tropical coastlines.

Corals are found across the global oceans including cold and deep water corals. However, the reef-building or hermatypic corals commonly colonize the tropical oceans within the limits of 30° North and South latitudes where the seawater temperature ranges between 18° and 30° Celcius, salinity varies between 32 and 40 parts per thousand and sea-floor substrate is hard and silt-free.

According to the World Atlas of Coral Reefs by Spalding *et al.* (2001), shallow-water coral reefs cover an estimated area of 2, 84, 300 sq km in world's oceans. Seventy-two percent of the total reef area is found in the Indo-Pacific region with Pacific Ocean sharing the major 40% while South-East Asia shares the rest 32%. Indian Ocean shares another significant proportion of 19% while the rest is in Caribbean and the Atlantic regions.

Occupying even less than 1% area of global oceans, coral reefs provide critical marine habitat to approximately 25% of marine organisms, including some of the rare avifauna (Buddemeier *et al.* 2004). Coral reef ecosystems are known as rainforests of the seas due to their high biodiversity and ecological productivity. They are the largest biogenic source of calcium carbonate and are carbon sinks in the oceans. They form a natural protective barrier to the coastlines against marine erosion, storm surges, tsunamis, flooding and help in formation and protection of associated ecosystems like seagrass beds and mangroves. Coral reefs harbor potential economic interests in terms of fishing, tourism, marine sports, constructional activities and extraction of bio-geochemicals having medicinal importance (Burke *et al.* 2011). Coral reefs have drawn attention as an eco-geomorphic indicator of earth's climate and eustatic history (Pandolfi 2011).

This unique natural heritage stands as a fragile empire in today's tropical oceans. Coral reefs are fighting a fierce battle to survive with a good health in future. Their battle for life starts within and then slowly becomes bigger, getting entangled with human beings and even the warming planet! At organism scale, corals need to protect themselves against several diseases and at community level corals fight various natural predators like Crown-of-Thorns (COTS) sea star, Parrot fishes or other organisms like zoanthids or even invasive algae like Kappaphycus who limit their habitat space. These ecosystem level disturbances result due to long-term effects of sea-water pollution, eutrophication, sedimentation and various other factors which affect the quality of seawater. Coral reefs face serious anthropogenic threats by destructive fishing practices, overfishing, tourism, coastal developments and commercial trades of souvenirs (Burke *et al.* 2011).

However, the most serious threat to coral reefs is the twin evils of warming and acidic oceans. When the sea-water temperature increases abnormally, the corals lose their colours and turn pale and white. This discoloration of coral tissues in the event of heat-stress is known as coral bleaching. The more the oceans absorb greenhouse gases from the earth's atmosphere, the seawater becomes more acidic and affects the skeletal health of corals and other calcifying organisms. Storms and cyclones, tsunami, earthquake and tectonic uplift, sea-level rise are other potential natural threats to coral reefs.

Field-based or *in situ* study of this natural wonder calls for snorkeling and SCUBA diving into seas and recording underwater observations. These methods are quite costly and time-consuming. Aerial photography and space imaging have aided to a considerable extent to extract information about coral reefs of the world. A synoptic image of this shallow water target from space has become the most powerful tool to harness a plethora of information – right from their detection to zoning of these marine habitats into different reef categories.

Geospatial inventories of coral reef ecosystems are major inputs for coral reef conservation and management action plans. At the global scale, two major initiatives have significantly contributed towards the current knowledge-base on world's coral reefs: the World Atlas of Coral Reefs published by United Nations Environment Programme (UNEP)'s World Conservation Monitoring Centre (WCMC) in 2001 and NASA's Millennium Coral Reef Mapping Project (MCRMP) launched in 2001 (Andrefouët *et al.* 2006). The UNEP WCMC project provided the first global overview of coral reef location, distribution and extent based on a digital coral reef inventory prepared at 1: 1000000 scale from the available US Defense Mapping Agency Operational Navigational Chart Series. As on date, NASA's MCRMP presents a global archive of Landsat-7 ETM+ satellite image based classified coral reef maps either as GIS compatible, validated vector data products or as unvalidated raster files.

As part of world coral reefs, Indian Ocean reefs showed signs of change after the episodic events of Mass Coral Bleaching in 1997-1998 and the Indian Ocean tsunami of 2004. In order to bridge the data gap on the country-level status of these coral reefs, Space Applications Centre (SAC) of Indian Space Research Organisation (ISRO) undertook a project to map the coral reef habitats of Indian Ocean at 1: 25000 scale, under the Earth Observations and Applications Mission (EOAM) Programme. SAC has already accomplished the mapping of Central Indian Ocean (CIO) coral reefs covering the coastlines of five Indian Ocean countries: India, Sri Lanka, Bangladesh, Maldives and British Indian Ocean Territory (BIOT) using Resourcesat-1 satellite data of 2004-2007 timeframe (Navalgund *et al.* 2010; Bahuguna *et al.* 2013). Coral Reef Atlas of the World, Vol.1 Central Indian Ocean is the first of the atlas series which charts 182 coral reef habitat maps along with their source satellite images for these five countries. This atlas depicts the Faros Atoll structures of Maldivian reefs as the largest pristine reef area in CIO; followed by BIOT while the continental, fringing reefs of India, Sri Lanka and Bangladesh are slowly degrading (Navalgund *et al.* 2010).

The present atlas is the second in the series showing the coral reefs of Red Sea and Gulf of Aden: a globally significant marine ecosystem. The coral reefs of Red Sea and Gulf of Aden have been mapped with Resourcesat-1 AWiFS data of 2004-2009 timeframe. Coral reefs of eight countries: Egypt, Sudan, Eritrea, Jordan, Saudi Arabia, Yemen, Djibouti and Somalia have been mapped and presented in this atlas.

Red Sea & Gulf of Aden

As part of north western Indian Ocean, Red Sea and Gulf of Aden (hereafter referred as RSGA) represent a globally significant marine ecosystem. RSGA region (as shown in Figure 2.1) is renowned for its unique marine and coastal environments with high species richness including many endemic species (Kotb *et al.* 2004, 2008). This region has been considered to be the most biologically diverse coral reef region even though they are much away and isolated from the South-East Asian reefs: the current center of Indo-Pacific coral reef diversity (Spalding *et al.* 2001). RSGA include some of the most northerly coral reef communities of the world. These reefs have evolved over a relatively short but unique geological history and have adapted to harsh climatic extremes in the present. Despite climatic extremes, natural stresses and human pressures, RSGA coral reefs maintain an overall healthy condition with more than 50% average live coral cover (Kotb *et al.* 2008).

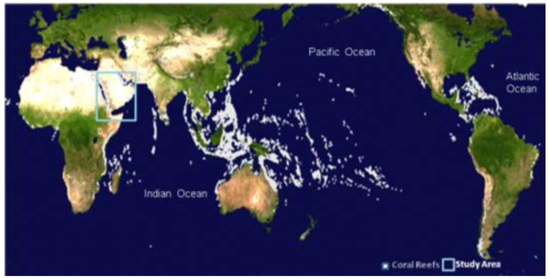


Figure 2.1 Location of Study Area: Red Sea and Gulf of Aden in the world

Red Sea

The Red Sea is a NW-SE oriented, narrow, elongated water body which extends over a length of 2270 km from 30° N in Gulf of Suez to 13° N at Bab-el-Mandeb where it joins the Gulf of Aden through which it connects to the Indian Ocean. The African countries of Egypt, Sudan, Eritrea and Djibouti share the western coast of Red Sea while Saudi Arabia and Yemen mark its eastern coast. Israel and Jordan too marginally share Red Sea's north-eastern coast defining the Gulf of Aqaba. In its northern part, Red Sea divulges into two smaller, narrow, elongated gulfs: Gulf of Suez and Gulf of Aqaba.

Geologically Red Sea is an incipient ocean defined by a characteristic basaltic sea-floor with a spreading rift system separating the African and the Arabian plate since the last seventy million years, i.e. from the late Cretaceous period (Behairy *et al.* 1992; Spalding *et al.* 2001). This young ocean has witnessed major environmental upheavals in a relatively short span of geological time and has history of connections and closures with proto-Mediterranean Sea and the Indian Ocean at different times (Medio *et al.* 2000). During the late Miocene and early Pliocene period, approximately five million years ago, the rifting process recommenced with a closure with the proto-Mediterranean Sea. A connection with the Indian Ocean was established which allowed the colonization of Indo-Pacific fauna and growth of coral reefs in shallow waters (Medio *et al.* 2000). Subsequently during an event of Pleistocene glaciation, Red Sea got completely isolated from the Indian Ocean with strong hypersaline conditions decimating the tropical fauna. Reconnection with the Indian Ocean probably occurred some seventeen thousand years ago (Spalding *et al.* 2001). Indian Ocean fauna reappeared following the Holocene transgression and approximately five thousand years ago, Red sea reached its present-day sea level. Thus, the present Red Sea reefs are very young which have recolonized and grown over older Pleistocene reefs (Medio *et al.* 2000; Spalding *et al.* 2001). Raised fossil reefs found on the Red Sea shores provide clear testimony to tectonic uplifts and sea-level changes of the past (Medio *et al.*2000) The Red Sea stretches over a length of 2000 km, has a width of 350 km and a maximum depth of 2800 m while its average depth is around 450 m (Shaked and Genin 2011). This is because 40% of the Red Sea is shallower than 100 m. Three main bathymetric regions are recognized in the Red Sea (Medio *et al.* 2000). These three regions include i) the shallow sedimentary plains (depth ~ 100 m), ii) the coastal shelves containing the coral reef zones (300-600 m) and iii) the central deep trough (600-2000 m). Red Sea is connected to the Indian Ocean through the narrow and shallow sill of Bab-el-Mandeb (29 km wide and 137 m deep; Shaked and Genin 2011). The submarine topography of Red Sea is irregular and is well exemplified by a series of submarine pinnacles rising from the ocean floor to the surface (Medio *et al.* 2000). The western margin of the Red Sea is steep with a narrow shelf and deep pull-apart basins with an oceanic crust while the eastern margin is relatively gentle and floored by attenuated continental crust (Shaked and Genin 2011).

Gulf of Aqaba & Gulf of Suez

The Gulf of Aqaba at the northern end is a similar deep basin which is separated from the Red Sea by a relatively shallow sill at the Strait of Tiran. The Gulf of Aqaba is a strike-slip rift system as the Arabian peninsula moved apart from the Sinai peninsula in a parallel direction. Gulf of Aqaba is 180 km long, 25 km wide and has an average depth of 900 m (Shaked and Genin 2011). The maximum depth reaches nearly 1850 m. Contrastingly, the Gulf of Suez is an abandoned, shallow spreading rift system, 320 km long, 70 km wide with an average depth of 30 m (Spalding *et al.* 2001; Shaked and Genin 2011). Gulf of Suez has a relatively flat sea floor with depths less than 90 to 100 m. At the mouth of the gulf, the depth abruptly increases to 300 m. The water circulation of the whole Red Sea is controlled at this steep shelf (Medio *et al.* 2000).

Climatic Conditions

Red Sea reefs are subjected to harsh climatic extremes including high and low temperatures and high levels of insolation. Mean Sea Surface Temperatures (SST) in the Red Sea vary from north to south. Low SSTs may drop to below 10°C in the Gulf of Suez while high values of SST ranging from 36° C to 38° C have been recorded in the southern Red Sea (Medio *et al.* 2000). Temperature extremes mostly occur in the inshore waters. Surface salinity typically increases from 36.5 parts per thousand (ppt) in the southern Red Sea to 40.5 ppt in the extreme north. In the shallow Gulf of Suez surface salinity increases to 42.5 ppt mainly through evaporation but also possibly due to the addition from ancient sub-surface salt deposits (Medio *et al.* 2000). Kleypas *et al.* 1999 have classified southern Red Sea as 'high temperature reef' while the central and southern Red Sea fall under 'high salinity reefs'. Water masses in the northern and the central Red Sea have low nutrient concentrations. During the summer, the southern Red Sea get enriched with nutrients and particulate organic matter through the inflow of Gulf of Aden water. Nutrient levels decreases from south to the north of Red Sea.

Red Sea, in general, experiences semi-diurnal tides of small amplitudes (Medio *et al.* 2000). Throughout the Red Sea, high temperatures coupled with the effects of coastal mountain ranges lead to localized onshore and offshore winds caused by differential heating and cooling of the mountains and the sea. These winds systems can temporarily overwhelm the prevailing wind effect which causes marked, localized rises and falls of sea level, exposing shallow biota to strong desiccation. Frequent flash floods on the Red Sea coast lead to the development of alluvial fans which have important consequences towards local coral reef survival and formation.

Gulf of Aden

The Gulf of Aden is less studied and documented as compared to that of Red Sea. Gulf of Aden occurs within the geographical limits of 11°49' N to 17°59' N latitudes and 38°34' E to 53°06' E longitudes. The Gulf of Aden is a wide, semi-enclosed sea bordered by Djibouti in the west, Yemen in the north and Somalia and the Yemeni islands of Socotra, Abd al Kiri, Darsa and Semha in the south. To the east, Gulf of Aden joins the Arabian Sea.

The Gulf of Aden is of similar tectonic origin to that of Red Sea. It is formed by spreading of the Sheba ridge which runs down the center of this basin and out into the Arabian Sea. In Gulf of Aden, coastlines are mountainous onshore, while offshore bathymetry is quite steep. The central part of the Gulf is more than 2000 m deep.

One critical oceanographic feature of the Gulf of Aden is seasonally reversing monsoon winds which operate over the entire Indian Ocean (Spalding *et al.* 2001). The Gulf of Aden is influenced by the seasonal upwelling of cool, nutrient rich waters from the Indian Ocean during summer which limits coral reef development and promotes planktonic and large algal bloom (Pilcher and Alsuhaibany 2000). Seasonal variability exists in the SST in this basin. SST is highest (31°-32°C) during May end and in the beginning of June while lowest SST is observed during July-August (29°-30°C), the degree of cooling depends on the strength of summer monsoon (Al Saafani 2008). The salinity in Gulf of Aden at 10 m depth varies from 36.3 ppt along the eastern Somalia coast to as high as 37.3 ppt in the center of the gulf. Gulf of Aden has narrow fringing reefs which are approximately few ten meters wide. Southern mouth of the Gulf has high quality shallow water reefs.

Chapter 3

Data Used

Coral reefs of Red Sea and Gulf of Aden have been mapped using Resourcesat-1 (Indian Remote Sensing Satellite: IRS-P6) satellite data. Resourcesat-1 satellite represents a unique earth imaging capability through its three tier imaging system providing high spatial and temporal resolution data from a single platform. This tenth satellite of IRS series has been operational since 17th October, 2003 with three on-board sensors: an Advanced Wide Field Sensor (AWiFS) and two Linear Imaging Self-Scanning Sensors (LISS-III and LISS-IV). AWiFS and LISS-III cameras are shown in Figure 3.1. The satellite is placed on a near-polar, sun-synchronous, low earth orbit at an altitude of 817 km with an inclination of 98.8°. Its Equatorial Crossing Time (ECT) is 10: 30 hrs. The specifications of Resourcesat-1 sensors are given in Table 3.1.

Figure 3.1 Resourcesat-1 AWiFS (left) and LISS III (right) Cameras

In order to map the vast expanse of coral reef areas of Red Sea and Gulf of Aden (approximately 18,120 sq km; Spalding *et al.* 2001), the medium-resolution AWiFS data have been preferred over LISS-III and LISS-IV data. AWiFS is a wide-angle (Field of View = ± 25°), medium-resolution camera with a swath of 740 km. This pushbroom instrument operates in four spectral bands which are identical to LISS-III sensor. The wide swath coverage enables AWiFS sensor to provide a five-day repetivity.

Table 3.1 Specifications of Resourcesat-1 AWiFS and LISS-III Sensors

Sensors	**Swath (km)**	**Spatial Resolution (m)**	**Spectral Bands (nm)**	**Radiometric Resolution (bits)**	**Temporal Resolution (days)**
AWiFS	740	56	G: 520-590 R: 620-680 N:770-860 S: 1550-1700	10	5
LISS-III	140	23.5	G: 520-590 R: 620-680 N: 770-860 S:1550- 1700	7	24

(Note: G: Green; R: Red; N: NIR and S: SWIR Channels of the sensors) (Source: NRSA 2003; Pandya *et al.* 2013)

Red Sea and Gulf of Aden coral reefs presented in this volume have been mapped for one-time with AWiFS data pertaining to 2004 to 2009 period. Archived AWiFS and LISS-III images available online at www.nrsc.gov.in were carefully selected to obtain cloud-free and low tide exposures of reefs of these two basins. Twenty-two AWiFS scenes and four LISS-III scenes were used for further analyses. Finally, eighteen AWiFS scenes and one LISS-III scene were selected to map the coral reefs. The LISS-III data has been used as a special case to illustrate the enhanced sensor capability in detecting additional features or details from the same reef viewed by AWIFS sensor on the same date.

Resourcesat-1 AWiFS and LISS III data coverage used for mapping Red Sea and Gulf of Aden reefs is shown in Figure 3.2 and details of these satellite data are given in Table 3.2.

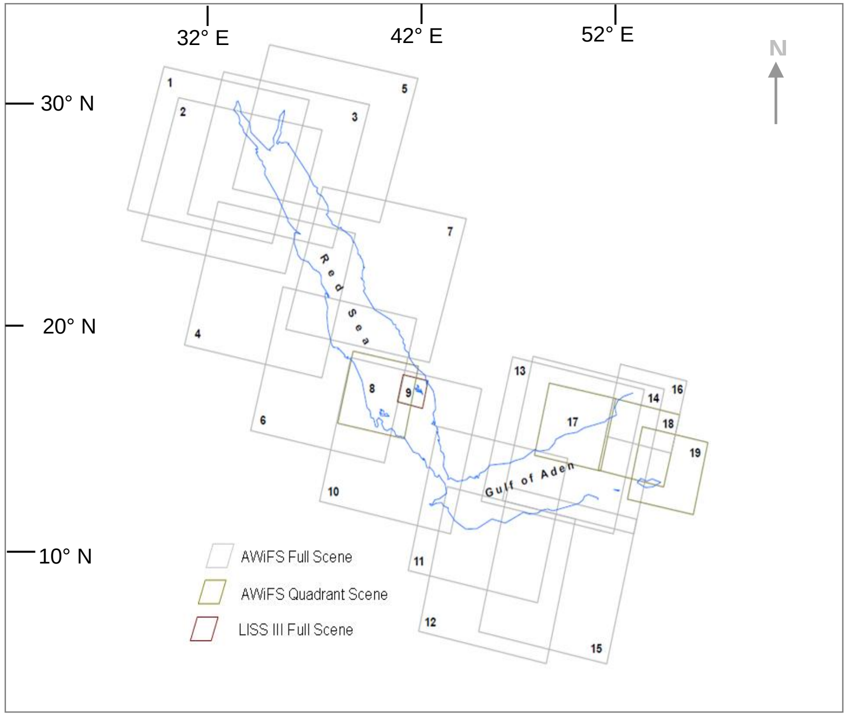


Figure 3.2 Resourcesat-1 AWiFS and LISS III Data Coverage for mapping Coral Reefs of Red Sea and Gulf of Aden

Table 3.2 Details of Resourcesat-1 Data used for mapping Red Sea and Gulf of Aden Coral Reefs

Sr. No.	Sensor	Scene Type	Path	Row	Date of Pass	Regional Coverage
1	AWiFS	Full Scene	53	51	8th June, 2007	Red Sea (Egypt, Israel, Jordan, Saudi Arabia)
2	AWiFS	Full Scene	54	53	13th February, 2007	Red Sea (Egypt, Israel, Jordan, Saudi Arabia)
3	AWiFS	Full Scene	56	52	19th March, 2007	Red Sea (Egypt, Israel, Jordan, Saudi Arabia)
4	AWiFS	Full Scene	57	57	25th August, 2005	Red Sea (Egypt, Jordan, Saudi Arabia)
5	AWiFS	Full Scene	58	51	16th January, 2007	Red Sea (Egypt, Israel, Jordan, Saudi Arabia)
6	AWiFS	Full Scene	61	60	22nd September, 2008	Red Sea (Sudan, Saudi Arabia)
7	AWiFS	Full Scene	62	57	2nd August, 2005	Red Sea (Sudan, Saudi Arabia)
8	AWiFS	Quadrant	65	60	25th February, 2006	Red Sea (Saudi Arabia. Yemen)
9	*LISS-III*	*Full Scene*	*65*	*61*	*25th February, 2006*	*Red Sea (Saudi Arabia. Yemen)*
10	AWiFS	Full Scene	65	63	12th October, 2008	Red Sea (Eritrea, Saudi Arabia, Yemen) and Gulf of Aden (Djibouti, Somalia)
11	AWiFS	Full Scene	70	65	12th November, 2007	Gulf of Aden (Yemen, Djibouti, Somalia)

Sr. No.	Sensor	Scene Type	Path	Row	Date of Pass	Regional Coverage
12	AWiFS	Full Scene	71	68	31st August, 2008	Gulf of Aden (Somalia)
13	AWiFS	Full Scene	73	63	8th May, 2009	Gulf of Aden (Yemen, Somalia)
14	AWiFS	Full Scene	74	63	22nd August, 2008	Gulf of Aden (Yemen, Somalia)
15	AWiFS	Full Scene	74	68	22nd August, 2008	Gulf of Aden (Somalia)
16	AWiFS	Quadrant Scene-D	75	60	21st January, 2004	Gulf of Aden (Yemen)
17	AWiFS	Quadrant Scene- A	75	64	16th April, 2006	Gulf of Aden (Yemen)
18	AWiFS	Quadrant Scene-B	75	64	16th April, 2006	Gulf of Aden (Yemen)
19	AWiFS	Quadrant Scene-C	80	63	24th March, 2006	Gulf of Aden (Yemen)

Classification System: The Theoretical Basis

One of the most successful application areas of space-borne optical remote sensing is coral reef habitat mapping. A synoptic view of a coral reef from space helps in visualization of this underwater target in a two-dimensional perspective. Globally, satellite imageries have become the most popular, cost-effective tool to study coral reefs as the next best alternative to underwater field surveys through SCUBA dives and snorkeling. The common principle in reef remote sensing is that coral reefs, as optically shallow water targets on planet earth, modify the incident light (from sun) in a different manner than its adjacent habitats like open ocean, beaches, seagrass beds, mangroves, etc. The reflected light (or the backscattered portion of the sun's electromagnetic spectrum) modified by coral reef is captured by the space-borne sensors and helps in distinguishing coral reef signatures from adjacent ocean and/or coastal habitats.

The field of coral reef habitat mapping based on satellite imageries has been continually enriched with technological advancements in optical (VNIR) sensor designs and refined reef mapping techniques. Till date, systematic visual interpretations of aerial photographs and fine-to-moderate spatial resolution satellite imageries remain one of the most successful and widely validated reef mapping techniques (Phinn *et al.* 2012). In common parlance, the term 'habitat' means the natural home or environment of an organism. However, in the context of *habitat mapping*, the term *habitat* embodies species assemblages and associated substrata (Mumby *et al.* 1997). The classic approaches perceive coral reefs as landforms of biological origin and accordingly define them with respect to two major attributes: geomorphological structure and benthic cover. These attributes are chosen because they exert a combined influence on the spectra recorded by a remote sensor and can be interpreted realistically within a remotely sensed image (Mumby and Harborne 1999). The spatial and spectral resolutions of these electro-optical sensors determine the level of habitat detail discernible from space. The level of habitat detail discriminated and mapped by the remote sensing system is termed as *descriptive resolution* (Mumby *et al.* 1997; Mumby and Harborne 1999). Descriptive resolution is hierarchical in nature. The hierarchical structure of classification scheme generally takes care of different user needs, technical expertise and remote sensing data sources.

A comprehensive, hierarchical, eco-geomorphological classification system has been developed at Space Applications Centre, ISRO to map the coral reef habitats of Central Indian Ocean (CIO) from Resourcesat-1 data (Navalgund *et al.* 2010). This classification system has its roots in earlier classification systems developed at Space Applications Centre to map Indian coral reefs at different scales (Nayak and Bahuguna 1997; Nayak *et al.* 2003). Reviewing global literature highlighting reef classification schemes (Hopley 1982; Holthus and Maragos 1995; Green *et al.* 1996, 2000; Mumby and Harborne 1999) from various parts of the world, the classification system developed for Indian coral reefs were refined for CIO reef habitats. The CIO reef classification system comprises of a four-level hierarchy where the first level conforms to reef typology, second and the third level describe intra-reef geomorphic zones and sub-zones and the fourth level enumerates benthic zones or the ecological categories. The ecological components are limited to assemblages of plants (algae, seagrass) and animals (live corals) and the inhabited substrata. An interpretation key has been generated for identification and mapping of reef features (as defined in this classification scheme) based on their optical properties and geomorphological attributes. Detailed discussion on CIO reef habitat classification scheme (Bahuguna *et al.* 2013), definitions of the coral reef classes and the interpretation key can be referred from the first volume of this atlas series (Navalgund *et al.,* 2010).

For mapping the coral reef habitats of Red Sea and Gulf of Aden, the CIO reef classification scheme has been further refined with reference to reef features discernible on Resourcesat-1 AWiFS data viewing this region. Additional literatures on reef classification system (Kuchler 1986; Andrèfouët 2003; Jameson *et al.* 2003 and Hopley 2011) have been reviewed for this purpose. This refined classification system follows a four-level hierarchy where one second order class or geomorphological zone, five third order classes or geomorhological sub-zones and one ecological category have been newly introduced. Five, tsunami-related (in reference to Indian Ocean Tsunami of 26th December, 2004) third-level classes have not been considered for Red Sea and Gulf of Aden reefs.

The classification system developed for mapping Red Sea and Gulf of Aden reefs from Resourcesat-1 AWiFS data is given as Table 4.1.

Table 4.1 Classification System for Red Sea and Gulf of Aden Coral Reef Habitat Mapping

Level I: Reef Type	**Level II: Geomorphological Zone**	**Level III: Geomorphological Sub-zone**	**Level IV: Benthic Zone**
Fringing/Platform/ Patch/Pinnacle Reef			
	Reef Front/Windward Reef Front*		
		Reef Edge*	
		Reef Slope*	
		Spur and Groove*	
		Outer Rim*	
		Channel*	
		Moat*	Live Corals, Algae*
		Reef Crest*	
		Algal Ridge/ Algal Pavement*	Algae*
	Reef Flat	Outer Reef Flat*	Coral Zone/**Aligned Coral Zone**/Mixed Coral Zone/Live Corals, Algae*
		Inner Reef Flat*	Algae, Seagrass, Live Corals*
		Sanded Reef Flat*	Algae, Seagrass, Dune Vegetation*
		Muddy Reef Flat*	Algae*
		Sandy Muddy Reef Flat*	Algae, Seagrass*
		Boulder Zone*	Algae*
		Rubble Zone*	Algae*
		Sand Cay*	
		Sandy Ridge*	Algae*
		Reef Flat Moat*	
		Pool*	
		Shallow Tidal Pool*	Algae*
		Blue Hole*	
		Coral Knolls*	
		Rocks*	

Level I: Reef Type	**Level II: Geomorphological Zone**	**Level III: Geomorphological Sub-zone**	**Level IV: Benthic Zone**
	Coastal Lagoon*		
	Coral Head*		Live Coral*
	Submerged Reef*		
	Coralline Shelf*		
Barrier Reef/ Ribbon Reef			
Atoll/Faros Atoll			
	Lagoon**		
		Shallow Lagoon (Depth: 1-5 meters)**	
		Lagoon of Intermediate Depth (Depth: 5-20 meters)**	
		Deep Lagoon (Depth >20 meters)**	
		Lagoonal Reef Slope**	
		Lagoonal Patch Reef**	
	Lagoonlet**		
Associated Classes			
	Spit*		
	Beach*		Dune Vegetation*
	Island*		
	Mudflat		
		Sub-tidal Mudflat	
		Inter-tidal Mudflat	
		High-tidal Mudflat	
	Mangrove		
	Jetty		

*: The geomorphological zones, sub-zones and benthic zones marked with asterisk (*) are common to all types of reefs.
**: The geomorphological zones, sub-zones marked with double asterisk (**) are common to Barrier and Atoll types of reefs.
Newly introduced classes appear in **bold font**.

Definitions and characteristics of the newly introduced classes are described below.

Second Level Class or Geomorphological Zone Category:

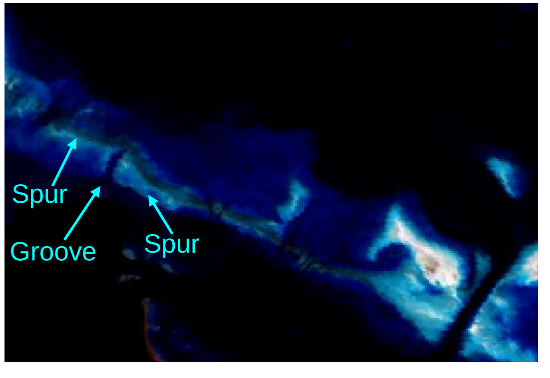
Coastal Lagoon:

Ideally a coral reef lagoon refers to the body of water that lies within an atoll (annular) reef or within a barrier reef. The term coastal lagoon refers to a shallow stretch of seawater, near or communicating with the sea, partly or completely separated from it by a low, narrow, elongated strip of land, such as a reef, barrier, barrier island, sand bank or spit. It often extends roughly parallel to the coast.

Third Level Class or Geomorphological Sub-zone Categories:

Spur and Groove:

Spur and groove form a comb-tooth structure common to many reef fronts. Best developed on the windward reef front, the structure consists of elongate channels or grooves, a few meters wide and deep, separated by seaward extending coral ridges or spurs. Grooves are commonly floored with coral rubble or carbonate sand while actively accreting spurs are covered with living corals. Where accretion has ceased spurs harbour associated benthic organisms.

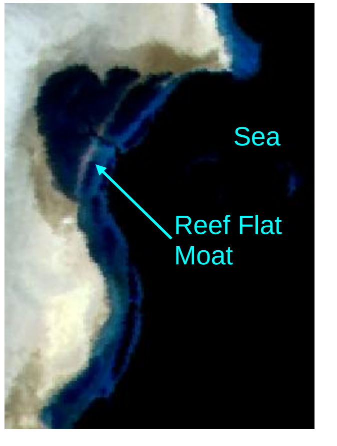


Channel:

Channels are linear, narrow, inshore extensions of reef front groves which act as conduits of seawater transport between the open sea and reefs (reef flats or lagoons).

Reef Flat Moat:

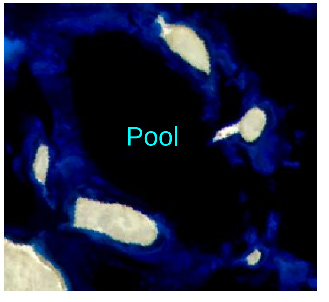
Reef flat moats are shallow, linear depressions within the reef flat where water is held during the low tides. Moats occur on most reef flats but are best developed where the tidal range is large, algal rims thrive, corals grow and storm frequency provide enough rubble and depositional events. Moats form when ebb-tide drainage is



impeded behind biologically constructed or sedimentary structures. The former includes reef crest, algal rims and algal terracettes. Sedimentary structures include storm ridges or ramparts (commonly of coral shingle) and minor ridges of sand and gravel. Moats confined by sedimentary structures are less permanent in nature. Moats are important habitats which support a diverse reef flora and fauna above the low tide level. Moderately sized and cemented/encrusted moats are physically more stable and typically harbour the most diverse communities, especially where moat water is flushed well daily. Small shallow moats tend to be less permanent and are vulnerable to biologically limiting thermal and salinity extremes.

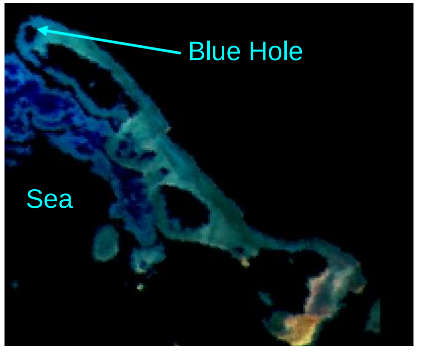
Pool:

The term pool generally refers to shallow depressions on reef flat filled with water in an ebbing tide condition. However, for Red Sea and Gulf of Aden, the term pool has been used for the deep oceanic depressions which appear as circular to elliptical structures with smooth to irregular margins in plan and in deep blue tone in standard AWiFS False Colour Composites (FCC).



Blue Hole:

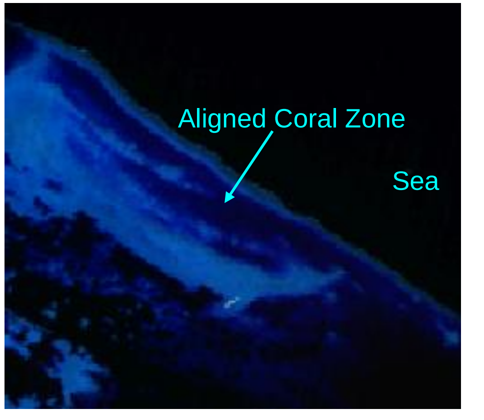
The term Blue Hole is used for a drowned sink hole in Bahamas. Blue holes are underwater karst caves; when found in shallow water, they have striking features because of the strong color contrast between the dark blue cave opening and the light blue surrounding seafloor. Blue hole is cylindrical in shape and appear circular in plan. Blue holes may have irregular shapes.



Fourth Level Class or Benthic Zone Categories:

Aligned Coral Zone:

Aligned coral zone is a zone of dense, parallel colonies separated by sandy channels. The aligned corals grow normal (perpendicular) to refracted wave fronts. The linearity of aligned coral zone is identical to that of spur and groove systems of the adjacent reef front



Methodology

Red Sea and Gulf of Aden coral reef habitat maps have been prepared following an improvised version of the methodology designed for Central Indian Ocean (CIO) reef habitat mapping. The earlier methodology adopted for CIO reef habitat mapping employed on-screen visual analysis and interpretation of Resourcesat-1 (IRS P6) multi-spectral data mainly from LISS sensors. For Red Sea and Gulf of Aden basins, coral reef habitat maps have been generated on GIS platform using Resourcesat-1 Advanced Wide Field Sensor's (AWiFS) standard FCCs as source data. Resourcesat-1 AWiFS data pertaining to 2004 to 2009 period (eighteen scenes) and LISS III data of 2006 (one scene) have been used for spatial inventory of Red Sea and Gulf of Aden coral reefs. Cloud-free images with maximum reef exposures have been preferred for one-time mapping of these reefs at eco-geomorphological level.

The methodology consists of five major steps viz. data pre-processing; subset interpretation; reef habitat map preparation, GIS database creation and reef area computation. These steps are discussed here in detail.

I. Pre-processing of Satellite Data:

Radiometrically and geometrically corrected Level 2 Standard digital data products of AWiFS and LISS III available in Landsat Ground Station Operators Working Group (LGSOWG) or Super Structure (SS) format have been used for this project. The original binary data were obtained in image formats using ERDAS IMAGINE image processing software. The four individual band layers were stacked for preparation of AWiFS and LISS III composites. Individual scenes were displayed as Standard False Colour Composites or FCCs by projecting the Green, Red and NIR spectral channels to the Blue, Green and Red colour guns of the software. Each individual scene has been geo-referenced with the help of ancillary information using the "Geometric correction" utility of the software. The header file is referred to get the scene co-ordinates: i.e. the scene center and the four respective corners of the scene as per the guidelines of the accompanying super.doc which lists the information structure in the entire header file. Standard geometric correction algorithm (first order polynomial model) has been used to incorporate the latitude-longitude information in the image data sets. The images were referenced to Geographic (Lat/Lon) projection and WGS 84 as spheroid and datum. Due care has been taken to ensure geo-referencing of the images with Root Mean Square Error (RMSE) to be less than 0.001. In order to increase the relative positional accuracy of the individual scenes within the spatial frame, scenes have been re-georeferenced wherever necessary on image-to-image basis for creation of seamless mosaics. Scene mosaics have been used for preparation of basin-scale (i.e. either Red Sea or Gulf Aden) images and for complete coastline coverage of each country belonging to Red Sea and Gulf of Aden. Basin-scale and individual country level index sheets (location guide to reef habitat maps) have been generated based on these image mosaics.

Each country's coastline has been visually analyzed for assessment of reef feature exposure with reference to published coarse resolution coral reef maps (Spalding et al. 2001; NOAA maps available at http://www.coral.noaa.gov/reefmaps/volume...; online, digital reef GIS maps from www.reefbase.gov site, etc.). Continental Shelf Boundary maps (available in the public domain from: http://www.state.gov/e/oes/ocns/opa/&/6065.html) compiled from U.S. Navy Surveys, U.S. Army Map Service Series and British Admiralty Charts have been used as a supplementary reference for locating coral reefs (as detected on AWiFS data) within territorial waters of the neighbouring countries.

For each country, the coastline has been broken into a continuous series of smaller segments or *subsets* based on a decision rule of natural "headland and bay" configuration of coastlines or considering the natural breaks in coastline fringing reefs. In case of off-shore reefs of a country, the entire group of reef-islands or reefs lying in proximity have been extracted as an individual subset. This segmentation approach has been adopted to extract the maximum possible details of reef features discerned by the AWiFS sensor. These Area(s) of Interest (AOI) have been further decomposed into smaller subsets either to magnify the feature details or to illustrate cases of high descriptive resolution. These subset images were extracted from the full AWiFS/LISS III scenes using the "subset image" function of the Data Preparation module of the software. The smallest image subset (representing a reef from Seven Islets, Sudan) extracted from a geo-referenced AWiFS full scene represents 35.56 sq km area on ground. The largest image subset has been extracted for Farasan Bank in Saudi Arabia which represents 96814.71 sq km ground area. The subset extracted from a geo-referenced LISS III image for Farasan Islands, Saudi Arabia, the extracted image represents a ground area of 3551.54 sq km.

The subset images were displayed as standard FCCs and were digitally enhanced. Image enhancements or more precisely radiometric enhancements in this case were carried out on the subset images for improvising the image appearance (for better appreciation of reef features) and interpretability. Among the ten radiometric enhancement methods available in the software's 'General Contrast' utility under Raster menu, most commonly, Percentage Look Up Table (LUT) method has been employed on the image subsets. For a smaller proportion of the subset images, Linear and Standard deviation stretches were also employed. In some exceptional cases, the Gamma method has been used to reduce the apparent effect of sun-glint. All these methods were employed without altering their standard parameters like clip-types, levels, slope and shift, scale, etc. Once enhanced, the brightness and the contrast levels of these subset images were again adjusted with the help of Contrast Tool to ensure the prominence of discernible reef features.

II. Subset Interpretation:

Individual image subsets showing coral reef habitats (either in totality as a spatial entity or as a partial 'zoomed in' view) were interpreted based on a hybrid approach. The interpretation is basically two-fold: viz. a) delineation of seaward reef boundary and b) digital annotation of reef features based on the classification system discussed in the previous chapter and the upgraded interpretation key. The signatures and extensive ground-truth supported knowledge of Indian coral reef features have been extrapolated for interpreting the coral reef habitats of Red Sea and Gulf of Aden. Extensive literature survey has also been carried out to guide the process of habitat mapping for Red Sea and Gulf of Aden.

a) Delineation of Reef Boundary:

Individual AWiFS and LISS III subsets were digitally zoomed at 1:25,000 scale and the maximum visible, seaward boundary of the reef were digitized onscreen in the form of Arc Coverage. The reef-type (line) symbol is attached to this vector layer.

b) Delineation of Reef Features:

Intra-reef geomorphic features (level II, III and IV of the classification system) have been delineated with the help of digital annotations with reference to the elements of visual interpretation like location, association, shape, size, tone, texture, etc. as mentioned in the interpretation key (Annexure- I) given in Coral Reef Atlas of the World, Vol.1 Central Indian Ocean (Navalgund *et al.* 2010).

For the benthic zone categories (level IV of the classification system) an additional step was followed for interpretation. The absolute and relative magnitude of the Top-of-the-Atmosphere (TOA) spectral radiance values in each of the four AWiFS bands were studied for the five major benthic categories (live coral, algae, seagrass, dune vegetation and mixed coral zone). Sets of look-up-table were created for each category from different AWiFS image subsets where benthic zone categories were present. Cluster of pixels matching with the trend of relative magnitude of TOA spectral radiance values in the four channels of the AWIFS data were then digitally tagged or annotated as the classified benthic zone.

The interpretation layers were superimposed on the image subsets and were subject to quality checks.

iii. Coral Reef Habitat Map Preparation:

Individual atlas plates or the coral reef habitat maps were prepared using ArcMap module of ArcGIS software. Country-wise map templates were designed including location maps where the image subsets and their corresponding interpretation layers were inserted as qualified data frames. For each reef habitat map, legend was updated as per the inserted data frame. The final atlas plates complete with all marginal information were again subject to quality checks and modified as per reprographic requirements.

iv. Reef Area Computation:

For individual reef habitat maps, the reef boundary (available as arc feature in coverage format) was exported into shape file format for easy editing in ArcMap. Additional polyline features of coastline and island boundary were created at 1:25,000 digital zoom for completing reef area polygons and clipping the island area located within the reef area. Once the shapefile was prepared, it was exported into coverage format for resolving dangling nodes to create polygon topology in ArcInfo. After topology building, these coverages were projected to Universal Transverse Mercator (UTM) Zones 36, 37, 38 and 39 (Projection: UTM, Datum: WGS 1984 covering Red Sea and Gulf Aden area). The polygon attribute table (.pat) was updated with an additional category field for adding the information on broad-scale reef categories like: reef type, coralline shelf, lagoon and island whichever is applicable. The vector attribute table was summarized based upon these categories in ArcGIS to obtain category wise reef area per subset. In order to avoid addition of overlapping subset areas, subset-wise vectors were merged as per requirement to create a final, country level vector mosaic to compute coral reef area at country level.

Finally, a seamless mosaic of the mapped reef area of Red Sea and Gulf of Aden have been prepared to facilitate up-to-date information on the above mentioned broad reef categories and their corresponding area statistics.

Table 5.1 Map Legend

Categories	**Legend**
Reef Types	
Fringing Reef	
Platform Reef	
Patch Reef	
Coral Pinnacle	
Atoll	
Faros Atoll	
Barrier Reef	
Ribbon Reef	
Submerged Coral Bank	

Geomorphological Zones and Sub-zones	
Reef Front	RFr
Reef Edge	RE
Reef Slope	RS
Spur and Groove	SpG
Outer Rim	Orm
Channel	Ch
Moat	Mo
Reef Crest	RC
Algal Ridge/Algal Pavement	AR
Reef Flat	RF
Outer Reef Flat	OR
Inner Reef Flat	IR
Sanded Reef Flat	SRF
Muddy Reef Flat	MR
Sandy Muddy Reef Flat	SMR
Boulder Zone	BZ
Rubble Zone	RZ
Sand Cay	SC
Sandy Ridge	SRi
Sand Patches	S
Reef Flat Moat	RFM
Pool	P
Shalllow Tidal Pool	p
Blue Hole	Bh
Coral Knoll	CK
Rocks	R
Coastal Lagoon	CL
Coral Head	CH
Submerged Reef	SR
Coralline Shelf	CS

Other Geomorphological Categories associated with Barrier and Atoll Types	
Lagoon	L
Shallow Lagoon (1-5 meters)	SL
Lagoon of Intermediate Depth (5-20 meters)	IL
Deep Lagoon (>20 meters)	DL
Lagoonal Reef Slope	LRS
Lagoonal Patch Reef	RP
Lagoonlet	Ll
Benthic Zones	
Coral Zones	CZ
Mixed Coral Zones	MCZ
Aligned Coral Zones	ACZ
Live Corals	LC
Algae	A
Algae (Macroalgae) dense	Ad
Algae (Matty)	A(m)
Seagrass	SG
Seagrass Dense	SGd
Algae+Seagrass	ASG
Dune vegetation	DV

Combination of Geomorphological and Benthic Zones	
Outer Reef Flat (Coral Zones)	OR(CZ)
Outer Reef Flat (Aligned Coral Zone)	OR(ACZ)
Outer Reef Flat (Mixed Coral Zone)	OR(MCZ)
Outer Reef Flat (Live Corals)	OR(LC)
Outer Reef Flat (Algae)	OR(A)
Inner Reef Flat (Live Corals)	IR(LC)
Inner Reef Flat (Algae)	IR(A)
Inner Reef Flat (Seagrass)	IR(SG)
Inner Reef Flat (Degraded)	IR(d)
Sanded Reef Flat (Algae)	SRF(A)
Sanded Reef Flat (Seagrass)	SRF(SG)
Sanded Reef Flat (Dune Vegetation)	SRF(DV)
Muddy Reef Flat (Algae)	MR(A)
Sandy Muddy Reef Flat (Algae)	SMR(A)
Sandy Muddy Reef Flat (Seagrass)	SMR(SG)
Boulder Zone (Algae)	BZ(A)
Rubble Zone (Algae)	RZ(A)
Sandy Ridge (Algae)	Sri(A)
Pool (Algae)	P(A)
Other Categories associated with Coastal Zone	
Spit	Spit
Mudflat	MF
Sub-tidal Mudflat	SM
Inter-tidal Mudflat	IM
High-tidal Mudflat	HM
Beach	B
Island	I
Mangroves	M
Jetty	J

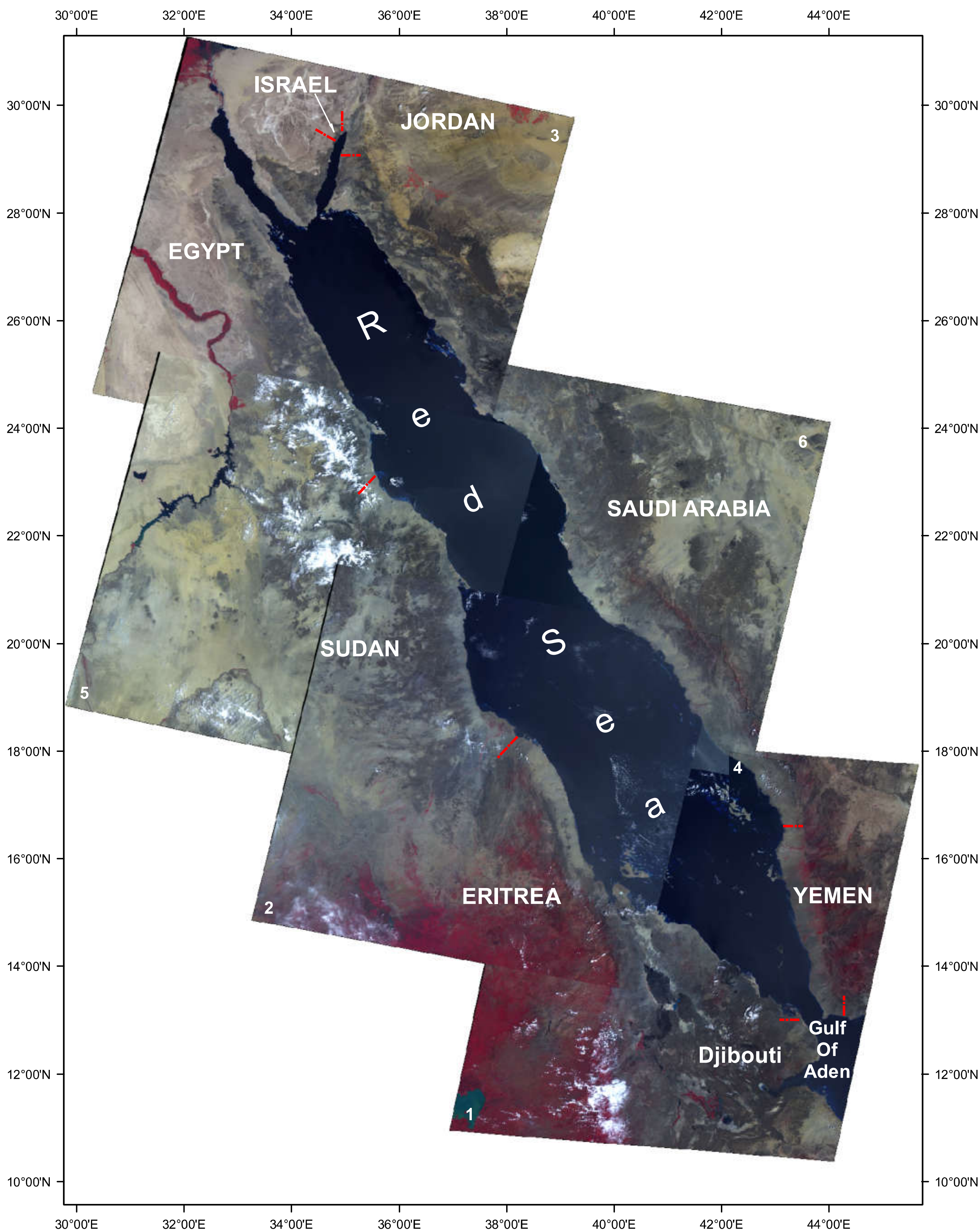


Figure. 6.1 Resourcesat-1 AWiFS mosaic showing Red Sea and surrounding countries.

Source: Resourcesat-1 AWiFS mosaic from data dated
(1) 12th October, 2008 (3) 19th March, 2007 (5) 25th August, 2005
(2) 22nd September, 2008 (4) 25th February, 2006 (6) 2nd August, 2005

International boundary delimiting coastlines of the countries surrounding Red Sea.

6.1.1. Egypt

Background

The 1800 km long, extensive coastline of Egypt represents the northern reaches of the Red Sea. The Egyptian coast extends along the Gulf of Suez, Gulf of Aqaba and the north-western Red Sea within the geographical co-ordinates of 23°10’ - 30°00’ N latitudes and 32°19’ - 36°20’ E longitudes. Egypt shares its boundary with the Mediterranean Sea in the north, Sudan in the south and with Israel to its east. The entire coastline is bordered by fringing reefs for most of its length along with off-shore fringing reefs surrounding thirty five small islands and several submerged reefs (Pilcher and Abou Zaid 2003).

Egypt’s coastline hosts a significant proportion and a considerable range of the Red Sea coral reefs, including a small number of reefs and islands lying in deep, off-shore waters from the continental shelf (Spalding *et al.* 2001). The diversity of Egyptian coral reefs can be attributed to their evolution in tune with the unique geological and biogeographic features of the area. In the north, the Red Sea rift system splits into the Gulfs of Suez and Aqaba, both have markedly different morphologies. Narrow fringing reefs have developed on the steeply shelving coastline in Gulf of Aqaba while at its southern mouth there are some relatively extensive areas of high quality shallow water reefs (Spalding *et al.* 2001). In Gulf of Suez, there are intermittent fringing reefs on the west coast while the east coast has discontinuous fringing, platform and patch reefs. In the Red Sea proper, fringing reefs extend from the strait of Gubal in the north to Mirear Island in the south, at the border with Sudan.

Two hundred and nine hard coral and 16 soft coral species have been reported from the Egyptian Red Sea (Kotb *et al.* 2008). Field surveys have established an average live coral cover of 48% (with 34% hard corals and 13% soft corals) in the reefs of Egypt (Kotb *et al.* 2008). It has been reported that coral reefs in Egypt range widely in coral cover and condition, with up to 85% live coral cover at some of the best sites (Kotb *et al.* 2004). Corals accounted for 55% of reef cover in the non-sheltered areas and 85% in the sheltered areas (Pilcher and Abou Zaid 2003). The percentage of live coral cover varies all along the coast with the highest cover occurring on reef edges and on reef walls. Egyptian coral reefs were considered healthy and free of any kind of anthropogenic stresses in the recent past (Pilcher and Abou Zaid 2003). The 1997-98 global coral bleaching event is known to have little effect on Egyptian coral reefs, but coral cover in some of the areas has declined by more than 30% due to coastal development, Crown-of-thorns starfish (COTS) outbreak, illegal anchoring, scuba diving, snorkeling and reef walking (Kotb *et al.* 2004). Until two specific bleaching events in 2007, there had been little evidence of climate change impacts on Egyptian coral reefs (Kotb *et al.* 2008). In 2007, there were two major bleaching events experienced by the Egyptian reefs. The one in March 2007 happened due to extreme low tide exposure of the reefs in Gulf of Aqaba to the south of Sinai peninsula while the other one was a thermal bleaching at the Rocky Island in October, 2007. However, the extent of coral mortality subsequent to these events was not quantified in these remote areas.

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Egypt have been mapped with Resourcesat-1 AWiFS data (5 scenes, dated: 25th August, 2005, 16th January, 2007, 13th February, 2007, 19th March, 2007 and 8th June, 2007). Detailed habitat characteristics of Egyptian reefs have been depicted in twenty-six reef habitat maps (Map No.6.1.1.1 to 6.1.1.26). Fringing reefs border the coast of Egypt with natural breaks right from the Gulf of Aqaba to Red Sea proper. These reefs fringing the Egyptian coast occur in discontinuous segments as periodic flooding from *wadis* (river valleys) resulting in soft bottom sharms or lagoons (Kotb *et al.* 2008). Off-shore reefs include island fringing reefs, platform and patch reefs with relatively less coral pinnacles. Habitat characteristics of the coral reefs of Egyptian coast is discussed here under three major coastal segments: i) Gulf of Aqaba, ii) Gulf of Suez and iii) Red Sea.

i) **Coral reefs of Gulf of Aqaba:**

The Gulf of Aqaba has been formed as a strike-slip rift system as the Arabian peninsula has moved apart from the Sinai peninsula in a parallel direction. The gulf is very deep, reaching about 2000 meters and remains deep right up to its northern shores (Spalding *et al.* 2001). At its southern mouth there is a shallow sill and some extensive areas of high quality shallow water reefs have developed on its eastern side. Narrow fringing reefs have developed along the steep coastal shelf. At the mouth of the *wadis* (river valleys) and across bays the fringing reefs extend outwards for up to 1 km from the shore (Pilcher and Abou Zaid 2003). Reef slopes are characteristically steep to vertiginous while reef flats have narrow widths of few tens of meters (Spalding *et al.* 2001). The same is evident in Map No. 6.1.1.1 to 6.1.1.2. To the south of Taba Protected Coastline (PCo) and Nuweiba Dive Center, AWiFS data dated 8th June 2007 could only detect the narrow fringing reef with reef edge and the reef flat categories. Reef slope and sanded reef flat could be detected in the reefs to the north of Nuweiba. Similar reef categories could be detected for the coral reef habitats of Abu Gallum Managed Resource Protected Area (MRPA) (Map No. 6.1.1.3) established in 1992. This area covers an area of 458 sq km (Spalding *et al.* 2001) and traverses several mountain ranges, wadi systems, freshwater springs and sand dunes (Pilcher and Abou Zaid 2003). The coral reef habitats are known to be associated with extensive seagrass beds that support significant marine life. Coral reef habitats of Abu Gallum are major SCUBA diving attraction points (Pilcher and Abou Zaid 2003). The blue hole structure near Dahab Protected Coast is around 100 m deep and is considered a major example at the global level (Gischler 2011). The coast fringing reef becomes relatively wider near Nabq Managed Resource Protected Area (MRPA) (Map No. 6.1.1.4). Reef edge, reef crest, reef flat and sanded reef flat categories could be detected within the reef habitats of Nabq MRPA. Sanded reef flat and pool are located within the reef flat. The Nabq MRPA, established since 1992, occupies an area of 600 sq km and encompasses critical coastal habitats of coral reefs, seagrass beds and hosts major avifauna (Pilcher and Abou Zaid 2003). The associated mangrove habitat represents the northern limit of their distribution in the Gulf of Aqaba. At the mouth of the Gulf of Aqaba, the major coral reef habitats of Egyptian coastline occur as Ras Mohammed National Park and Tiran- Senafir National Park (Map No. 6.1.1.5), established in 1983, occupying areas of 460 sq km and 371 sq km respectively (Spalding *et al.* 2001). The Tiran Island has been selected to view the intra-reef features in more detail. The reef habitat occurs in the sheltered part of the Gulf, adjacent to the Tiran Island, with a clear distinction between the outer and inner reef flats. Channels, moats and pools are major intra-reef features in the northern side of the reef while a prominent blue hole structure is noticed onto the eastern part of the reef flat. Sandy substrate is evident in case of the inner reef flat along with narrow sanded reef flats in the central portion of the reef. An algal ridge is however noticed in the coast fringing reef of Nabq MRPA. This area has high diversity of flora and fauna, including coral reefs, seaweed and seagrass beds, mudflats, mangroves and other halophytic vegetation (Pilcher and Abou Zaid 2003). Ras Mohammed National Park is an important sea turtle developmental habitat and serves as Egypt's major marine environmental education centre.

ii) **Coral reefs of Gulf of Suez:**

The abandoned, spreading rift system of Gulf of Suez is about 320 km long and 70 km wide, (Shaked and Genin 2011) with an average depth of 30 meters (Spalding *et al.* 2001). Small, discontinuous patch reefs occur on the eastern coast of Gulf of Suez. These reefs rest on calcareous sandy substrate within 1 to 5 meters depth (Pilcher and Abou Zaid 2003). On the western coast, the intermittent fringing reefs are well developed within 1 to 5 meters depth. There are extensive reefs in the southern Gulf of Suez, on the Sinai peninsula near Ras Mohammed and surrounding the Ashrafi Islands (Pilcher and Abou Zaid 2003). Gulf of Suez is subjected to considerable climatic extremes associated with its northerly latitude, shallow waters and high salinity and accordingly has low species diversity as compared to the rest of the Red Sea (Spalding *et al.* 2001).

Extensive coral reef development is seen in the Ras Mohammed National Park, AWiFS data dated 8th June 2007 (Map No. 6.1.1.6). The coast of Sinai peninsula is fringed with a continuous reef with prominent reef flat discerned into outer and inner reef flats. Exposure of reef crest is detected in the northern side while reef slope has been detected at number of places. A long, linear moat divides the reef flat into outer and inner reef flats in the central section while pools with irregular boundaries have been detected on the reef. Live corals could also be detected at one location on the reef in southern part. The reef adjacent to the coastline however appears muddy. In the northern side of Ras Mohammed National Park in Gulf of Suez, an off-shore platform reef of Sha'ab Ali appears which have been selectively magnified to view the intra-reef details (Map No. 6.1.1.6; subset:1). The off-shore reef of Sha'ab Ali appears as a twin structure with prominent zonation of the outer and the inner reef flat along with deep oceanic pools and channels. Reef categories like reef edge, reef slope and moats could be detected in its eastern half. Three distinct patch reefs appear near Sha'ab Ali: one in the north and two to the south. Reef flats and reef slope could be detected for the patch reefs. Coral pinnacles dot the fringing reef in the northern side. It has been reported that two series of COTS outbreak occurred in the Ras Mohammed National Park in 1994 and in 1998. The first outbreak was relatively a minor one while the 1998 outbreak was extensive and probably continued through 1999 and 2001 although major control programmes were implemented (Kotb *et al.* 2008).

The coast fringing reef continues towards the north beyond Ras Garra (Map No. 6.1.1.7) upto El Tor (Map No. 6.1.1.8) on the Sinai peninsula. Exposure of reef crest is only found at two locations while the reef flat could be distinguished into outer and inner reef flats. Near Ras Garra, the inner reef flat is quite wide as compared to a narrow outer reef flat. In the southern part the reef flat adjacent to the coast appears muddy. The reefs detected as patch reefs or coral pinnacles however appear submerged. To the north of El Tor, upto Abu Durba (Map No. 6.1.1.8), the coast fringing reef becomes very narrow and assume an intermittent character. Intermittent segments of the fringing reef appear near Ras Abu Rudeis (Map No. 6.1.1.9) and to the south of it. Reef crest and reef flat zones could be detected on AWiFS data dated 8th June, 2007 while the reef flat could be separated into outer and inner reef flats where the reef widens just south to Ras Abu Rudeis. An off-shore platform reef and a small chain of coral pinnacles appear on the coast. The same trend continues with narrow, intermittent reef segments near Abu Zenîma and to the south of Ras Matarma (Map No. 6.1.1.10). The reef flat could be distinguished into outer and inner reef flats near Ras Matarma while only the reef flat could be seen near Abu Zenîma.

The coast fringing reef continues north of Ras Sedr (Map No. 6.1.1.11). A prominent algal ridge rims the reef flat near Ras Sedr while the reef flat has sandy substrate in the north. Just adjacent to the coast the reef flat is muddy one along with algae. Towards the extreme northern end of Gulf of Suez (Map No. 6.1.1.12), the reef fringes the coast on the eastern side. Only in the southern part the reef flat can be distinguished into outer and inner reef flat. Reef slope is exposed only at one place while a small portion of the reef flat appears as sanded reef flat.

On the west coast, in Gulf of Suez, the fringing reef appears adjacent to the headland near Al Adabiya (Map No. 6.1.1.13), with the reef flat clearly distinguished into outer and inner reef flat. A long, linear moat separates the reef and the adjacent coastal flat. Mangrove vegetation occurs as an associated habitat. Fringing reefs appear in small intermittent segments on the mainland coast in the eastern Gulf of Suez (Map No. 6.1.1.14) with only reef flat and edge being detected from AWiFS data dated 8th June 2007.

Coral reefs continue to fringe the Egyptian mainland on the west coast of Suez and near Zafarana (Map No. 6.1.1.15) the reef flat can be distinguished into outer and inner reef flats. Algae substrates are also observed on the reef flat towards the north while a spit extends onto the sea towards the southern part as shown on this map. To the south of Zafarana, the narrow fringing reef continues on the mainland coast (Map No. 6.1.1.16). The reef flat can be distinguished into outer and inner reef flats and in the northern part has one prominent, elongated pool. Down south near Ras Gharib and Ras Shu Kheir (Map No. 6.1.1.17) upto the stretch where Egyptian mainland coast enters the Straits of Gubal (Map No. 6.1.1.18), the fringing reef becomes intermittent and narrow with reef flat and partial exposures of the reef slope at very few places.

iii) **Coral reefs of Red Sea Coast:**

In the Red Sea proper, extensive fringing reefs continue from the Straits of Gubal to Mirear Island at the border with Sudan. Straits of Gubal (Map No. 6.1.1.19), where the Gulf of Suez opens into the main Red Sea, abound with diverse fringing reefs rimming some major off-shore islands while on the mainland coast, fringing reefs occur from the northern headland of Gubbet el Zeit to south of Hurghada. The reefs here generally extend over a width of 25 to 150 m (Pilcher and Abou Zaid 2003). The mainland reef fringes the coastal headlands in the north and narrows down to the south of Hurghada. The width of the reef varies continuously and the reef flat could be separated into outer and inner reef flats at two places. The reef slope gets exposed in two places. In the central portion however the reef appears muddy. The off-shore reefs have four major fringing reefs (namely Gubal Island, Tawîla Island, Shādwan Island and Gifatin Island); six platform reefs, eighteen patch reefs and good number of small coral pinnacles are found more towards the coastal waters.

Three off-shore islands have been selectively zoomed to view their intra-reef details (Map No. 6.1.1.19A; subset: 1). Ashrāfi Island is a NNW-SSE oriented, long, elliptical reef with a deep, oval shaped pool in its south. Reef slope and reef crest categories could be properly detected on AWiFS data dated 8th June 2007. However, the reef flat could not be discerned into outer and inner reef flats. There is a crescent-shaped moat in the northern part which divides the reef flat while in the southern part, the reef flat gets occasionally submerged on the edges. Patch reef and coral pinnacles occur to the right of Ashrāfi Island. Gubal and Tawîla Islands (Map No. 6.1.1.19A; subset: 2) are connected through a continuous fringing reef system. The reef flat extends towards the north of Gubal Island with a moat separating the reef crest and the reef flat. A narrow, crescentic pool occurs within the reef flat. The reef is absent on the eastern side of the Gubal Island but continues on the west and join the Tawîla Island. The reef flat has intermittent depressions, even a blue hole structure and can be separated into outer and inner reef flats. The extended portion of the reef flat towards the south show proper exposures of the reef slope with comparatively shallow pools. A deep, reef flat moat occurs in the southwestern part of the reef. The reef appears submerged on the eastern side. Gifatin Island (Map No. 6.1.1.19A; subset: 3) represents an off-shore fringing reef with a reef flat appearing with outer and inner reef flats. The reef flat has a major pool towards the eastern side whereas reef slope gets exposed at few places. The reefs of Straits of Gubal and Gifatin Island have been proposed as a major Marine Protected Area (MPA) site because of diverse, well-developed reefs and rich reef associated fauna (Pilcher and Abou Zaid 2003). In a recent field assessment, Hurghada site appeared to have the maximum number (48) of coral species and recorded the highest diversity (Mohammed 2012). These islands are also known as important sea turtle and seabird nesting sites. Current threats include fishing and anchor damage along with recreation pressures (Pilcher and Abou Zaid 2003).

Down south to Hurghada, coral reefs intermittently fringe the Egyptian coast upto the major headland of Ras Abu Soma (Map No. 6.1.1.20). Ras Abu Soma coastal region is characterized by beautiful sandy beaches, some coral islands and very healthy, fringing coral reef communities (El-Gamily *et al.* 2001). One of the major off-shore reef island down south to Ras Abu Soma Bay is Safaga Island (Map No. 6.1.1.20; subset: 1). Coral reefs fringe the Safaga island with a wider reef flat in the north and relatively narrow reef flat in the southern part. On the western side, the reef flat could be distinguished into outer and inner reef flats with exposure of reef slope category. A small pool is located in the northern side next to a small portion of sanded reef flat while onto the east the reef slope is separated into outer and inner reef flats through a prominent, elongated moat. This mangrove lined island is also a seabird nesting site (Pilcher and Abou Zaid 2003). Current threats include shipping and a small-scale fishery. Anchor damage to living coral reefs and long term effects of oil pollution throughout the shoreline have been reported as major human-induced changes on the coastal habitats of Ras Abu Soma region (El-Gamily *et al.* 2001).

South of Port Safaga, the coral reefs fringe the Egyptian mainland almost continuously upto Marsa Alam (Map No. 6.1.1.20 to 23). The coral reefs fringe a cliffy coastline (Map No. 6.1.1.21) and the reef flat is too narrow to be resolved into outer and inner reef flats as apparent from the AWiFS data dated 8th June, 2007. However, sanded reef flat, moat and pool have been detected at certain places. Down south to Quseir dive Center (Map No. 6.1.1.22), the cliffy coastline is interrupted with wadis and reef crest, reef slope and reef flat categories are detected along with moat and pools at places. From Marsa Alam (Map No. 6.1.1.23) to Shalate in, the mainland fringing reefs widen up to 500 m (Pilcher and Abou Zaid 2003) and two elongated platform reefs lie off the mainland coast along with eight coral pinnacles. Reef flat, moat and pool were detected on the coastal reefs while the platform reefs were selected for a magnified view for their intra-reef details (Map No. 6.1.1.23; subset: 1). For both the platform reefs, the reef flat could be separated into outer and inner reef flats and each one has prominent algal ridges on their eastern margin. The exposure of reef slope has always been noted on the western side. The southern reef has a sanded reef flat along with an inner reef flat dominated with algae. The Egyptian Environmental Affairs Agency (EEAA), the Egyptian Environmental Policy Programs (EEPP) and international organizations are strengthening the protection of coral reefs and other marine habitats. In 2003, Wadi El Gemal Hamata Protected Area (PA) was declared to protect the coral reefs, mangroves, seagrass meadows and terrestrial habitats to the south of Marsa Alam (Kotb *et al.* 2004). Similar coast fringing reefs continue even south of Abu Ghusun (Map No. 6.1.1.24). The reef extends in width in the southern portion. At the central part the reef flat could be distinguished into outer and inner reef flats. In the extended portion, the reef flat appears muddy adjacent to the land while the seaward portion appears submerged. Exposure of reef slope is also noticed at few places and a small sand patch is also observed on the seaward part of the reef. The offshore platform reefs lie to the north of the extended, coastal reef. A sandy ridge could be detected on the northern platform reef. A small mangrove patch is detected on this segment of the Egyptian coast in the southern part.

The narrow reef fringes the Egyptian coast up to the headland of Ras Banas and thereafter continues with intermittent breaks on the mainland coast in Foul Bay (Map No. 6.1.1.25). A prominent algal ridge is seen in the coastal reef to the north of Ras Banas while the reef flat can be separated into outer and inner reef flats only to the south of the headland where the reef widens out. Exposures of reef slope are detected at certain sites. Predominance of algae in the inner reef flat is also observed. Towards the extreme south, the reef flat appears muddy. This part of the Egyptian coast is also dotted with patch reefs and coral pinnacles. One of the major patch reefs has been zoomed to view the intra-reef details (Map No. 6.1.1.25; subset: 1). An algal ridge is observed in the northern side while the reef flat has its best exposure in the extreme east. Deep pools are also observed.

Fringing reefs on the mainland coast of Egypt gradually increases in their width in the south and culminates into the Geziret Mirear reef structure, extending 12 km from the shore at the Sudanese border (Map No. 6.1.1.26). A moat is seen in the coast fringing reef. The off-shore island of Zabargad, off-shore reefs and Geziret Mirear reefs have been selectively magnified to view their intra-reef details (Map No. 6.1.1.26A; Subset: 1, 2 and 3). Zabargad Island is a small sea turtle nesting island 40 km off-shore surrounded by coral reefs (Pilcher and Abou Zaid 2003). The reef shows classic macro zonation of reef crest, reef slope and reef flat. Subset 2 shows the off-shore coral reefs which could be detected with AWiFS data dated 25th August, 2005 but could not be mapped due to image resolution and scale consideration. The northern part of the Geziret Mirear reef structure falls in the territorial waters of the Egyptian coast. The reef shows a classic zonation of outer and inner reef flats separated through moats. Pools and coral knolls appear in the central depression. Exposures of reef slope are noticed at certain places. A sand cay is also detected on the reef. The southern boundary of the reef is extremely crenulated and the southern parts of the reef appear in submerged condition. Coral pinnacles dot the southern boundary of this magnificent reef structure.

The frequencies of classes detected for coral reef habitats of Egypt are represented in Figure: 6.1.1.1. The geomorphological class: reef flat is the commonly detected class along with the sub-zone of reef edge. Reef slope could be detected in the Egyptian reef habitats with relatively higher frequency; in fifty percent cases the reef flat could be separated into outer and inner reef flats. Deep oceanic pools and moats dominate as major geomorphological sub-zones in the reef structures of Egypt. Live corals and algae have been detected as benthic zones with very less frequency. Mangroves show relatively less association with coral reef habitats on the coast of Egypt.

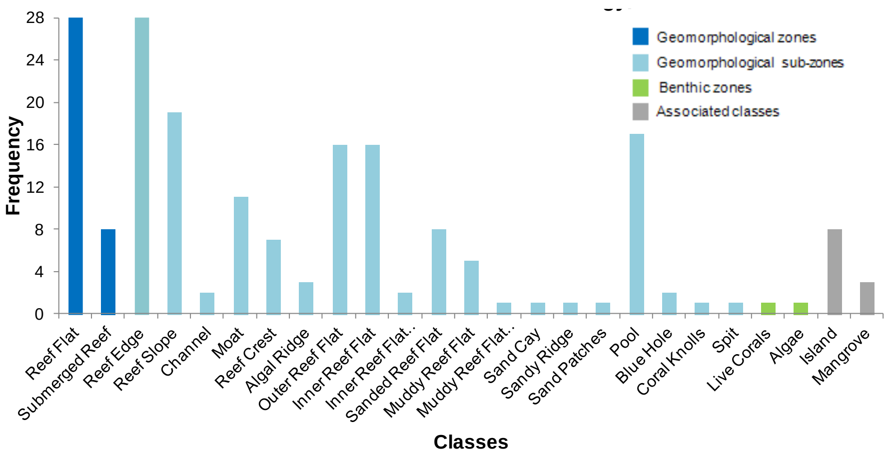


Figure 6.1.1.1 Frequency of classes detected for coral reef habitats of Egypt

Areal Extent of Coral Reefs of Egypt

The coral reef habitats of Egypt as mapped from AWiFS data cover a total area of 1469.39 sq km. Reef area corresponding to each habitat map is summarized in Table No. 6.1.1.1. Coral reef habitats between Jemsa and Hurghada and off-shore reefs in Straits of Gubal occupy the maximum coral reef area of 401.49 sq km while coral reef habitats in western Gulf of Suez (segment 1) occupy the minimum reef area of 0.47 sq km.

Summary

Coral reef habitats on the coast of Egypt represent mainland fringing reefs with intermittent breaks along with offshore fringing reefs including platform, patch and coral pinnacles. Intra-reef geomorphic details could be discerned and delineated from Resourcesat-1 AWiFS data for fifty to sixty percent of the total Egyptian coral reef habitats. Detail mapping of the coastal reefs in Gulf of Aqaba and some of the offshore reefs demand a high resolution data. In most of the cases reef edge and reef flat categories could be detected for the Egyptian reefs. Exposure of reef slope could also be marked in many cases. For half of the reef habitats, the reef flat could be separated into outer and inner reef flats. One major characteristic of Egyptian reefs is predominance of deep oceanic pools within the reef systems. As an associated habitat, mangroves are relatively sparse in the immediate vicinity of the reef habitats on the coast of Egypt.

Table 6.1.1.1 Areal Extent of coral reefs of Egypt

Map No.	Location	Reef Area (sq km)
6.1.1.1	Coral reef habitats to the south of Taba PCo	5.80
6.1.1.2	Coral reef habitats near Nuweiba dive Center	8.05
6.1.1.3	Coral reef habitats of Abu Gallum MRPA and Dahab PCo	14.10
6.1.1.4	Coral reef habitats of Nabq MRPA	12.29
6.1.1.5	Coral reef habitats of Nabq MRPA and Ras Mohammed NP	84.25
6.1.1.6	Coral reef habitats of Ras Mohammed NP and offshore reefs of Sha'ab Ali	199.10
6.1.1.7	Coral reef habitats to the south of Ras Garra	34.26
6.1.1.8	Coral reef habitats between Abu Durba and El Tor	4.90
6.1.1.9	Coral reef habitats surrounding Ras Abu Rudeis	18.71
6.1.1.10	Coral reef habitats near RA's Matarma and Abu Zenîma	11.64
6.1.1.11	Coral reef habitats to the north of Ras Sedr	13.78
6.1.1.12	Coral reef habitats in northernmost part of Gulf of Suez	13.93
6.1.1.13	Coral reef habitats near Al-Adabiya	3.75
6.1.1.14	Coral reef habitats in western Gulf of Suez (segment 1)	0.47
6.1.1.15	Coral reef habitats surrounding Zafarana	16.11
6.1.1.16	Coral reef habitats in western Gulf of Suez (segment 2)	31.23
6.1.1.17	Coral reef habitats near Ras Gharib and Ras Shu Kheir	15.89
6.1.1.18	Coral reef habitats in western Gulf of Suez (segment 3)	8.12
6.1.1.19	Coastal coral reef habitats between Jemsa and Hurghada and off-shore reefs in Straits of Gubal	401.49
6.1.1.20	Coral reef habitats of Safaga Island and surroundings	57.17
6.1.1.21	Coral reef habitats of Quseir Dive Center and surroundings	29.03
6.1.1.22	Coral reef habitats of Egypt : Red Sea coast (segment 1)	28. 74
6.1.1.23	Coral reef habitats near Marsa Alam and offshore reefs	34.73
6.1.1.24	Coral reef habitats to the south of Abu Ghusun and offshore reefs	45.55
6.1.1.25	Coral reef habitats of Ras Banas and Foul Bay	138.31
6.1.1.26	Coral reef habitats of Gezirat Mirear and off-shore island of Zabargad	237.99
	Total	**1469.39**

The healthy and diverse coral reefs of Egypt have been reported under anthropogenic threats (Pilcher and Abou Zaid 2003) and until 2007 climate change impacts were rather unknown to these reefs (Kotb *et al.* 2008). The 1997-98 global coral bleaching event had little effect on the reefs of Egypt (Kotb *et al.* 2004). In 2007, coral reefs of Egypt experienced intense bleaching and mortality due to extreme low tide exposures in March while in October bleaching and mortality were recorded due to thermal stress (Kotb *et al.* 2008). Serial COTS outbreaks in 1994, 1997, 1998 as experienced by the Egyptian reefs, especially in Gulf of Aqaba is another source of major ecological stress to these coral reefs (Kotb *et al.* 2004; Kotb *et al.* 2008). The other natural threats include flooding, coral diseases like black and white band diseases and predator outbreaks like COTS, gastropod snails like Coralliophila and Drupella (Pilcher and Abou Zaid 2003).

Egyptian coral reefs have been affected by a wide range of anthropogenic impacts. The greatest impact on these reefs has been the explosion of coastal tourism and resort development since the 1980s with substantial growth of resort towns in Sinai and along the mainland Red Sea coast (Spalding *et al.* 2001; Kotb *et al.* 2004; Kotb *et al.* 2008). Artificial beach creation for resort development degrades the coral reef habitats through sedimentation and increasing water turbidity (Kotb *et al.* 2008). There have also been reports of reef damage from anchoring and grounding of tourism boats. Tourism damage also includes direct impact of divers and snorkelers and indirect impacts like landfill, dredging for developing coastal tourism (Kotb *et al.* 2008). Unsustainable fishing practices through increase in commercial fishing, destructive fishing, heavy trawling and ship groundings all lead to habitat destruction and ecosystem loss. Shark fishing and sea cucumber collection had emerged as recent threats on Egyptian reefs however both have been banned by the Egyptian Government in 2004 (Kotb *et al.* 2008). Egyptian reefs have also been threatened from oil spills and solid waste disposal from the vessels (Kotb *et al.* 2004). Anthropogenic activities along the Egyptian coastline are highly varied; include areas of intensive use and considerable reef degradation (like Hurghada, Safaga and Sharm El Sheik) but also have remote, unimpacted pristine reefs (Spalding *et al.* 2001).

Considerable proportions of Egyptian coral reef habitats are protected in Gulf of Aqaba and all the fringing reefs around the islands in the Red Sea (Spalding *et al.* 2001). The reefs of Sinai peninsula have undergone active management since the early 1990s. Ras Mohammed, Nabq, Abu Galum, Gebel Elba, Tiran-Senafir, Wadi El Gemal Hamata, Red Sea Islands, all have been protected as MPAs or PAs. The Egyptian Environmental Affairs Agency (EEAA), the Egyptian Environmental Policy Programs (EEPP) and international donors are strengthening protection of the reefs and other marine habitats (Kotb *et al.* 2004). The legal framework for the protection of coral reefs has been implemented in several parts of the Egyptian coast and has so far performed excellent (Kotb *et al.* 2004). Coral reef habitats of Egypt as mapped from AWiFS data occupy a total area of 1469.39 sq km and appear in good health condition barring the localized impact areas of Hurghada, Safaga and Sharm El Sheik.

Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.1 represents Results > under **Basin 1. Red Sea**
6.1.1 represents Results > under Basin 1. Red Sea > for **Country 1. Egypt**
6.1.1.1 represents **Coral Reef Habitat Map** of **Egypt coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

1. South of Taba PCo
2. Near Nuweiba Dive Center
3. Abu Gallum MRPA and Dahab PCo
4. Nabq MRPA
5. Nabq MRPA and Ras Mohammed NP
6. Ras Mohammed NP and offshore reefs of Sha'ab Ali
7. South of Ras Garra
8. Between Abu Durba and El Tor
9. Surrounding Ras Abu Rudeis
10. Between RA's Matarma and Abu Zenîma
11. North of Ras Sedr
12. Northernmost part of Gulf of Suez
13. Near Al-Adabiya
14. Western Gulf of Suez (segment 1)
15. Surrounding Zafarana
16. Western Gulf of Suez (segment 2)
17. Near Ras Gharib and Ras Shu Kheir
18. Western Gulf of Suez (segment 3)
19. Between Jemsa and Hurghada and off-shore reefs in Straits of Gubal
20. Safaga Island and surroundings
21. Quseir Dive Center and surroundings
22. Egypt : Red Sea coast (segment 1)
23. Near Marsa Alam and offshore reefs
24. South of Abu Ghusun and offshore reefs
25. Ras Banas and Foul Bay
26. Geziret Mirear and off-shore island of Zabargad

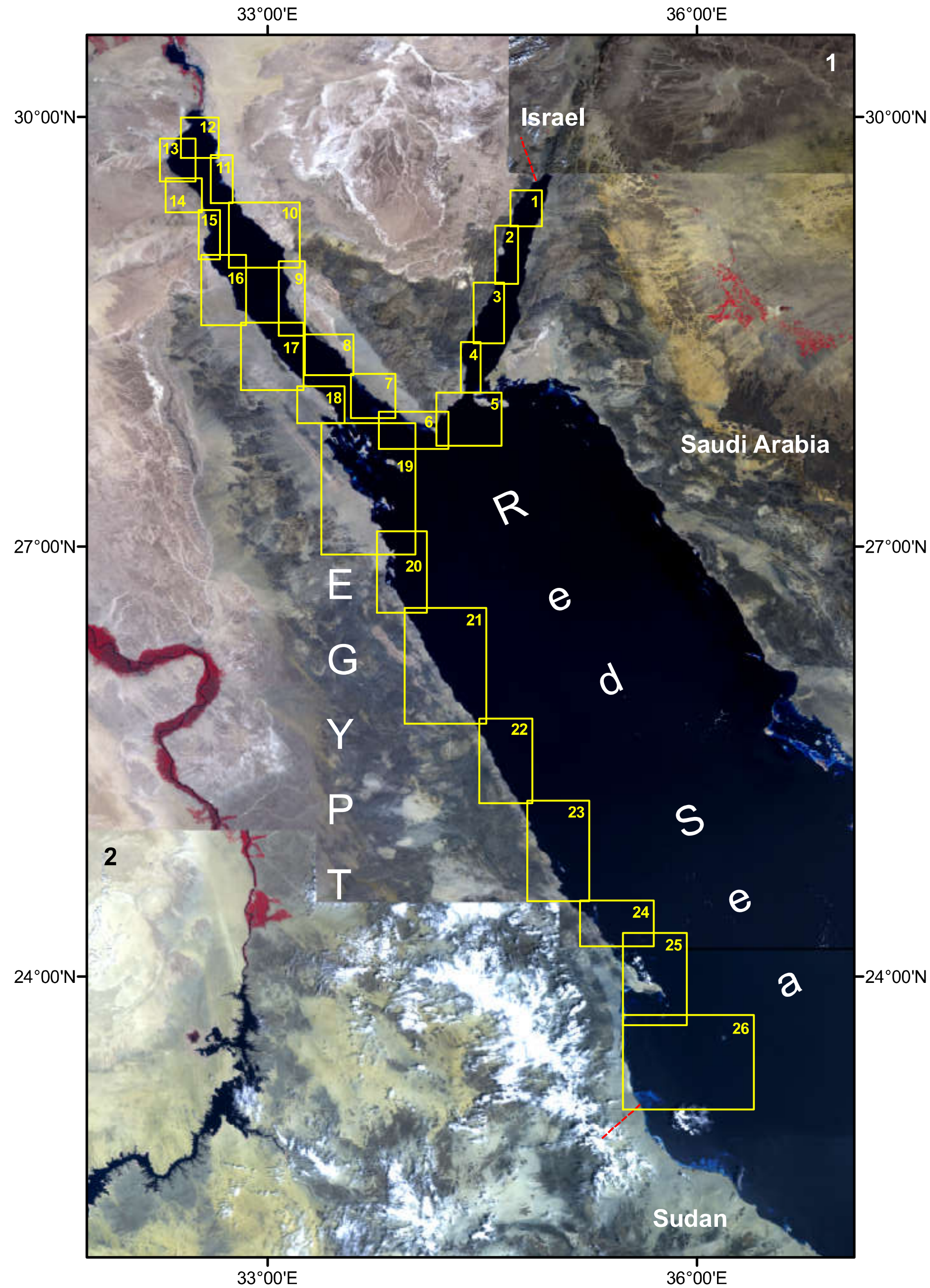
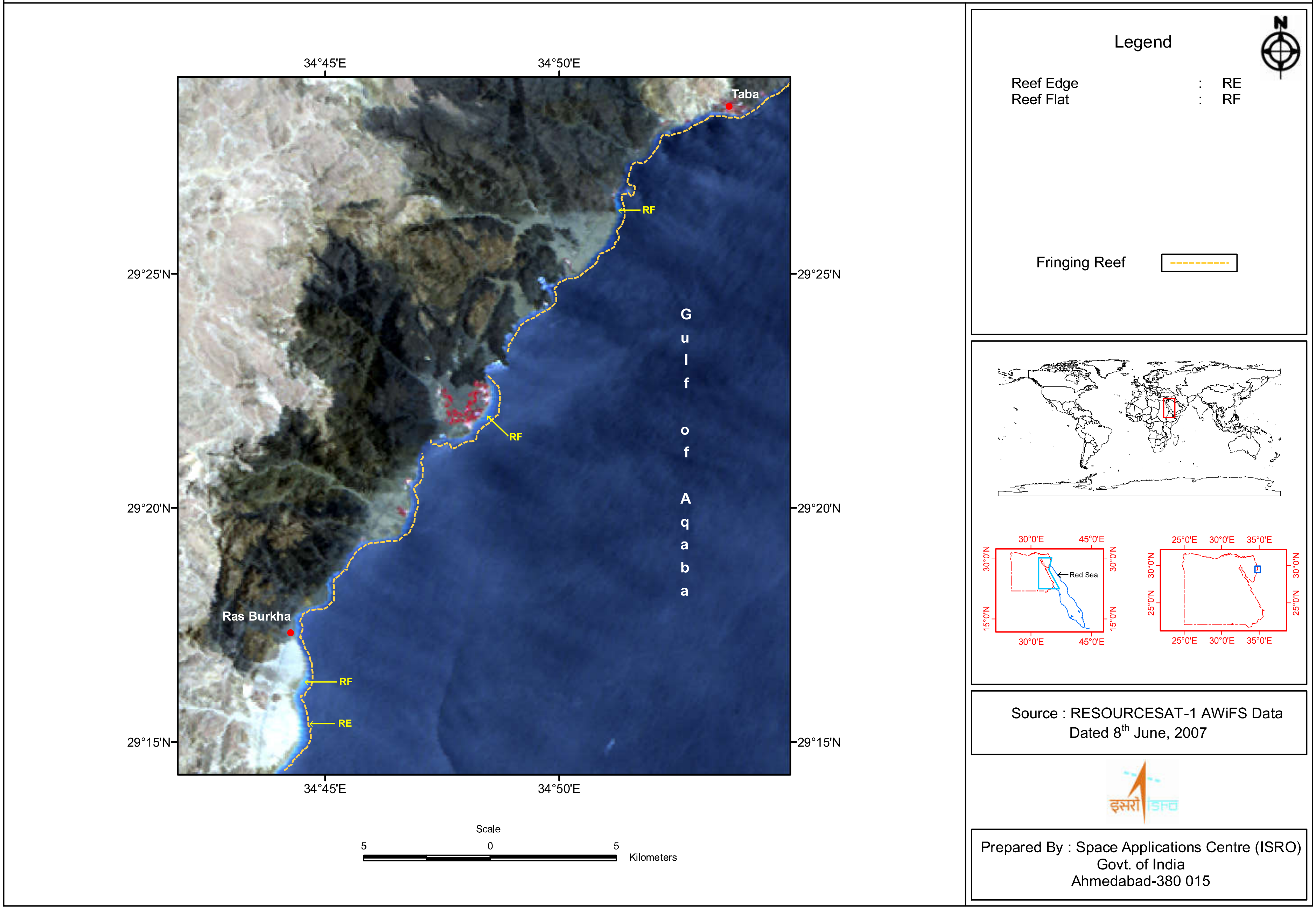


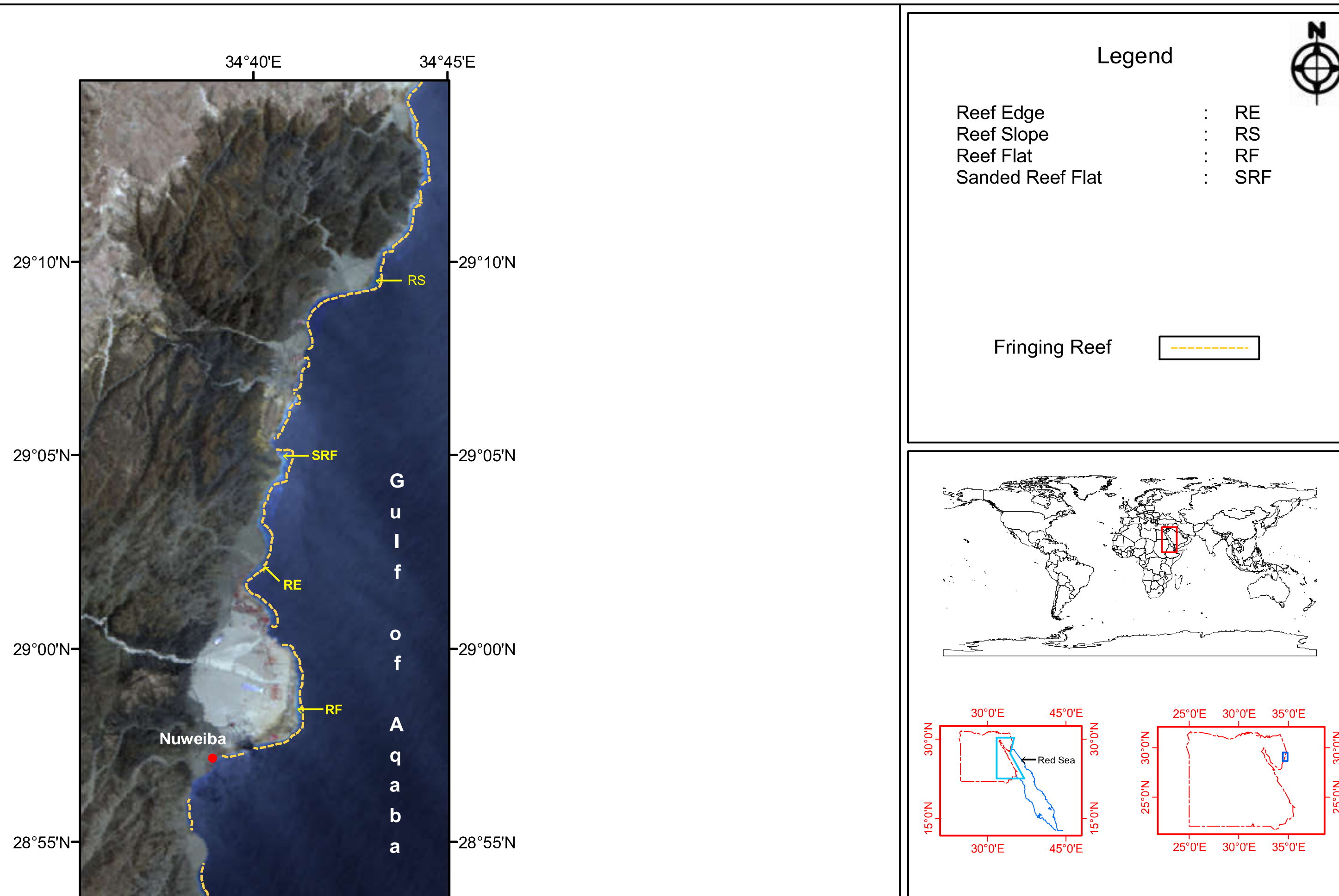
Figure 6.1.1 Index to coral reef habitat maps of Egypt

--- International boundary

Source: Resourcesat-1 AWiFS mosaic from data dated: 19th March, 2007 (1) and 25th August, 2005 (2)



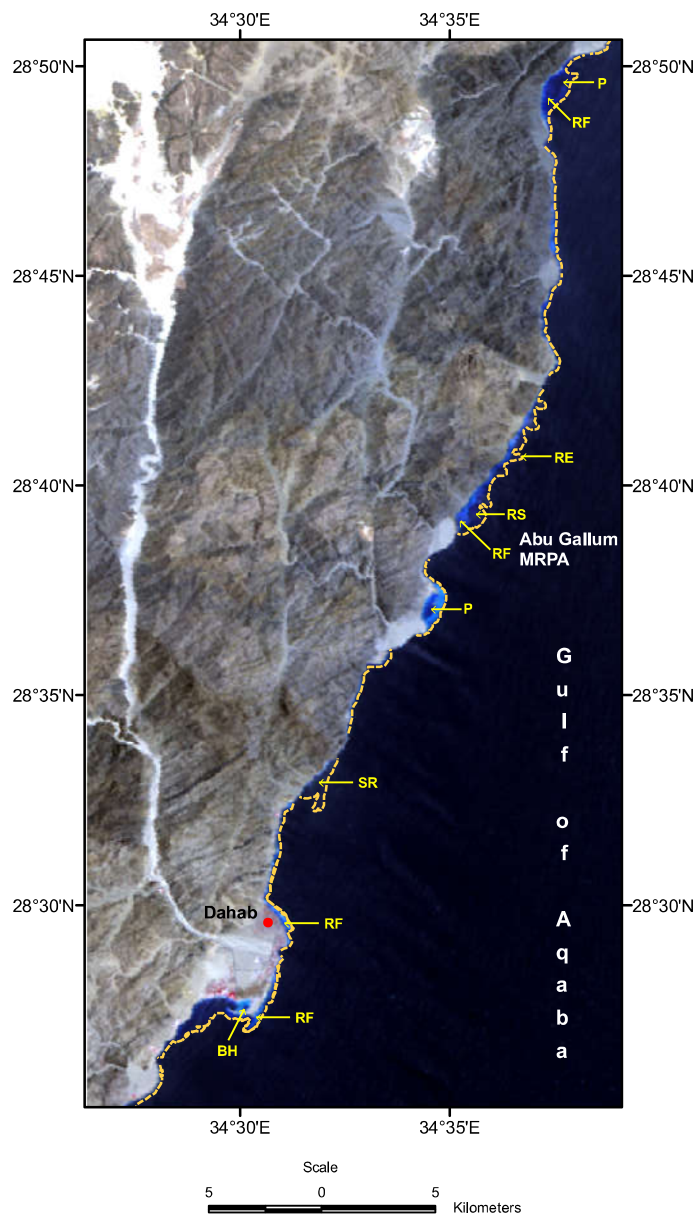
Map 6.1.1.1 : Coral reef habitats to the south of Taba PCo



Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

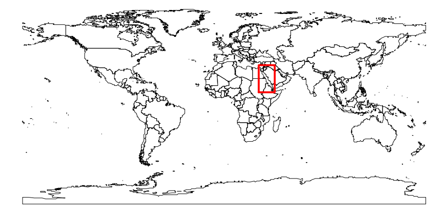
Map 6.1.1.2 : Coral reef habitats near Nuweiba Dive Center

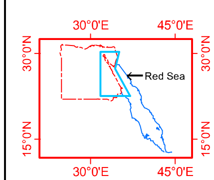


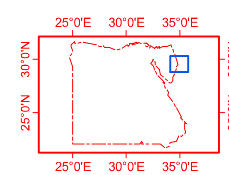
Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Pool	:	P
Blue Hole	:	BH
Submerged Reef	:	SR

Fringing Reef







Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
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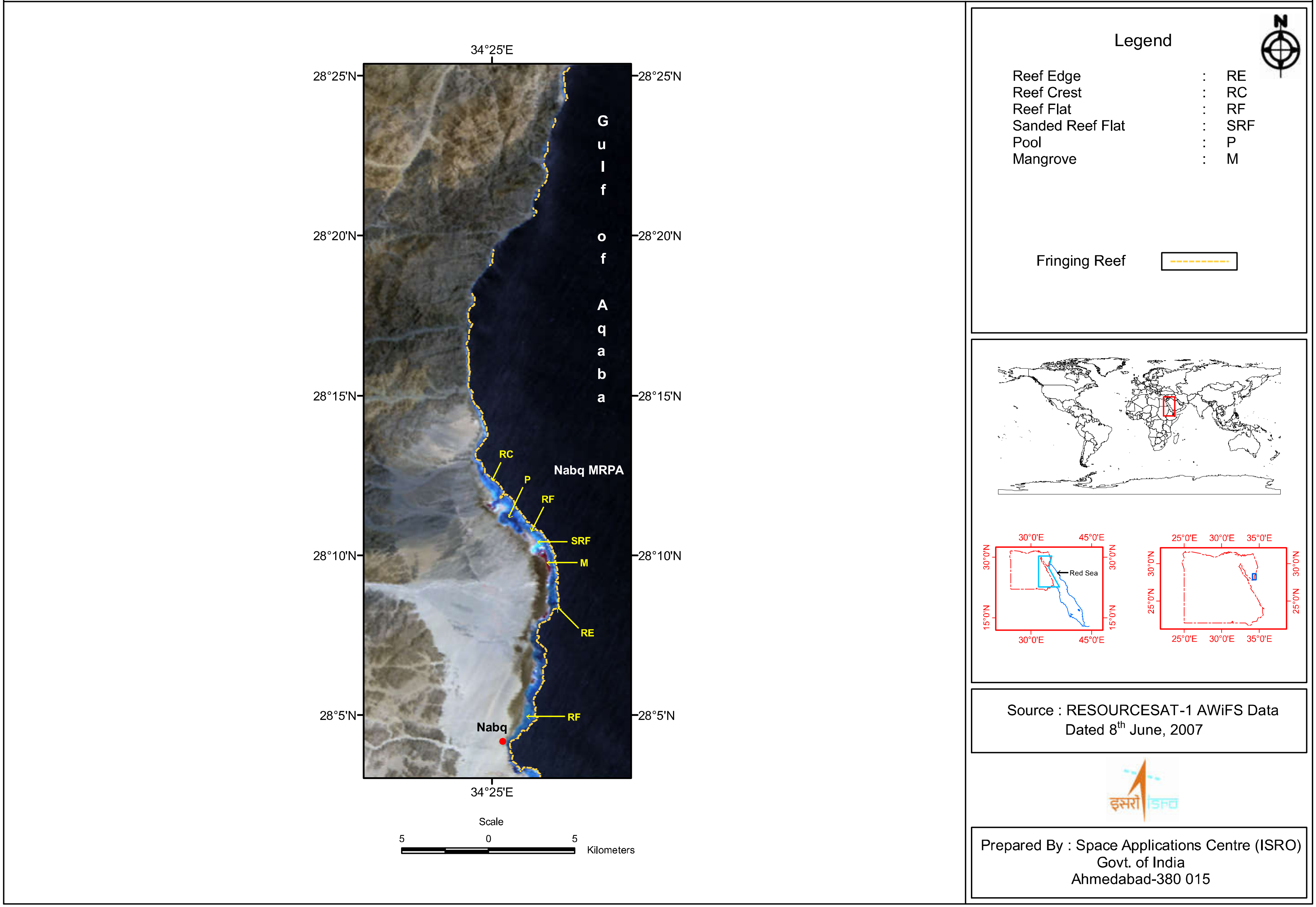
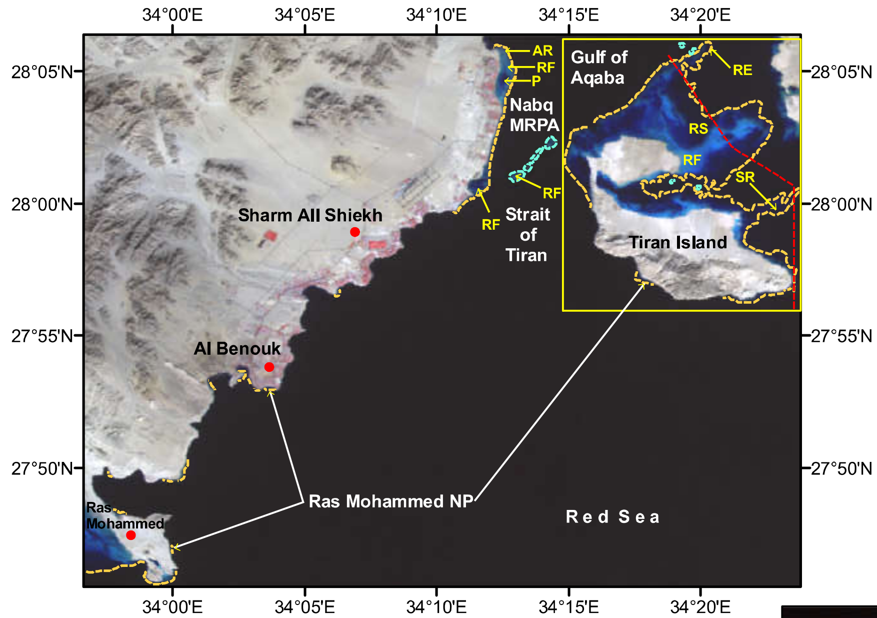
Ahmedabad-380 015

Map 6.1.1.3 : Coral reef habitats of Abu Gallum MRPA and Dahab PCo

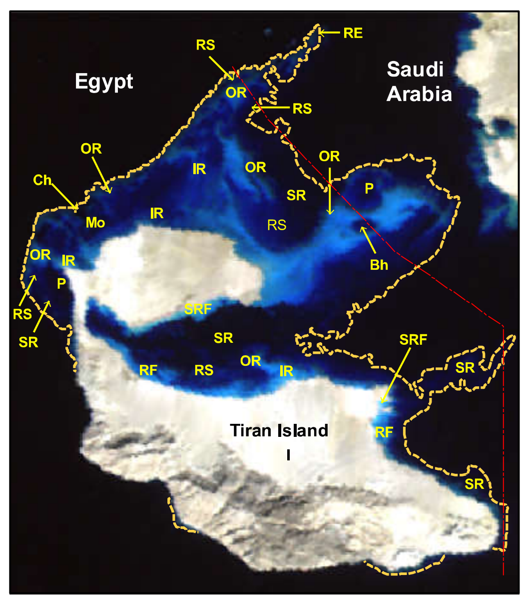


Map 6.1.1.4 : Coral reef habitats of Nabq MRPA



Scale

10 0 10 Kilometers



Scale

5 0 5 Kilometers

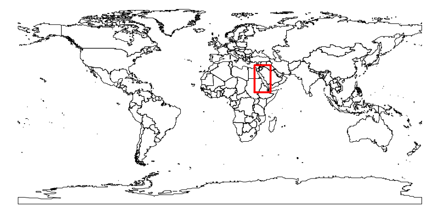
N

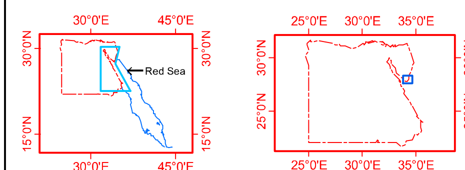
Legend

Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Moat	:	Mo
Algal Ridge	:	AR
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Pool	:	P
Submerged Reef	:	SR
Island	:	I

Fringing Reef

Coral Pinnacle

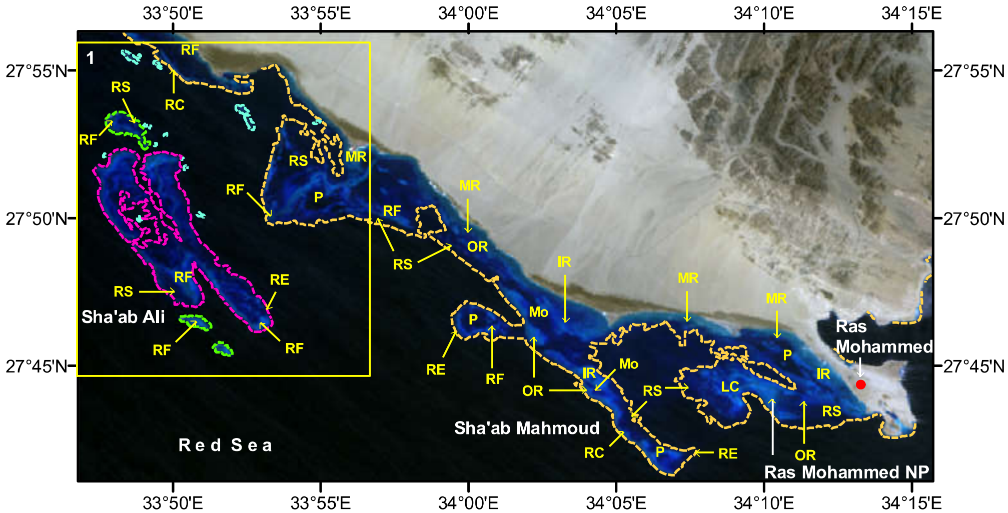




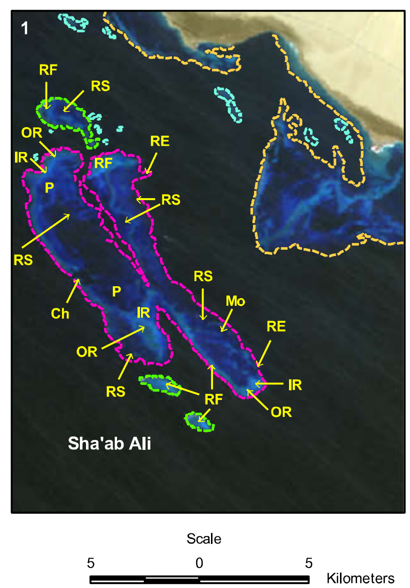
Source : RESOURCESAT-1 AWiFS Data
Dated 16th January, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.1.5 : Coral reef habitats of Nabq MRPA and Ras Mohammed NP



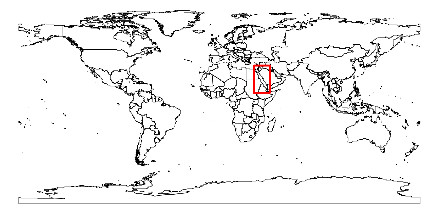
28°15'N

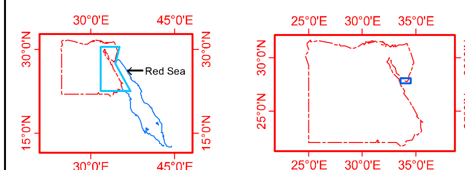


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Crest	:	RC
Channel	:	Ch
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Muddy Reef Flat	:	MR
Pool	:	P
Live Coral	:	LC

Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle





Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
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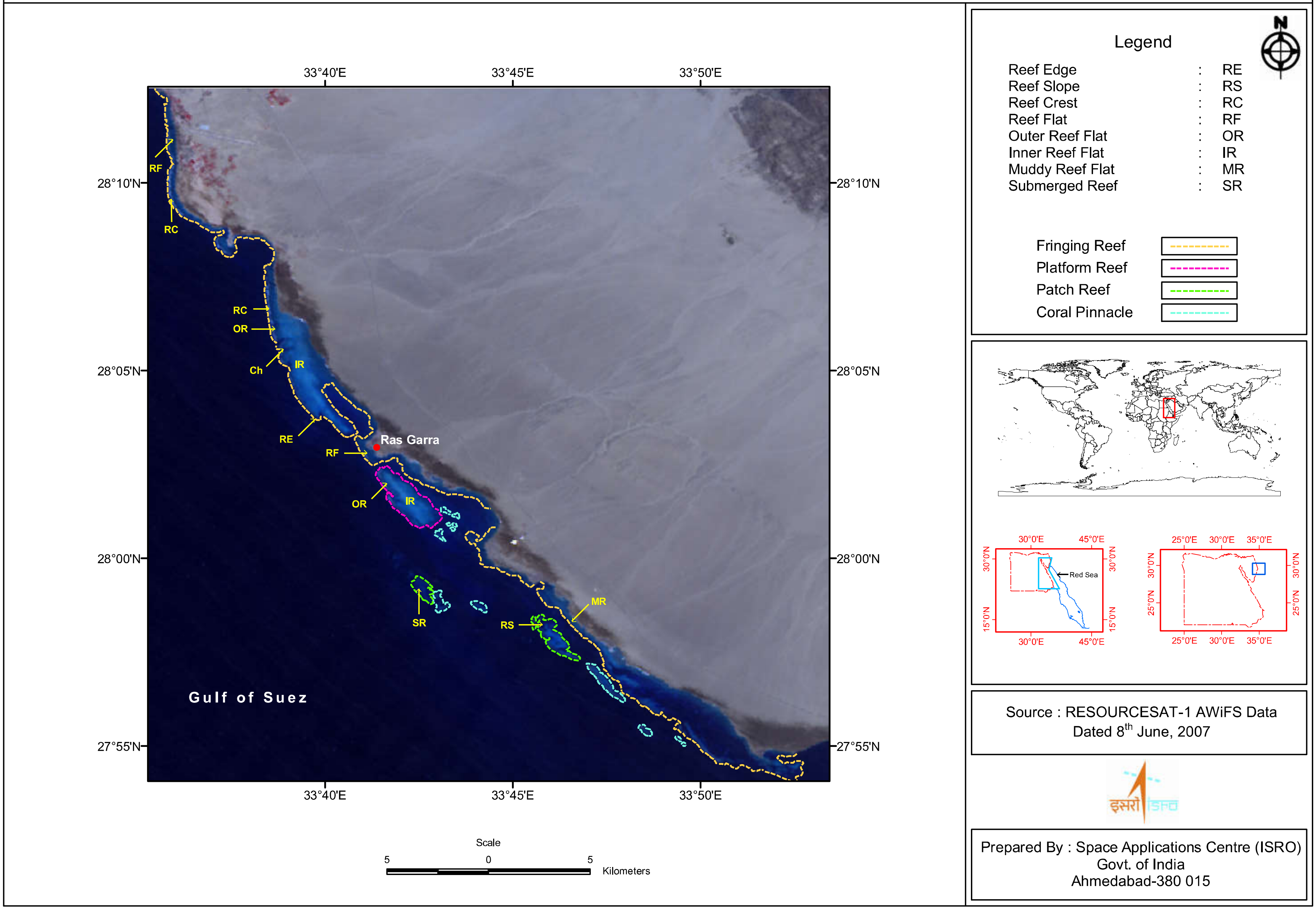
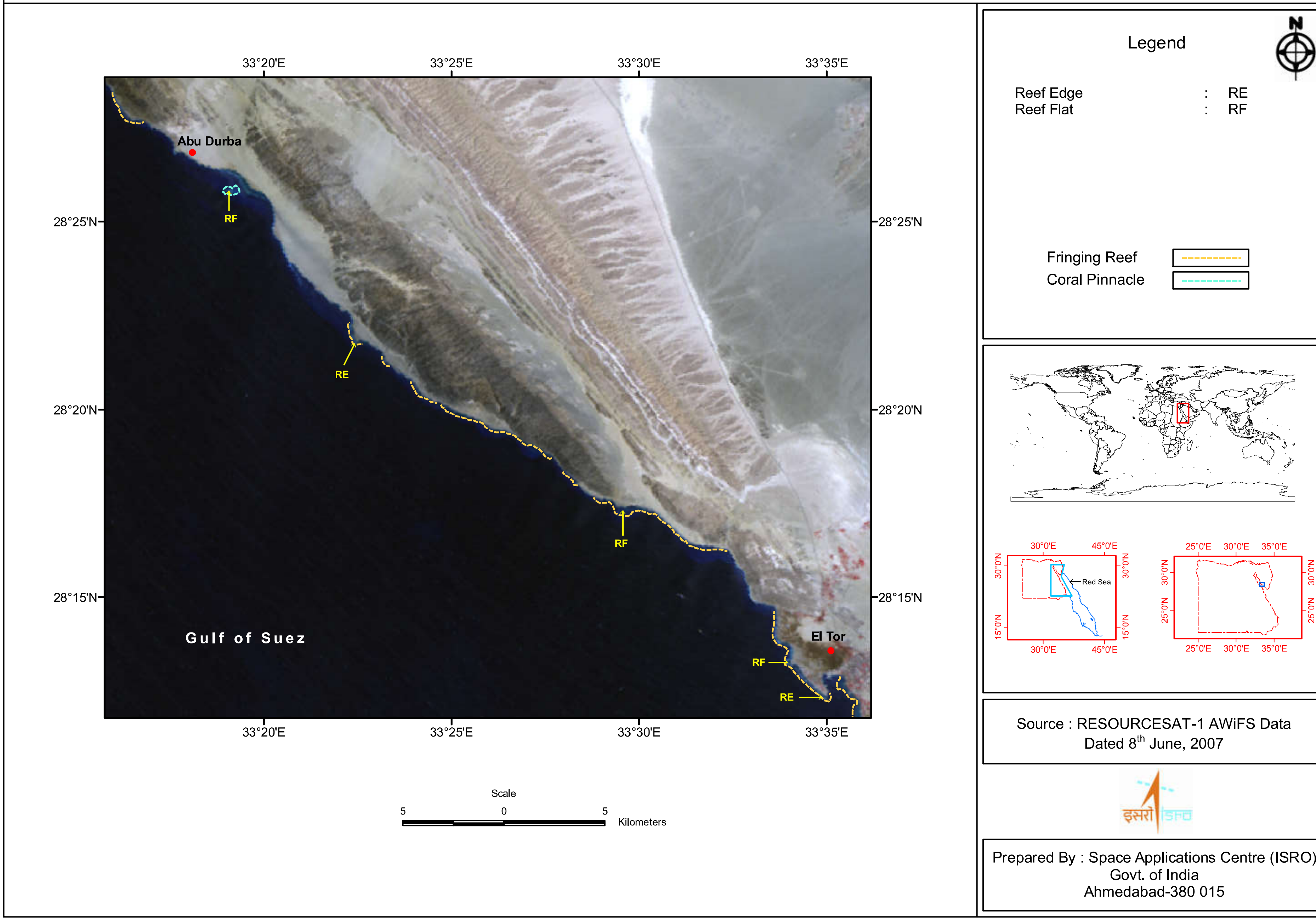
Ahmedabad-380 015

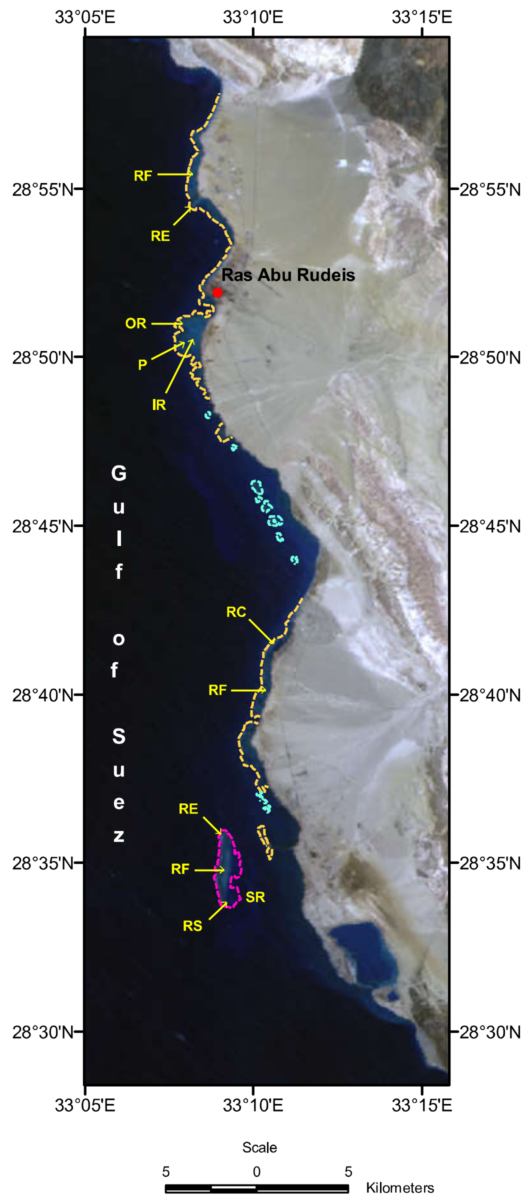
Map 6.1.1.6 : Coral reef habitats of Ras Mohammed NP and offshore reefs of Sha'ab Ali



Map 6.1.1.7 : Coral reef habitats to the south of Ras Garra



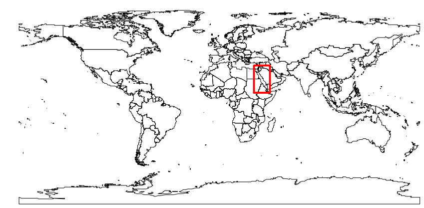
Map 6.1.1.8 : Coral reef habitats between Abu Durba and El Tor

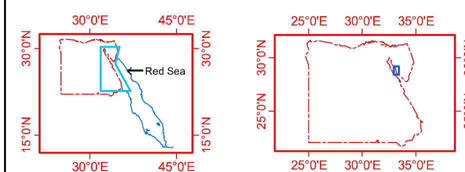


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Crest	:	RC
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Pool	:	P
Submerged Reef	:	SR

Fringing Reef
Platform Reef
Coral Pinnacle

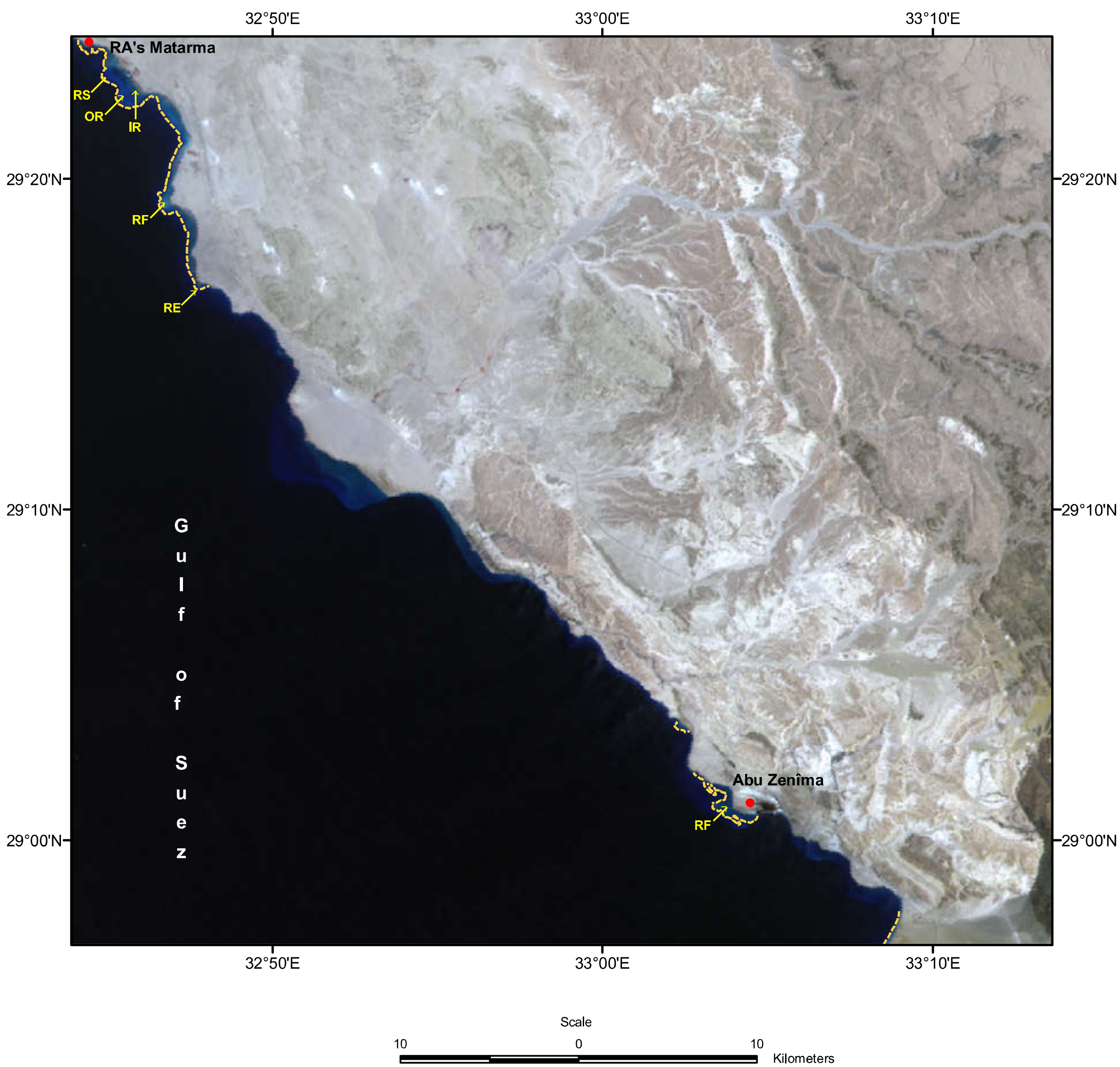




Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

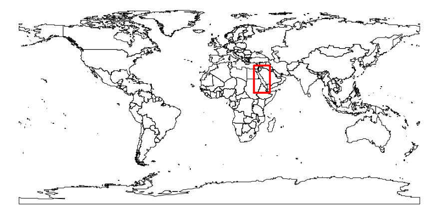
Map 6.1.1.9 : Coral reef habitats surrounding Ras Abu Rudeis

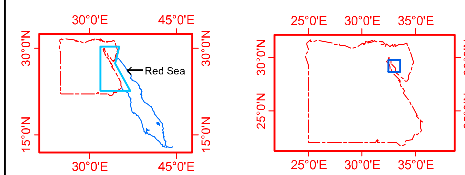


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR

Fringing Reef





Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

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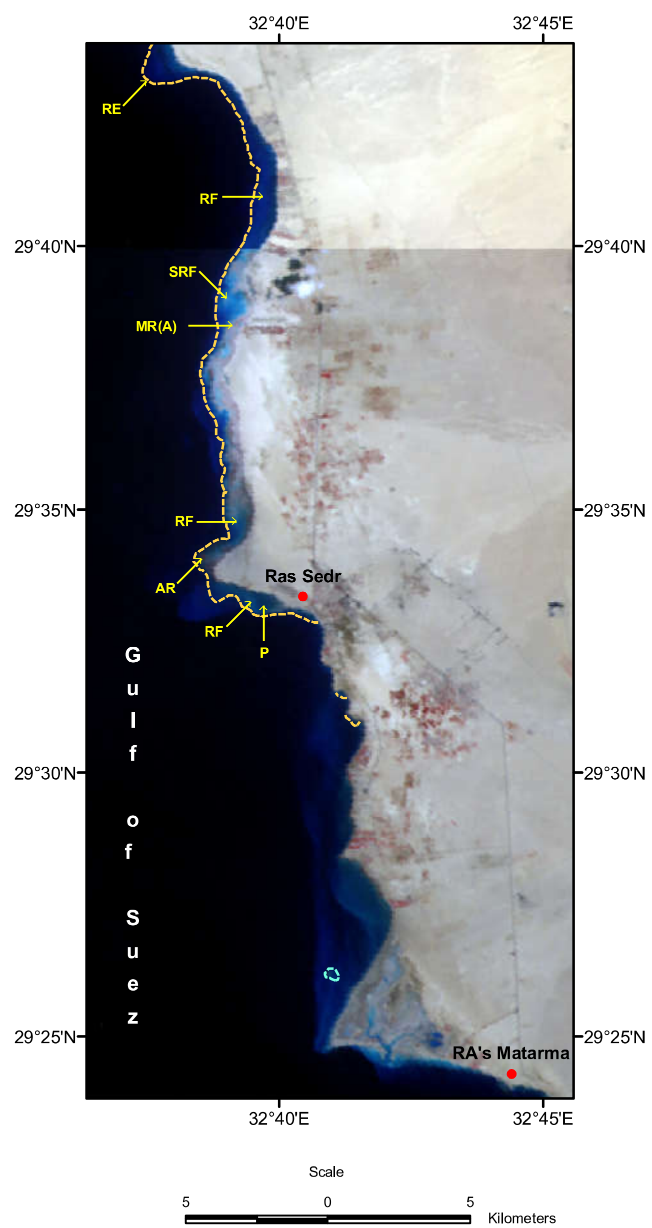
Map 6.1.1.10 : Coral reef habitats between RA's Matarma and Abu Zenîma

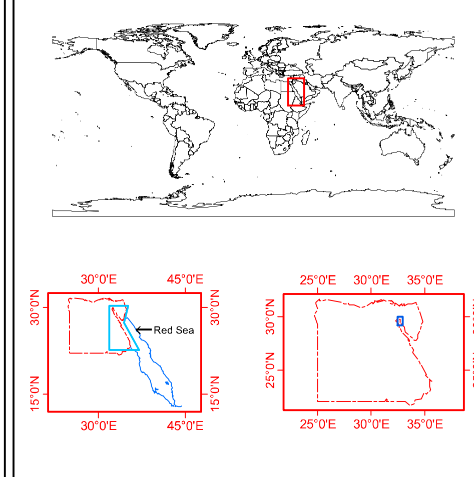


Legend

Reef Edge	:	RE
Algal Ridge	:	AR
Reef Flat	:	RF
Sanded Reef Flat	:	SRF
Muddy Reef Flat (Algae)	:	MR(A)
Pool	:	P

Fringing Reef

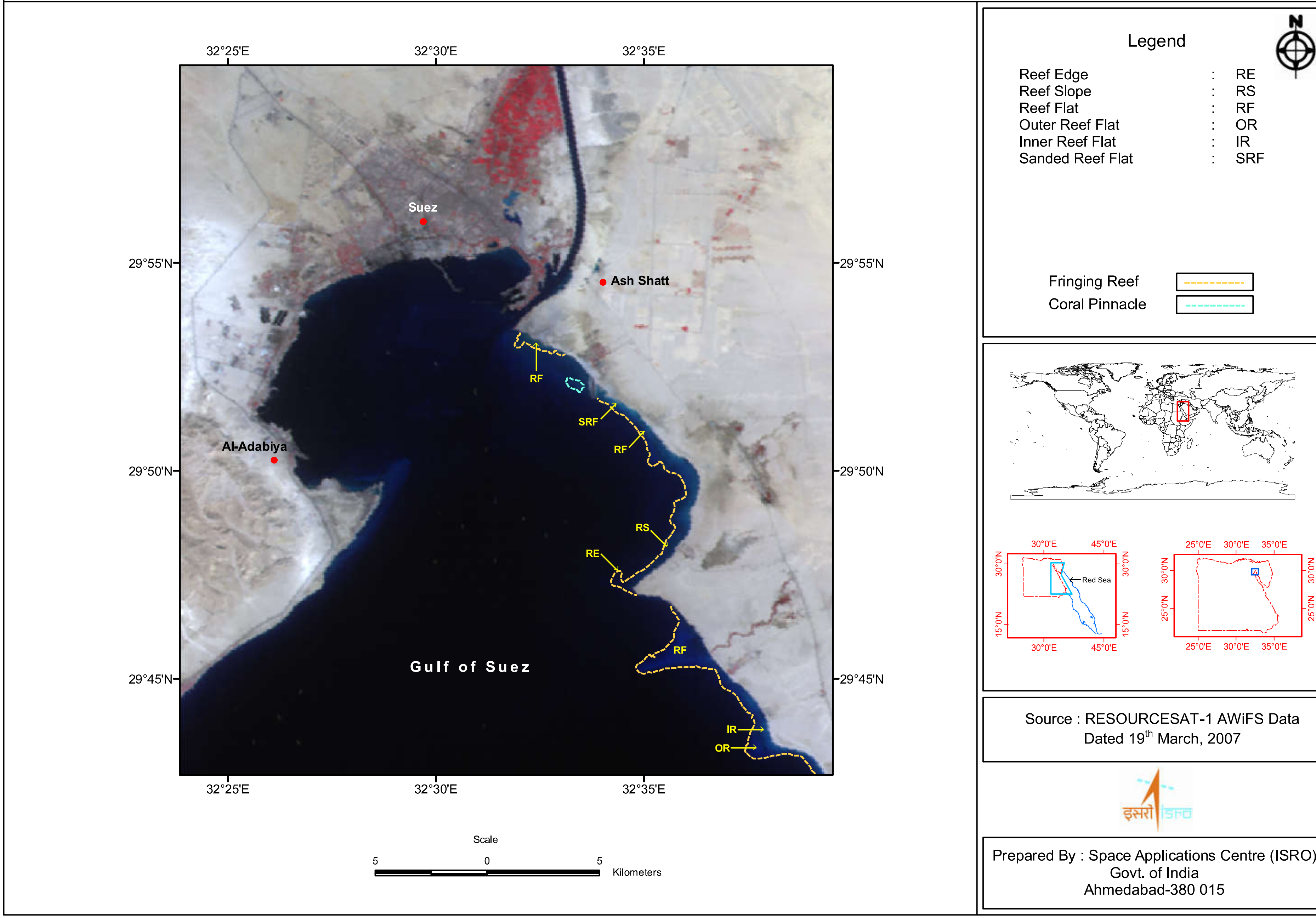
Coral Pinnacle



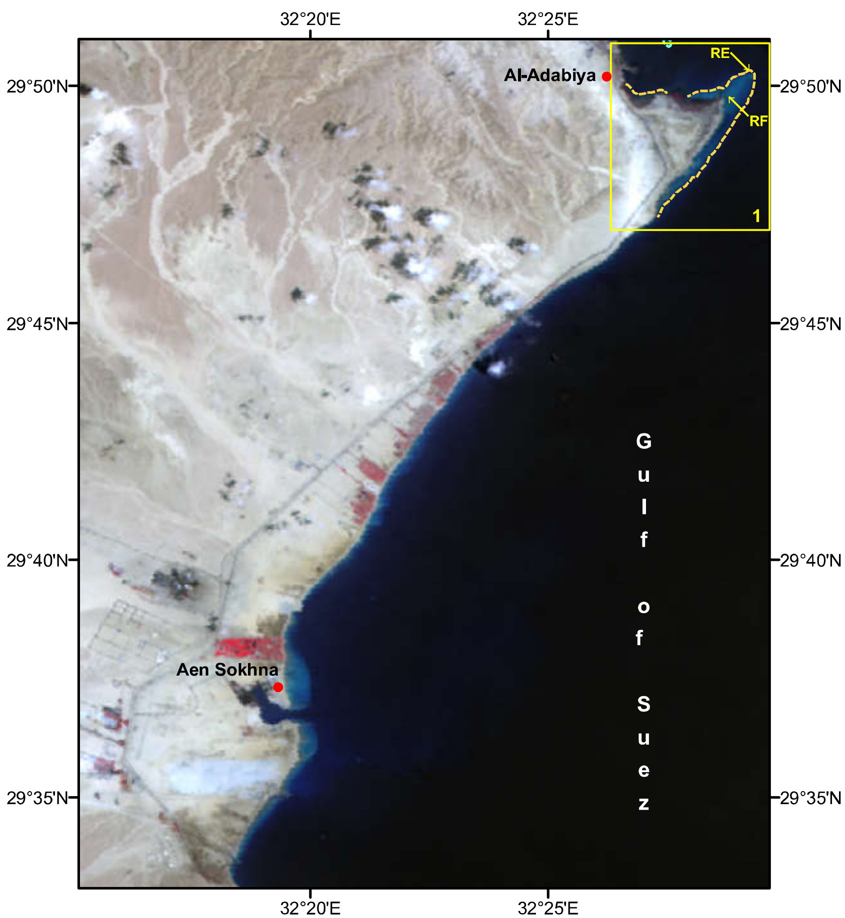
Source : RESOURCESAT-1 AWiFS Data
Dated 19th March 2007 & 8th June,2007

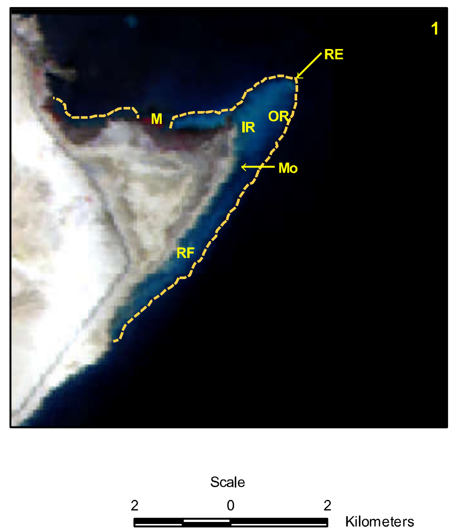
Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.1.11 : Coral reef habitats to the north of Ras Sedr



Map 6.1.1.12 : Coral reef habitats in northernmost part of Gulf of Suez



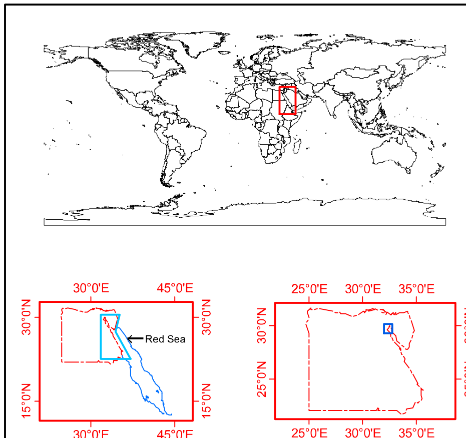


Legend

Reef Edge	:	RE
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Mangrove	:	M

Fringing Reef

Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
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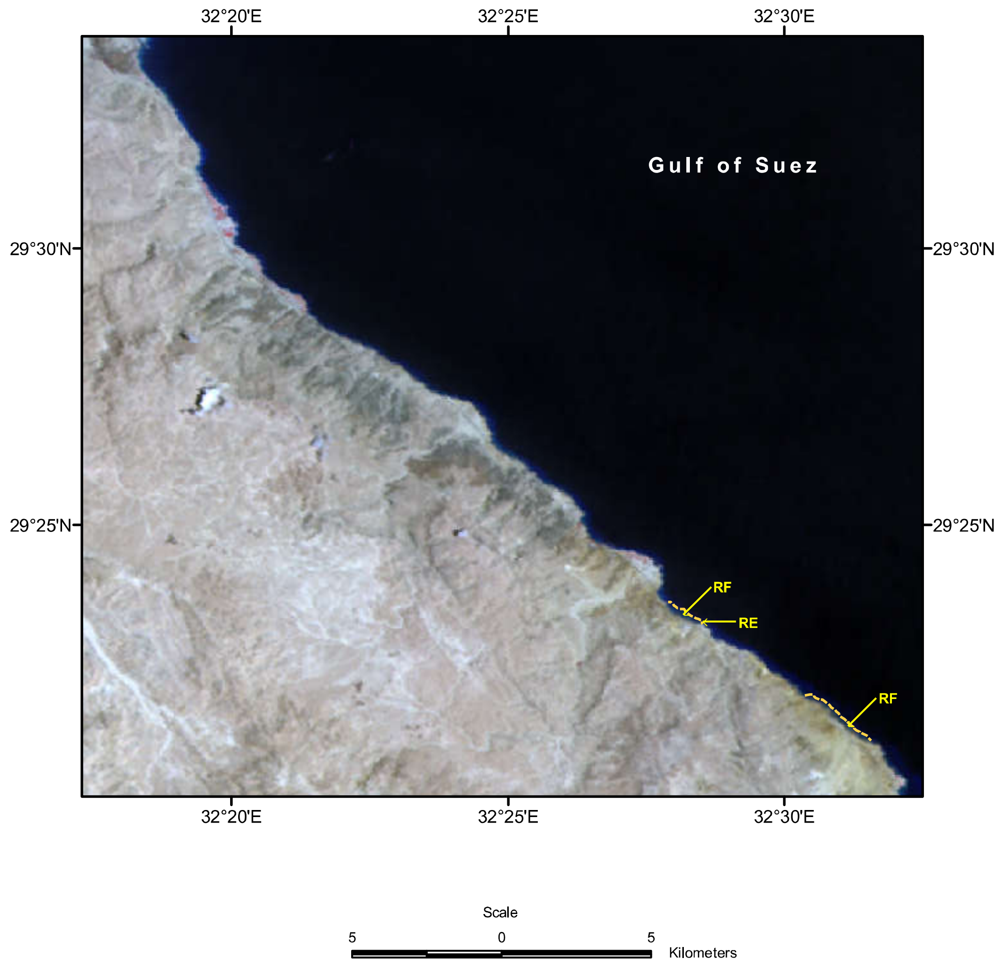
Ahmedabad-380 015

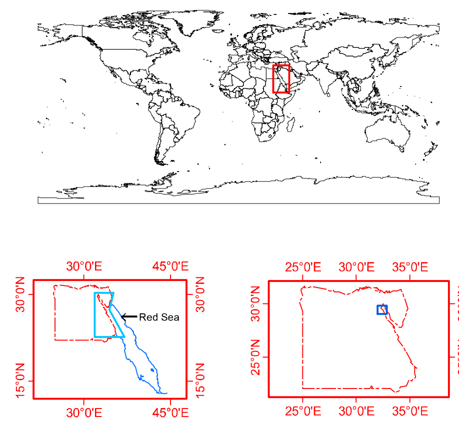
Map 6.1.1.13 : Coral reef habitats near Al-Adabiya



Legend

Reef Edge : RE
Reef Flat : RF

Fringing Reef



Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

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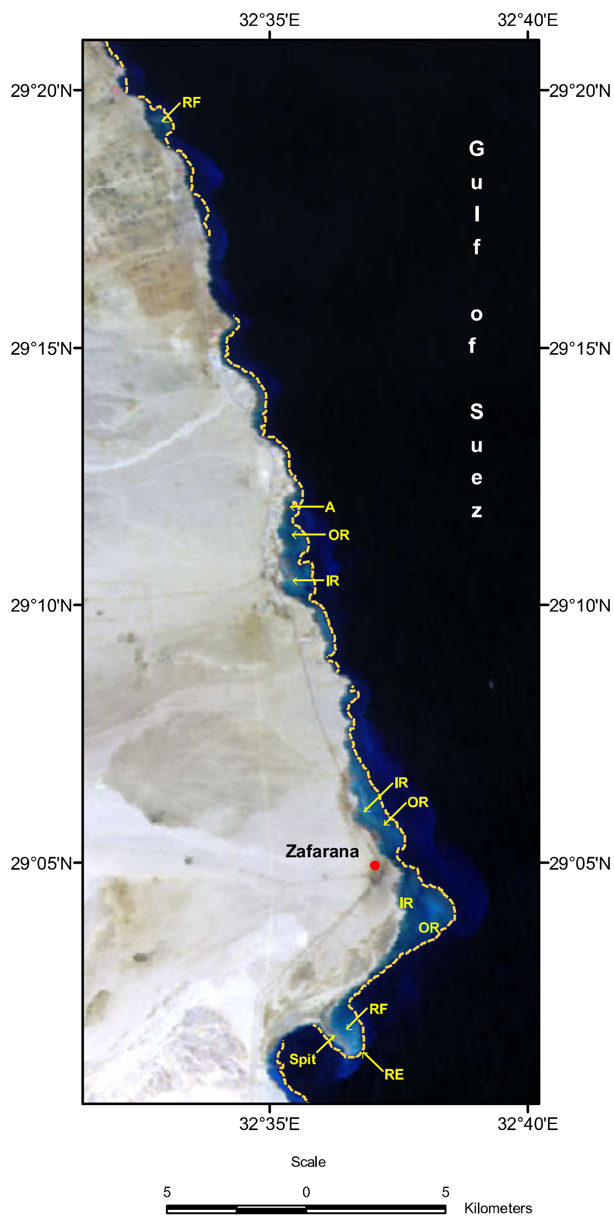
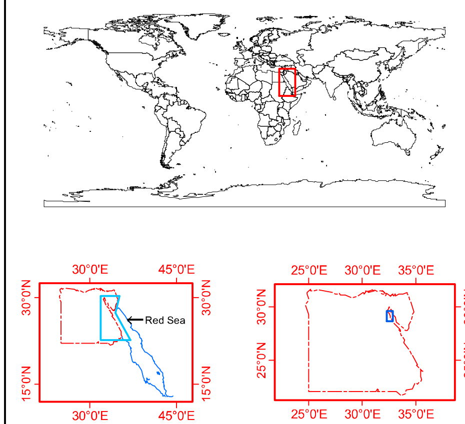
Map 6.1.1.14 : Coral reef habitats in western Gulf of Suez (segment 1)



Legend

Reef Edge	:	RE
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Algae	:	A
Spit	:	Spit

Fringing Reef



Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

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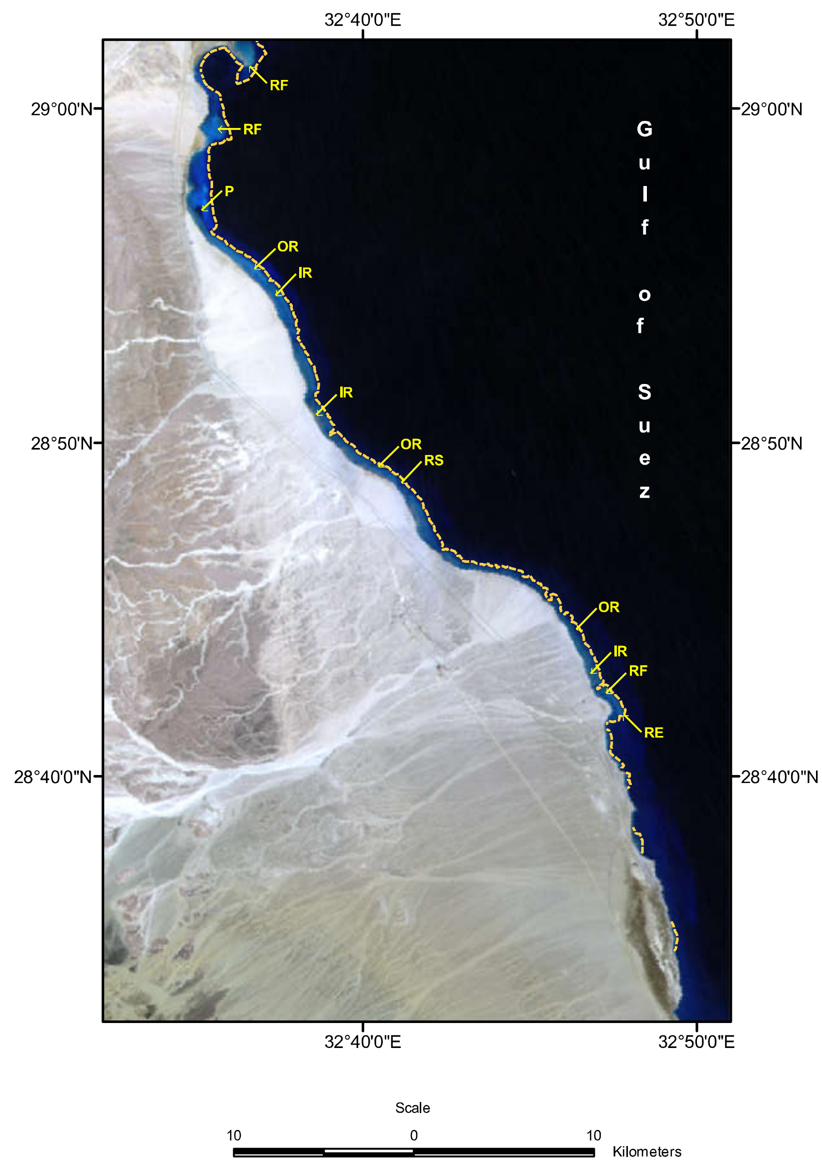
Ahmedabad-380 015

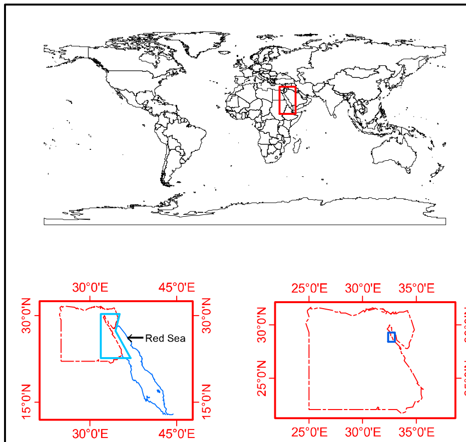
Map 6.1.1.15 : Coral reef habitats surrounding Zafarana



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Pool	:	P

Fringing Reef



Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
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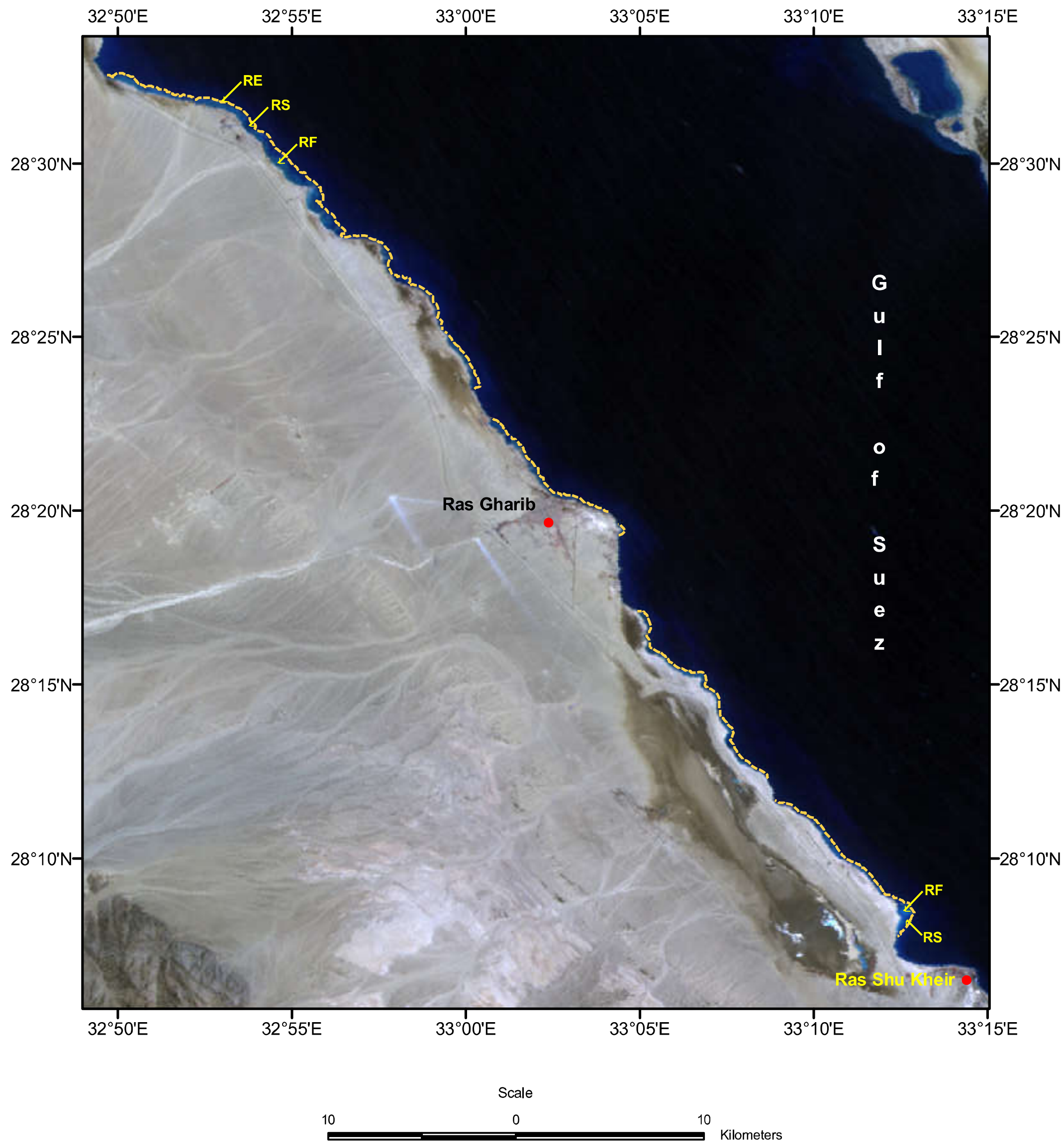
Ahmedabad-380 015

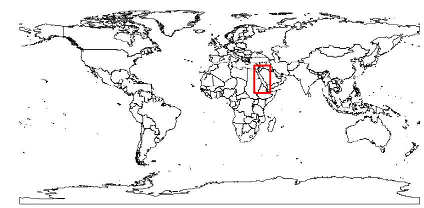
Map 6.1.1.16 : Coral reef habitats in western Gulf of Suez (segment 2)

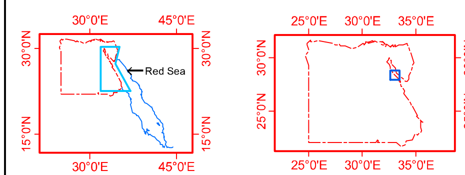


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF

Fringing Reef





Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

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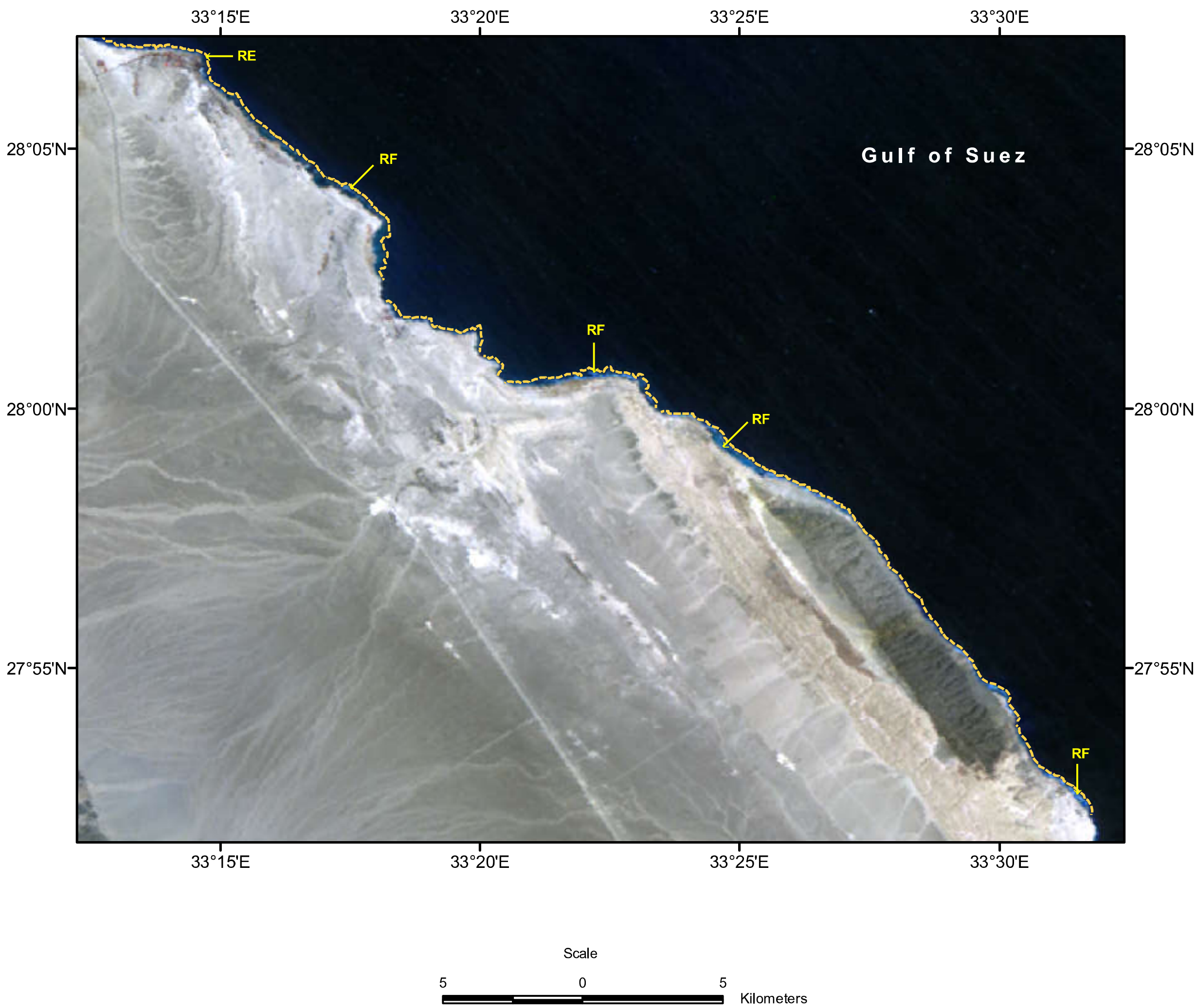
Govt. of India
Ahmedabad-380 015

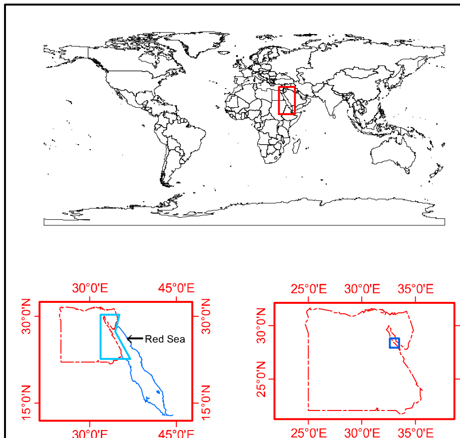
Map 6.1.1.17 : Coral reef habitats near Ras Gharib and Ras Shu Kheir



Legend

Reef Edge : RE
Reef Flat : RF

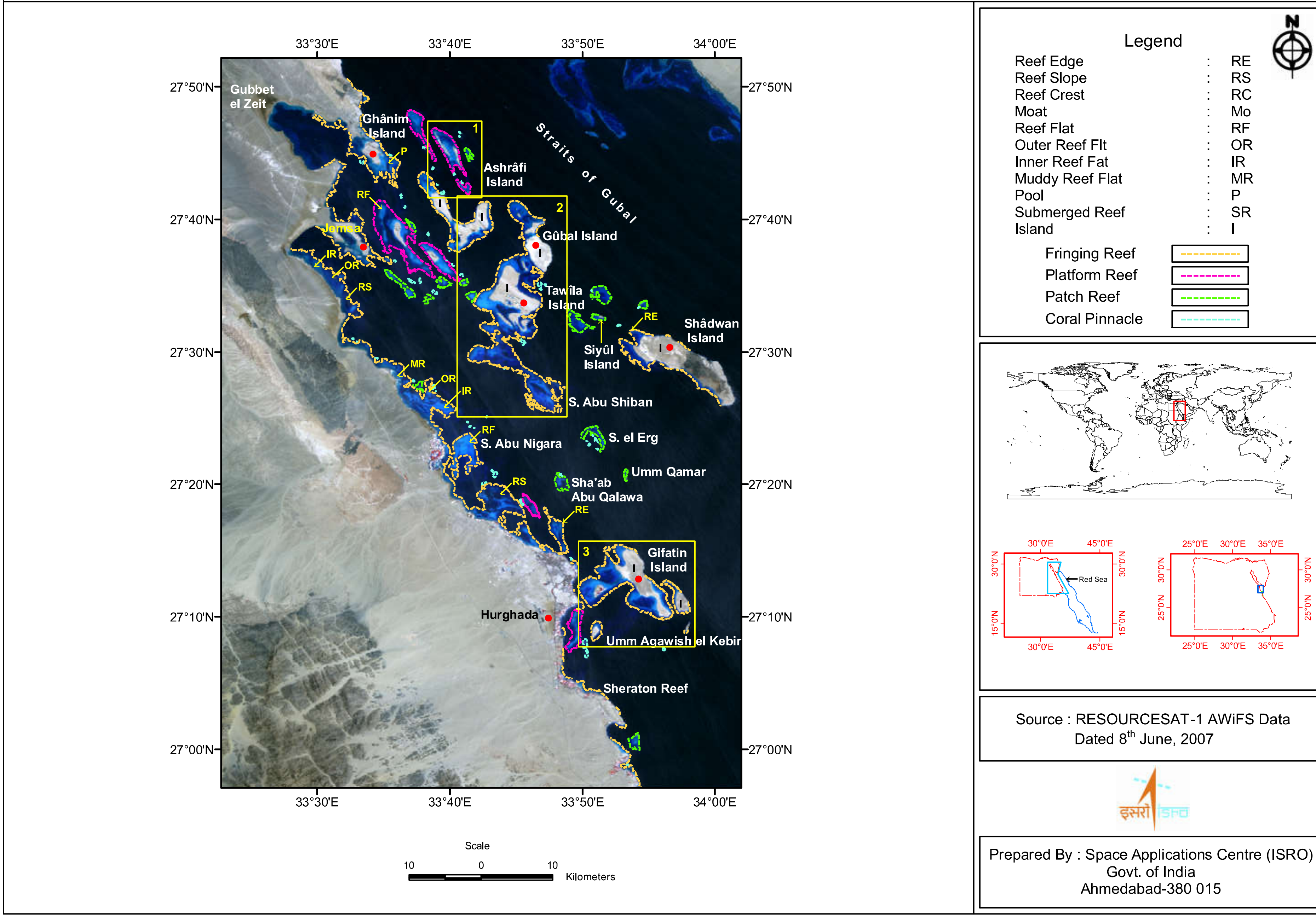
Fringing Reef



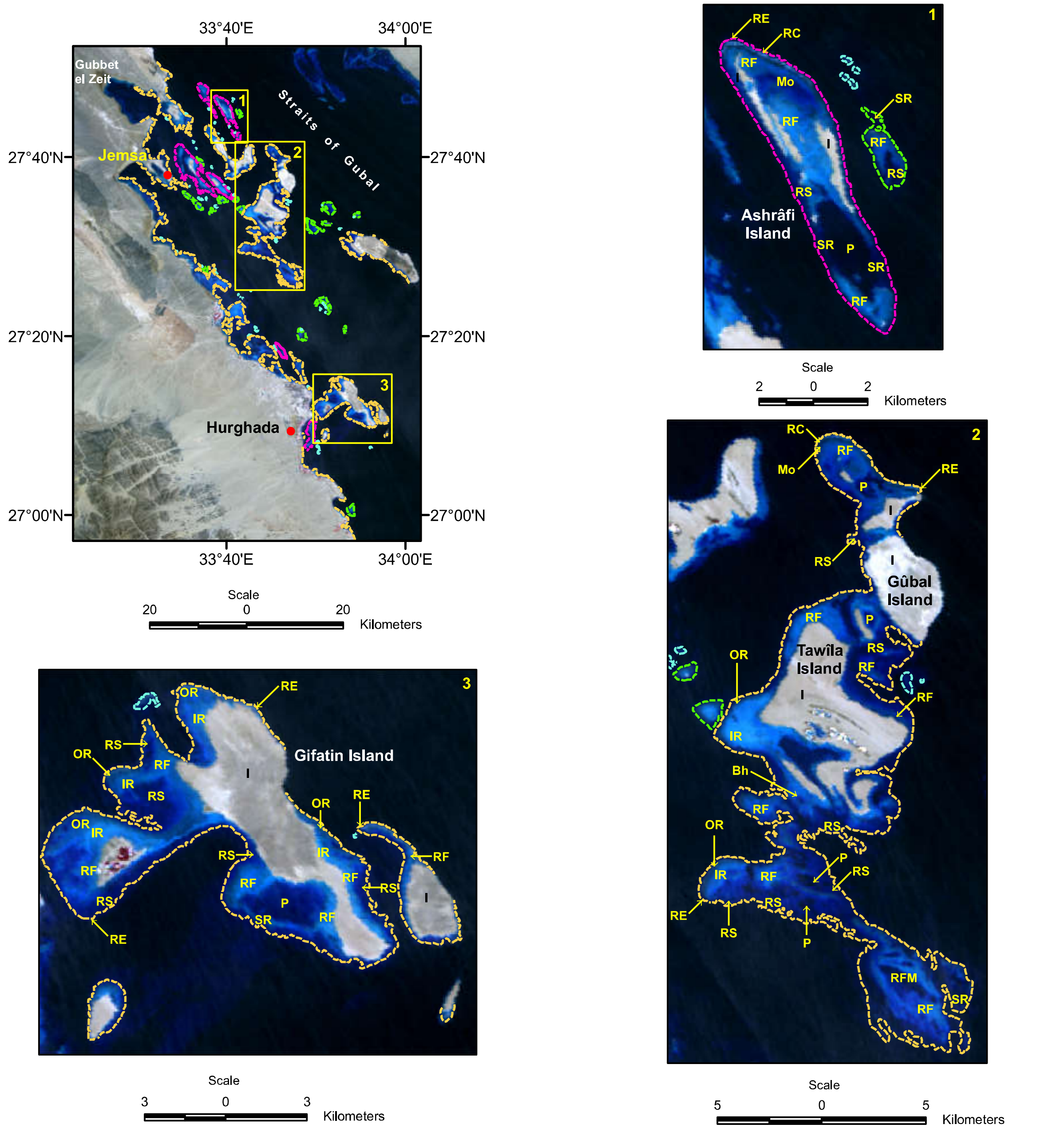
Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.1.18 : Coral reef habitats in western Gulf of Suez (segment 3)



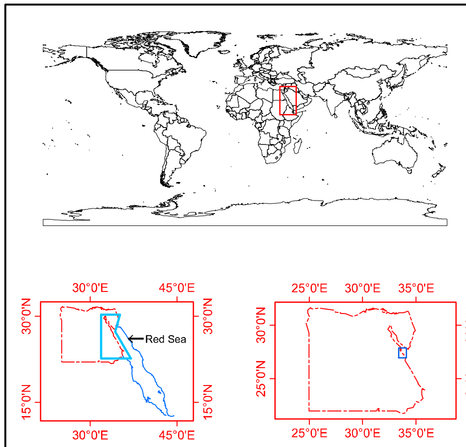
Map 6.1.1.19 : Coastal coral reef habitats between Jemsa and Hurghada and off-shore reefs in Straits of Gubal



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Crest	:	RC
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Reef Flat Moat	:	RFM
Pool	:	P
Blue Hole	:	BH
Submerged Reef	:	SR
Island	:	I

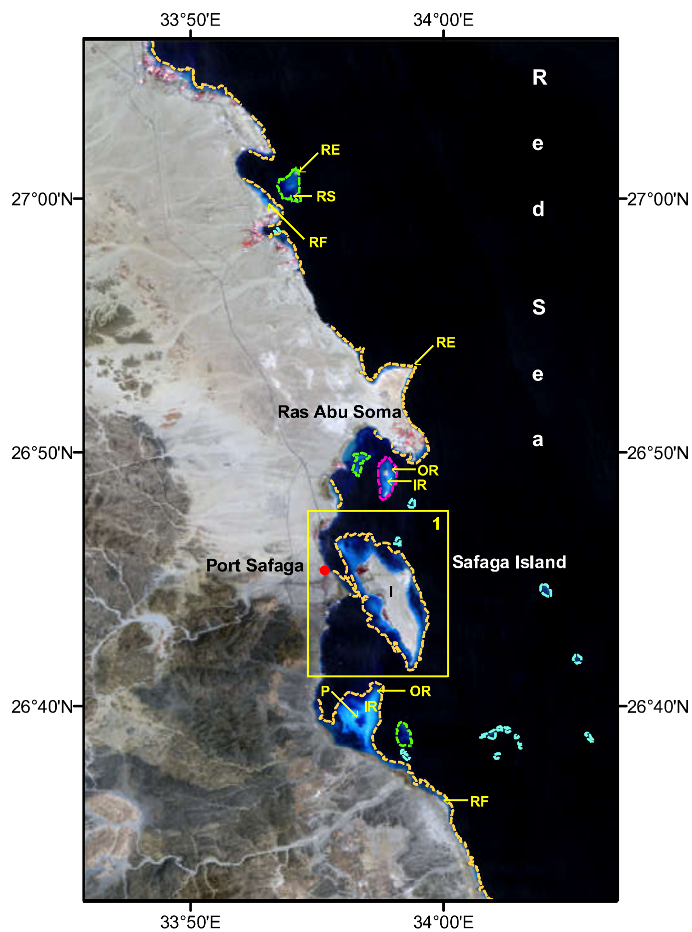
Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle

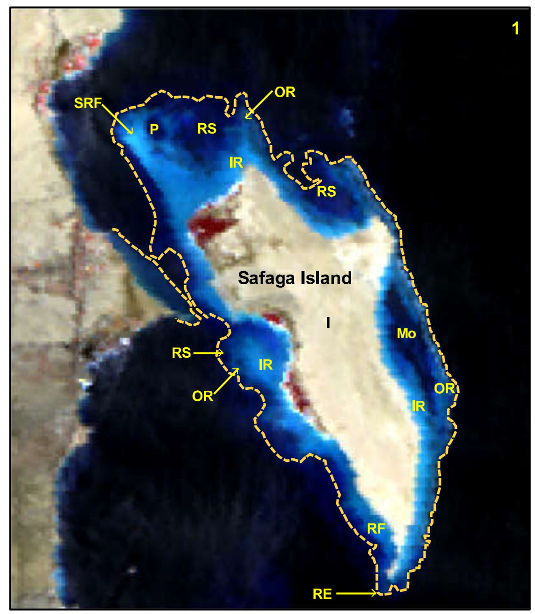


Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.1.19A : Selected coral reef habitats of Straits of Gubal

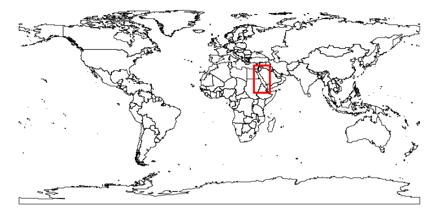


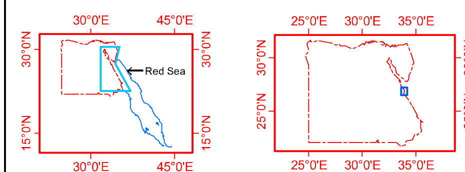


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Pool	:	P
Island	:	I

Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle

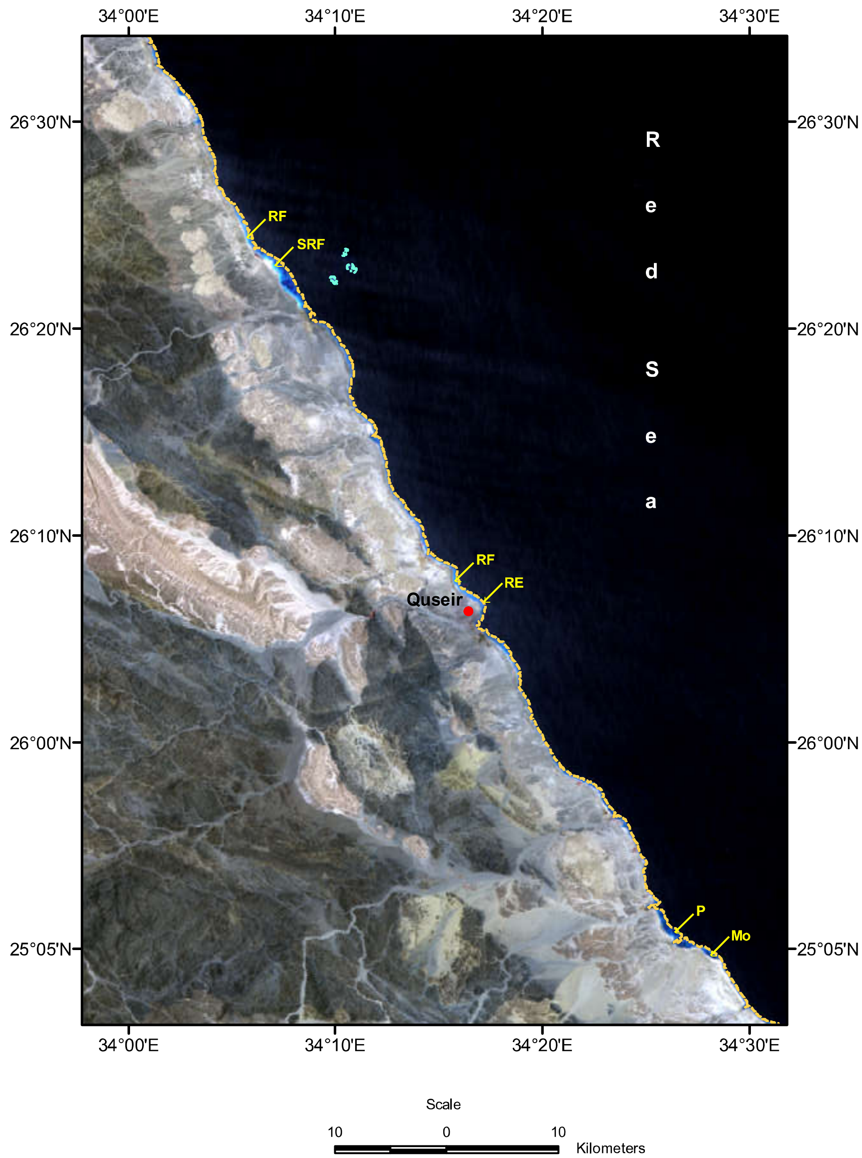




Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

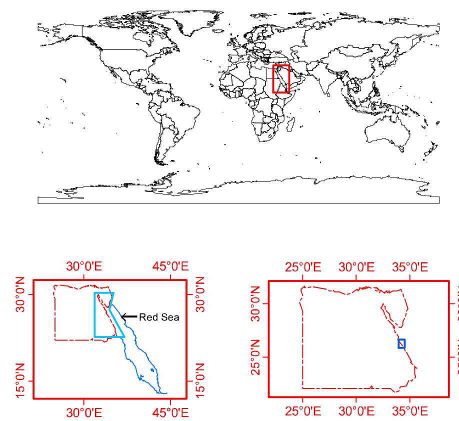
Map 6.1.1.20 : Coral reef habitats of Safaga Island and surroundings



Legend

Reef Edge : RE
Moat : Mo
Reef Flat : RF
Sanded Reef Flat : SRF
Pool : P

Fringing Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
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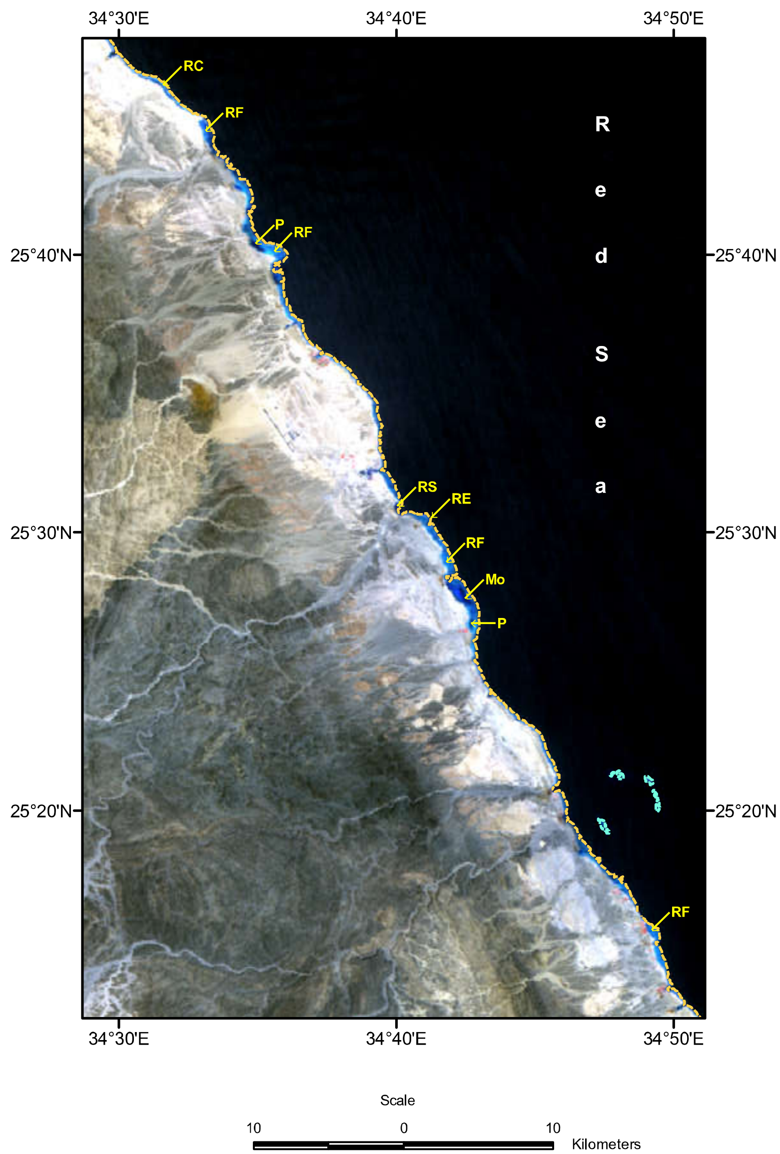
Ahmedabad-380 015

Map 6.1.1.21 : Coral reef habitats of Quseir Dive Center and surroundings

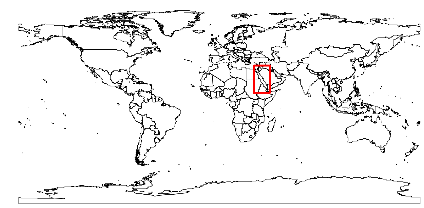


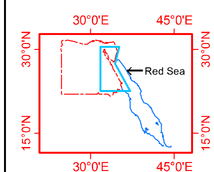
Legend

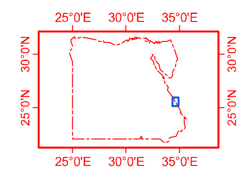
Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Flat	:	RF
Pool	:	P

Fringing Reef

Coral Pinnacle







Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
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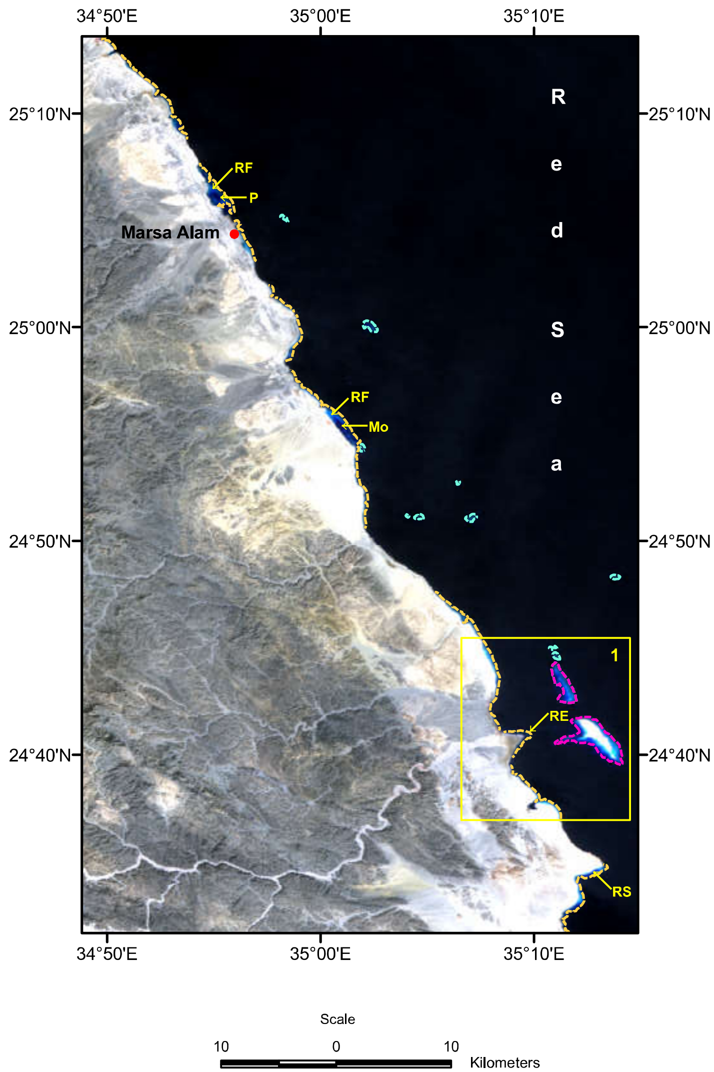
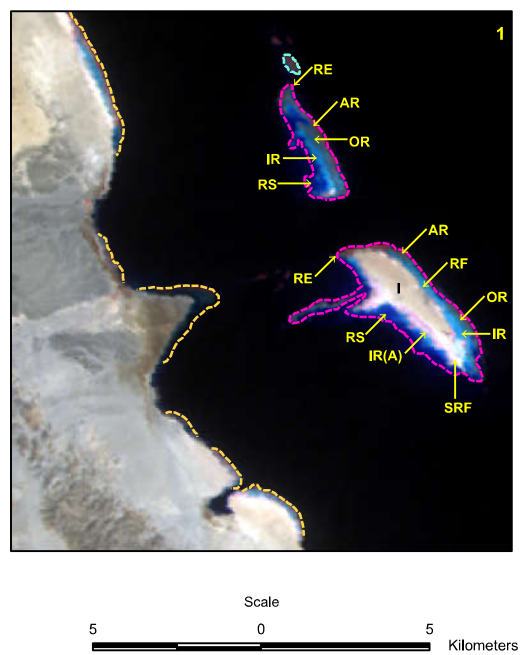
Map 6.1.1.22 : Coral reef habitats of Egypt : Red Sea coast (segment 1)

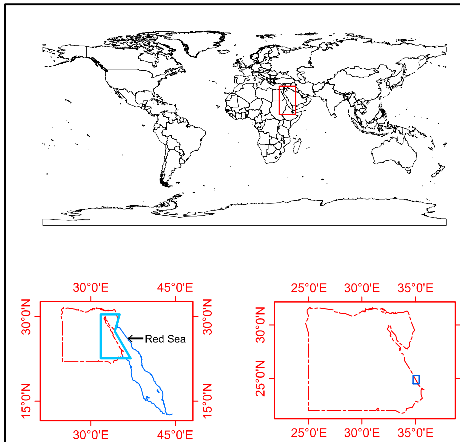




Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Algal Ridge	:	AR
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Inner Reef Flat (Algae)	:	IR(A)
Sanded Reef Flat	:	SRF
Pool	:	P
Island	:	I

Fringing Reef
Platform Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 13th February, 2007 & 19th March 2007

Prepared By : Space Applications Centre (ISRO)
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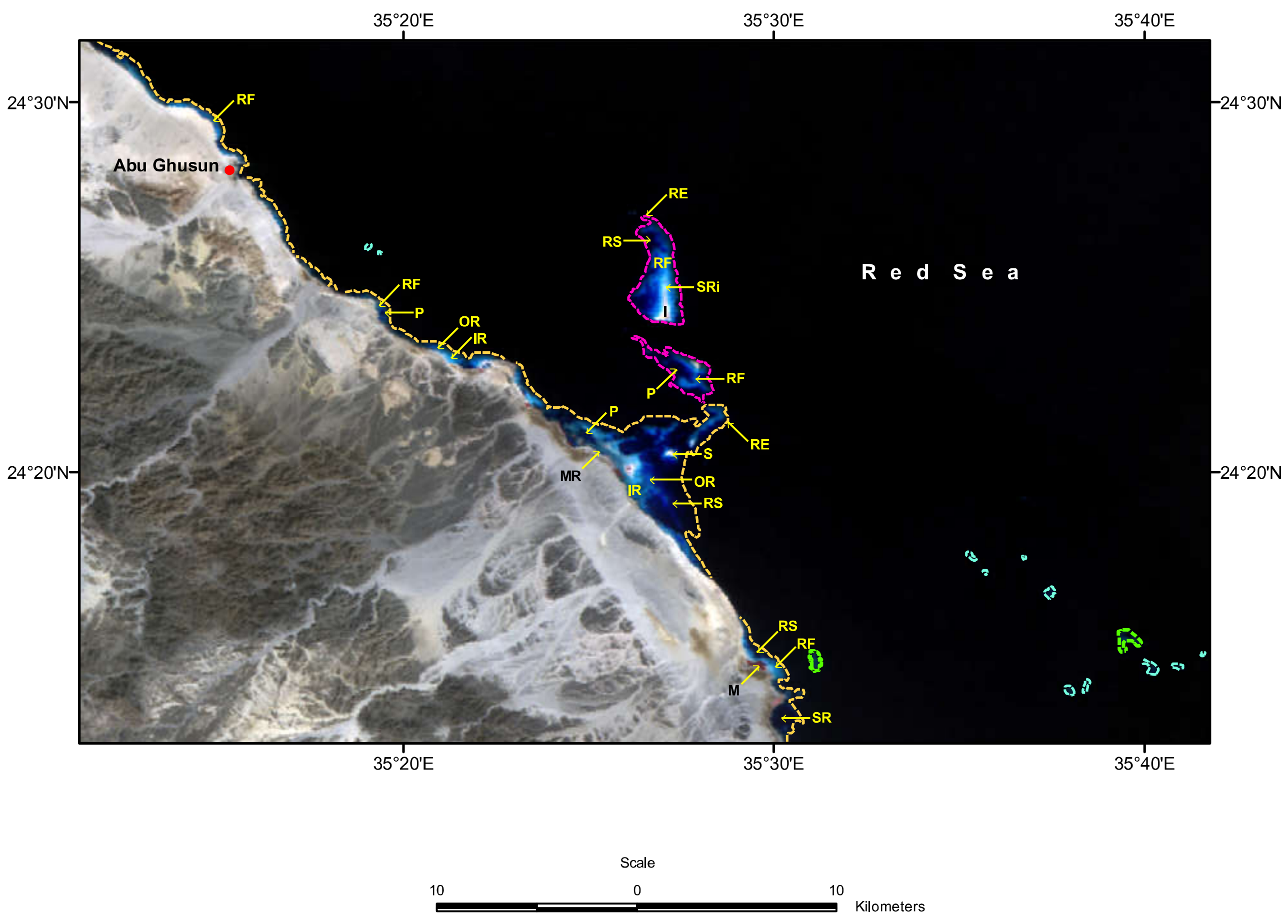
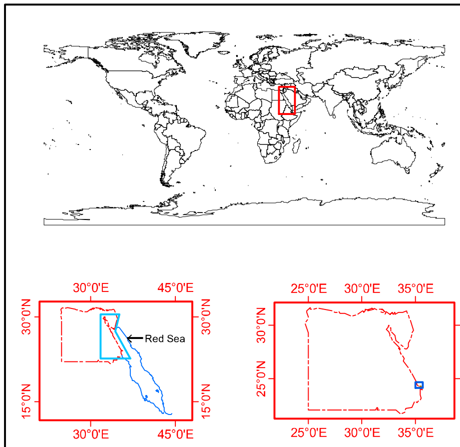
Map 6.1.1.23 : Coral reef habitats near Marsa Alam and offshore reefs



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Muddy Reef Flat	:	MR
Sandy Ridge	:	SRi
Sand Patches	:	S
Pool	:	P
Submerged Reef	:	SR
Island	:	I
Mangrove	:	M

Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 13th February, 2007

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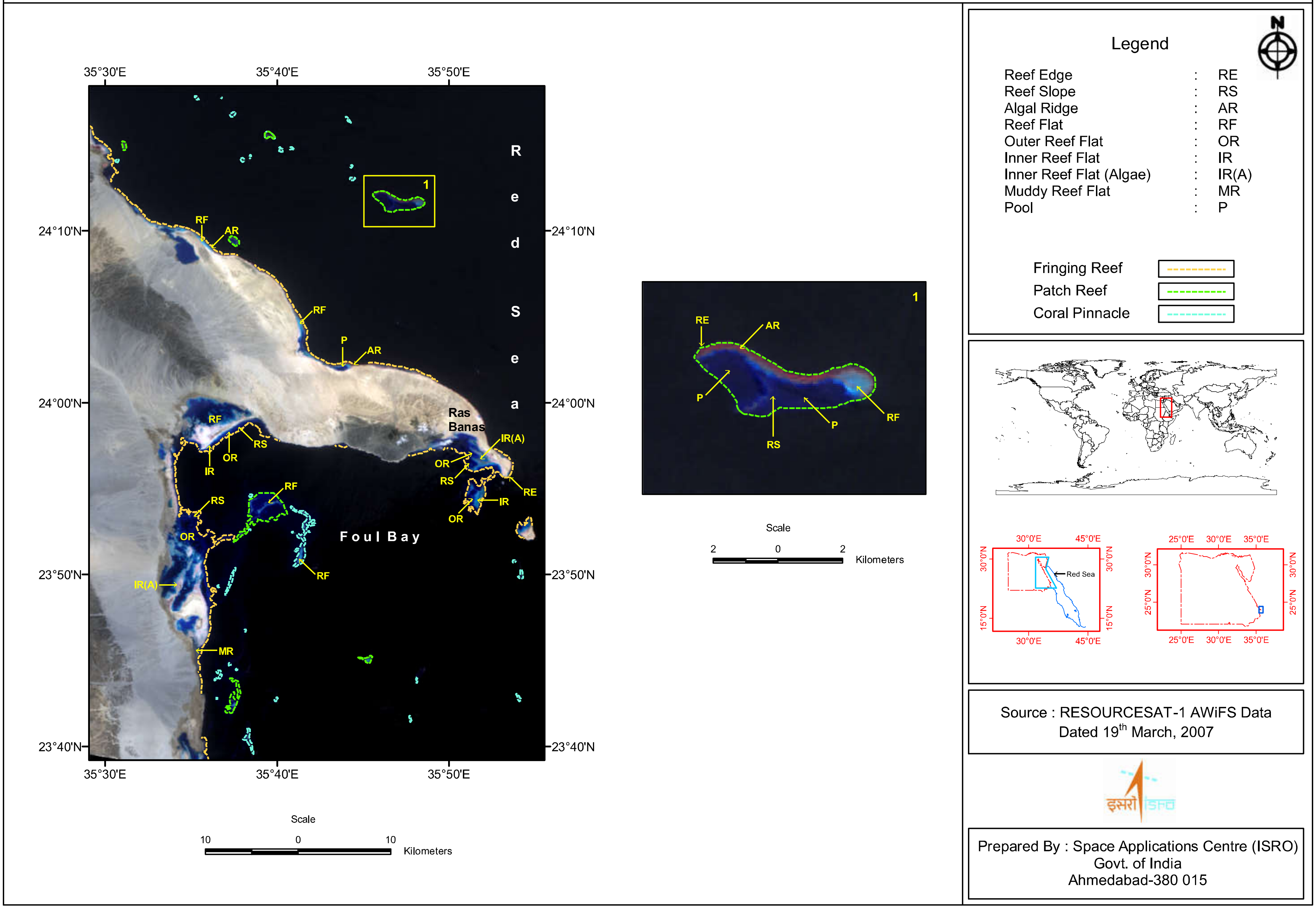
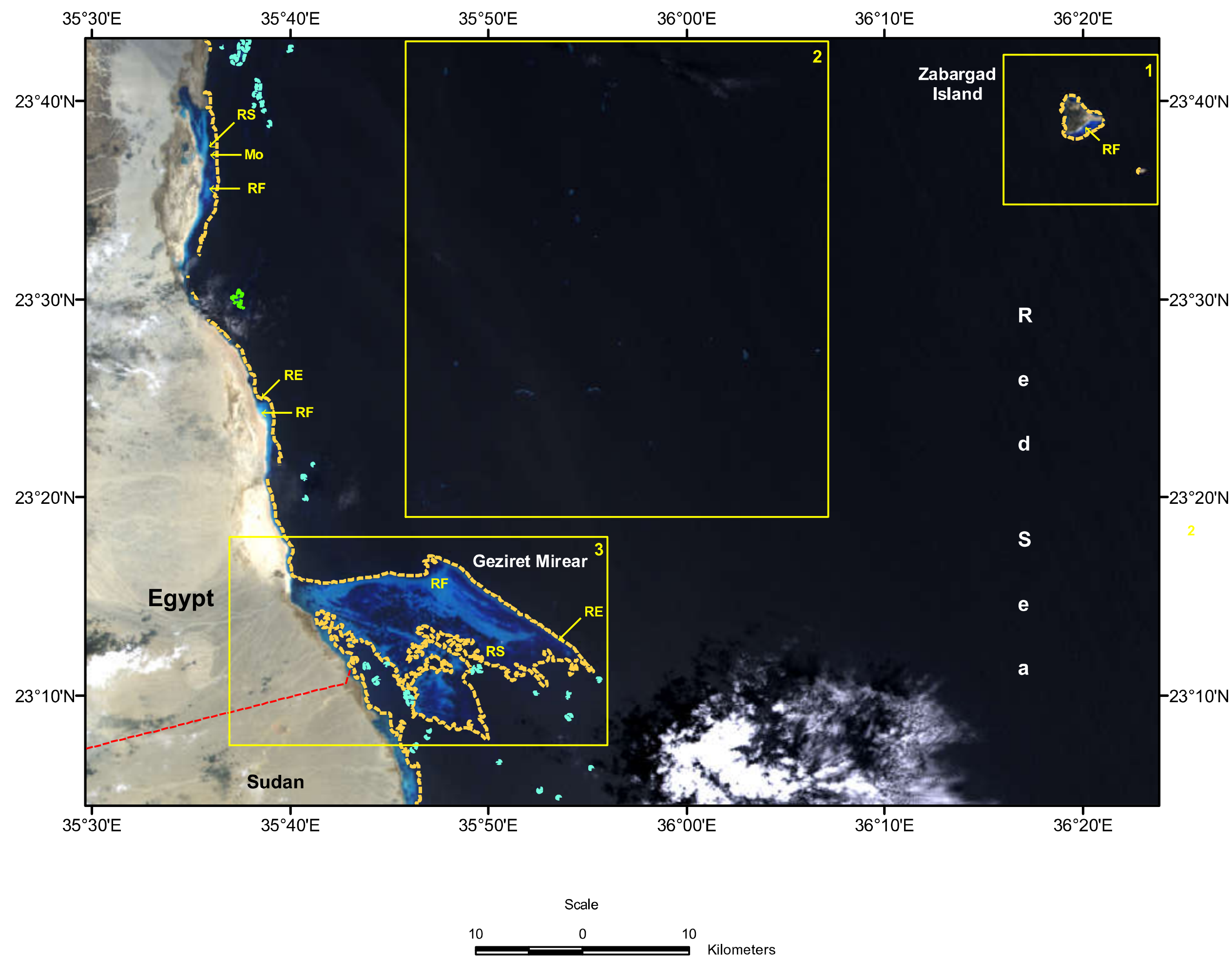
Map 6.1.1.24 : Coral reef habitats to the south of Abu Ghusun and offshore reefs



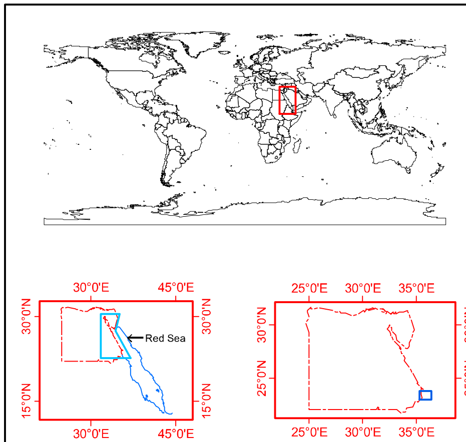
Map 6.1.1.25 : Coral reef habitats of Ras Banas and Foul Bay



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Crest	:	RC
Reef Flat	:	RF
Pool	:	P
Island	:	I

Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 25th August, 2005

Prepared By : Space Applications Centre (ISRO)
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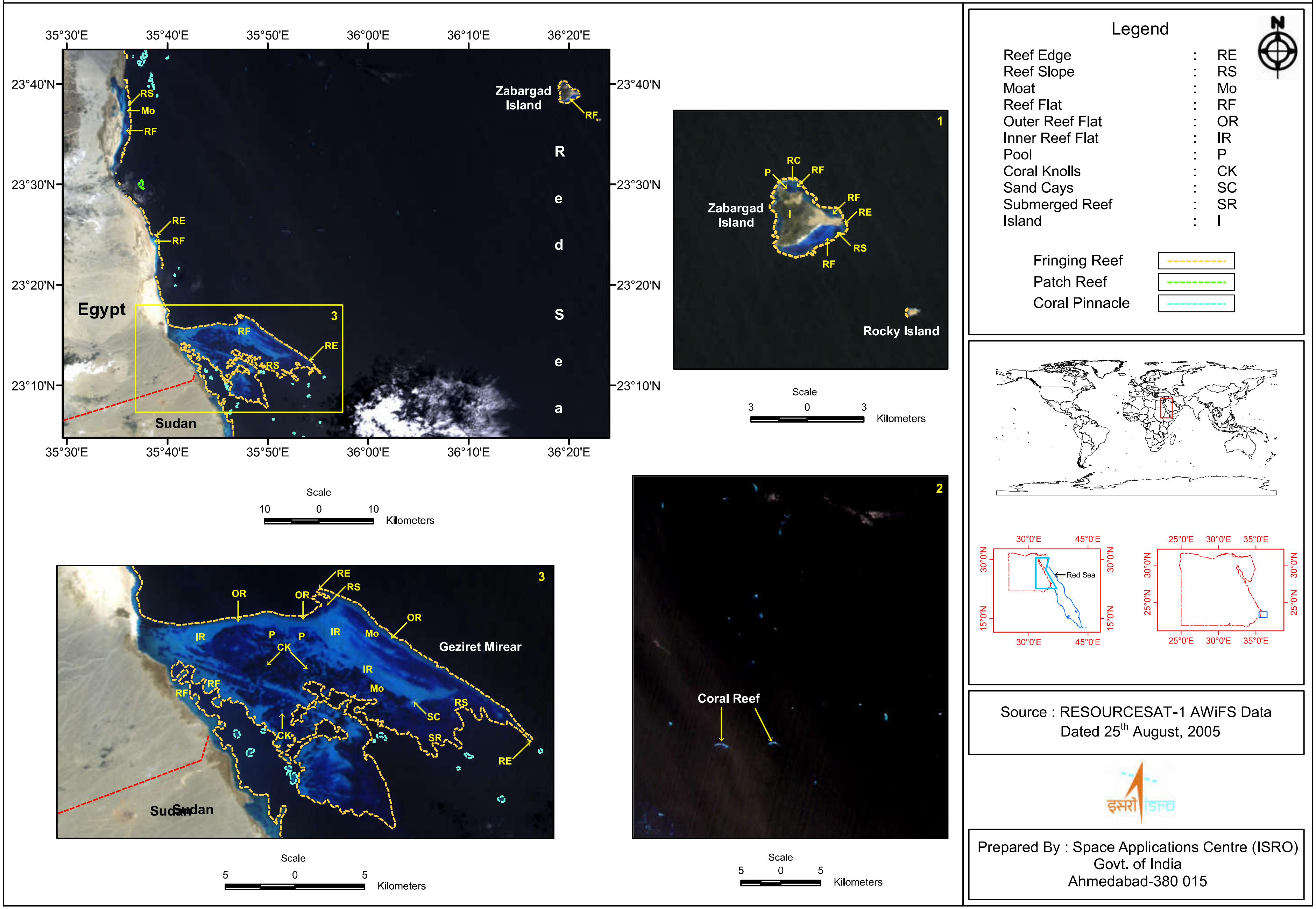
Map 6.1.1.26 : Coral reef habitats of Geziret Mirear and off-shore island of Zabargad



Map 6.1.1.26A : Selected coral reef habitats of Geziret Mirear and off-shore island of Zabargad

6.1.2. Sudan

Background

The 750 km long coastline of Sudan represents the west coast of the central Red Sea. The coast of Sudan extends within the geographical co-ordinates of 18°00′ - 23°06′ N latitudes and 35°35′ - 38°38′ E longitudes. Sudan shares its boundary with Egypt in the north and Eritrea in the south. The north-south oriented coastline of Sudan is characterized with a steep continental shelf which widens and inclines gently to the south of 20° N latitude (Spalding *et al.* 2001). Coral reefs fringe the Sudanese coast including bays and inlets and stretch farther out to the sea where the coast has wide alluvial fans. The Sudanese coast is marked with variable biodiversity environments (Kotb *et al.* 2008). Coral reefs have flourished in Sudanese waters where salinity ranges from 39 to 41 ppt and the water transparency is very high, reaching up to 70 metres (Pilcher and Nasr 2003).

Sudanese coast encompasses three primary coral reef habitats: an extensive near-continuous coastal fringing reef, a complex off-shore barrier reef system and the oceanic atoll of Sanganeb which is a Marine Protected Area (MPA) of global importance (Klaus *et al.* 2008). Sanganeb atoll is the only true atoll among many atoll-like features which mark both the west and east coasts of central Red Sea. Field surveys have established an average coral cover of 40% (with 25% hard corals and 15% soft corals) in Sudanese reefs which are generally in good health condition (Kotb *et al.* 2008). These reefs are among the most biologically diverse reefs in the entire Western Indian Ocean region (Spalding *et al.* 2001). The coastal fringing reefs had suffered massive damages in the 1997-98 bleaching event while the off-shore reefs were unaffected and still remains in good health condition (Kotb *et al.* 2004). Recovery in the coastal reefs has been patchy, with periodic COTS outbreak (as in 2007) affecting the rate of recovery. Damages from coral eating mollusk *Drupella* and coral diseases are minimal on these reefs (Kotb *et al.* 2004).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Sudan have been mapped with Resourcesat-1 AWiFS data (3 scenes, dated: 2nd and 25th August, 2005 and 22nd September, 2008). Detailed habitat characteristics of Sudanese reefs have been depicted in thirteen reef habitat maps (Map No.6.1.2.1 to 6.1.2.13). Near continuous coral reefs fringe the coast of Sudan along with an off-shore barrier reef system and the oceanic atoll of Sanganeb. Fringing and patch reefs along with coral pinnacles are located off-shore too. The near-continuous coastal fringing reef runs right from the Egypt border to the coastal plains facing the off-shore Saqir Island and this whole length of Sudanese coast is also dotted with off-shore fringing, patch and pinnacle types of reefs. The Sanganeb atoll (near Port Sudan) and the barrier reef appear in the southern part of the Sudanese coast.

The northern coast of Sudan is fringed by a long, continuous reef (Map No.6.1.2.1, 6.1.2.2) with shallow reef flats few tens of meters wide (Spalding *et al.* 2001). This coastal fringing reef starts south of the magnificent reef structure of Geziret Mirear (Map: 6.1.2.1) and show distinct zonation between reef slope and reef flat. The reef flat can be separated into outer and inner reef flats. In certain parts the reef flat is deposited with sand. A shore parallel, linear reef flat moat is detected in the southern part of the reef. Forty five coral pinnacles have been detected from the AWiFS data dated 25th August, 2005. The reef flat relatively widens out down south (Map: 6.1.2.2) and can be visible separated from the reef slope. The reef flat can be distinguished into outer and inner reef flats, the latter turning into sanded reef flats in the shoreward margins. Two coastal lagoons are located in the northern side, with the larger one dotted with small coral knolls. Narrow channels are maintaining a link between these coastal lagoons and the open sea. The inward margin of the coastal lagoons appears muddy and very small pockets of mangroves are located near the smaller lagoon. Two semi-circular pools are also located on the reef flat. A long, wide reef flat moat is located in the southern part of the reef. Ten off-shore coral pinnacles have been detected in this part of the Sudanese coast.

Near Siyal and Rawabel islands, the coastal fringing reef widens out and is interspersed with deep pools and has a crenulated boundary (Map: 6.1.2.3). The reef flat can be distinguished into outer and inner reef flat at certain places and the reef flat area adjacent to the coastline appears muddy. Sanded reef flats are also seen in two distinct locations on the reef. One reef flat moat is found to separate the muddy reef flat from the reef flat. Presence of algae is also noticed on the reef flat. Off-shore fringing reefs of Siyal and coral pinnacles of Rawabel islands could only be detected with AWiFS data dated 2nd and 25th August, 2005. However, detail mapping of these islands require high resolution data. Eight patch reefs and one hundred and forty four coral pinnacles have been detected in this segment of the Sudan coast. Farther south, the coastal fringing reef narrows down (Map: 6.1.2.4) and widens out near Gezirat Halaib El-kebir island. Only in few places the reef flat can be distinguished into outer and inner reef flats. Sanded reef flat is noticed near the island. At certain places, moats separate reef slope and reef flat while the reef flat is interspersed with pools near the Gezirat Halaib El- kebir island. One patch reef and twenty six coral pinnacles have been detected in this segment of the Sudanese coast.

The narrow reef fringes the Sudanese coast from Ras Hadarba to Ras Abu Shagara along with twenty nine off-shore coral pinnacles and six major atoll-like structures along with coral knolls (Map: 6.1.2.5). In this segment, the soft sediment coast of Sudan is dissected by shore-perpendicular terrestrial streams. An atoll structure and a portion of the coastal fringing reef (Map: 6.1.2.5; subset: 1 and 2) have been zoomed to show the intra-reef details. The small atoll shows classical reef zonation in terms of reef edge, reef crest, outer and inner reef flats along with a lagoon. However, exposure of reef slope could not be detected for this atoll reef. In case of the narrow coastal fringing reef (subset: 2) the reef flat could be separated into outer and inner reef flats in the central part. At certain places the inner reef flat has turned into sanded reef flat. Shore-parallel, reef flat moats and shore-perpendicular channels along with pools criss-cross the reef flat in this portion. Exposure of reef crest and reef slope however could not be detected even in this case of coastal reef.

There are extensive fringing and patch reefs in Dungunab Bay (Map: 6.1.2.6) which has been declared as an MPA (Kotb et al. 2004). Coral reefs of Dungunab Bay and Shambaya Islands have been zoomed (Map: 6.1.2.6, Subset: 1 and 2 respectively) to depict the intra-reef details. A narrow reef fringes the coast both in and out of the bay area. In the outer side of the bay, the reef bridges the main headland with the mainland coast, little north of Muhammad Qol. Wide linear moats separate the reef slope from reef flat which shows signs of extensive sand deposition in form of sanded reef flat, sandy ridge, sand cays and isolated sand patches. At certain places the reef flat can be distinguished into outer and inner reef flats. One patch reef and six coral pinnacles are found within the bay. The off-shore patch reefs near Shambaya Islands show classic reef zonation in terms of reef slope and reef flat which can be further classified into outer and inner reef flats. Reef flat moat is detected on one of the patch reef. In this segment of the Sudan coast total four patch reefs and ninety six coral pinnacles have been detected with AWiFS data dated 25th August, 2005. Corals are widespread and generally healthy inside Dungunab Bay and showed patchy mortality after 1997-98 bleaching event (Kotb *et al*. 2004). In some areas mortality reached to 90% within 0 to 15 m depth while other areas remain unaffected.

Down south on the coast of Sudan, coastal fringing reefs appear along with off-shore atoll-like structures and few coral pinnacles (Map: 6.1.2.7). A segment of the coastal fringing reef to the north of Ara Kiyai and an off-shore atoll (Map: 6.1.2.7; subset: 1 and 2 respectively) have been zoomed to show the intra-reef details. The coastal fringing reef can be distinguished into reef slope and reef flat zones. The reef flat is separated into outer and inner reef flats with shore-parallel, linear moats of different widths. At certain places the reef flat is also criss-crossed with channels. In some places, the inner reef flat has turned into sanded reef flat. A thin line of algae is also detected on the reef flat. In case of the off-shore atoll-like structure, the reef crest, reef flat and lagoonal reef slope along with isolated sand patched could be detected from AWiFS data dated 22nd September, 2008. In this segment of the Sudan coast, five coral pinnacles have been detected.

The coastal fringing reef continues farther south on the mainland coast towards Port Sudan along with the off-shore atolls of Sanganeb, Wingate and Towartit reefs (Map: 6.1.2.8). A portion of the fringing reef along with the Sanganeb atoll MNP has been shown as a zoomed (Map: 6.1.2.8, subset: 1) view. The reef flat, separable into outer and inner reef flats, in general appear sediment loaded. Shore-parallel, linear moats separate the outer and inner reef flats. A mixed coral zone is detected on the reef flat. Sanganeb, 30 km from Port Sudan, is the only atoll in the Red Sea and cover a small area of 6.5 km by 1.5 km (Kotb *et al.* 2004). Coral cover on the back reef and reef flat has been reported to vary between 10% and 30% while on the outer reef wall the coral cover ranges between 40% and 70% before a vertical drop to debris slope (Kotb *et al.* 2004). AWiFS data proves to be coarse to detect intra-reef details of the Sanganeb atoll. Sanganeb atoll has been barely affected in 1997-98 bleaching event and remains in very good condition (Kotb *et al.* 2004). Towartit reefs have lower coral cover and less coral diversity (Kotb *et al.* 2004).

Coral reef habitats near Suakin on Sudan coast include the coastal fringing reef and the off-shore reefs of Suakin archipelago (Map: 6.1.2.9 and 6.1.2.10). A portion of the coastal fringing reef has been selected for nested zooms to magnify the intra-reef features (Map: 6.1.2.9, subset: 1 and 2). Near Suakin, the fringing reef is divided into a northern and southern portion through a channel. In the northern portion the reef flat is separated from the reef slope through a shore-parallel, linear moat. The inner reef flat appears muddy and there is a sanded reef flat with algae cover. In the southern part there is an algal ridge and the reef flat is dominated with algae. In the central portion (subset: 2), the reef structurally encloses a coastal lagoon with live corals. The reef flat **is** marked with channels, reef flat moats and a mixed coral zone is located on the outer reef flat. Five coral pinnacles and twenty four atoll**-**like structures are detected in this segment of the Sudanese coast. Suakin archipelago (Map: 6.1.2.10) comprises of five off-shore fringing reefs, thirty coral pinnacles and six atoll- like structures in the Red Sea. Only in cases of few reefs (fringing and pinnacle types) the reef slope and the reef flat could be distinguished while in case of the atoll structures the reef flat and the lagoon could be detected from AWiFS data dated 2nd August, 2005 and 22nd September, 2008. For detail mapping of these off-shore reefs, high resolution data is required.

A complex barrier reef system is encountered on the Sudanese coast, almost where the continuous reef fringing the mainland coast comes to an end (Map: 6.1.2.11). The barrier reef system has a hooked structure with an orientation transverse to the coastline and thereafter following a shore-parallel orientation. The barrier reef complex includes the off-shore Saqir Island along with isolated reef patches in its fringe. The reef flat is criss-crossed with deep channels, two major and numerous deep pools along with few blue hole structures. The outer and inner reef flats can be separated along with exposures of reef slope. The reef flat has a cover of algae in Saqir Island and in the small island of the main barrier reef. The barrier reef encloses a large lagoon with patch and pinnacle reefs along with a small barrier reef. The coastal fringing reef appears muddy and has a cover of algae. In case of off-shore Green reef, the patch reef shows distinct zonation between outer and inner reef flats along with sanded reef flat. A reef flat moat is detected in this reef too. In this segment of the Sudanese coast, nine patch reefs and thirty six pinnacles have been detected with AWiFS data dated 22nd September, 2008.

Remaining islands of the Suakin archipelago include major off-shore fringing reefs of Talla Talla Kebir, Talla Talla Saghir, Masamirit, and Seven Islets (Map: 6.1.2.12). This part of the Suakin archipelago includes sixteen fringing reefs, two coral pinnacles and one atoll-like structure. Talla Talla Kebir and one island of Seven Islets have been selectively zoomed (Map: 6.1.2.12; subset: 1 and 2) to depict the intra-reef features discerned with the help of AWiFS data. Talla Talla Kebir is an off-shore fringing reef which shows classic zonation of reef slope, reef crest, outer and inner reef flats. A coralline shelf is also seen in case of this reef. In case of the reef from Seven Islet only the reef flat along with an algal ridge could be detected. For detailed mapping of these reefs of Suakin archipelago, very high resolution data is required. Thick aggregations of COTS damaging the coral reefs of Talla Talla Saghir have been reported in late 2007 (Kotb *et al.* 2008).

Fringing reefs reappear on the mainland coast of Sudan in its southern end, near its border with Eritrea (Map: 6.1.2.13). Coral reefs fringe the headlands. The reefs located to the north of Er Rih Island appear muddy and the inner reef flats are covered with algae. To the south of Er Rih Island the reefs have a comparatively better health as the muddy reefs are limited near the mainland coves while the reef flat facing the open sea bears sand depositions. Accordingly sanded reef flats are noticed. In close proximity of the Er Rih Island, the inner reef flat and sanded reef flat is covered with algae. Subtidal mudflat and mangrove vegetations are found here as associated habitats.

The frequencies of classes detected for coral reef habitats of Sudan are represented in Figure: 6.1.2.1. The geomorphological class: reef flat is a commonly detected class which could be well separated into geomorphological sub-zones of outer and inner reef flats. Lagoon and coastal lagoons have also been detected in association with fringing, barrier and atoll-type of reef structures. Coralline shelf is detected only once. Reef edge and reef slope are the most commonly detected geomorphological sub-zones. Significant proportion of the Sudanese reef flat appears as sanded reef flats. Moats, reef flat moats and pools have been detected quite frequently within the reef structures. Algae, mixed coral zone and live corals have been detected as the benthic zones with algae recording the highest frequency among the benthic categories. Mangrove and sub-tidal mudflats show relatively less association with coral reef habitats on the Sudan coast.

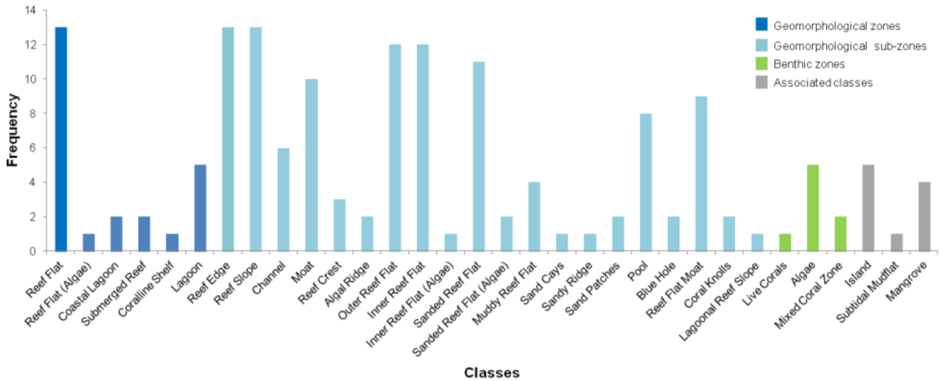


Figure 6.1.2.1 Frequency of classes detected for coral reef habitats of Sudan

Areal Extent of Coral Reefs of Sudan

The coral reef habitats of Sudan as mapped from AWiFS data cover a total area of 1582.35 sq km inclusive of lagoons and coastal lagoons. Reef area corresponding to each habitat map is summarized in Table No. 6.1.2.1. Coral reef habitats of Sudan coast with offshore islands of Siyal and Rawabel occupy the maximum coral reef area of 285.87 sq km while coral reef habitats of Suakin Archipelago (Seil Ada Kebir and surroundings) occupy the minimum reef area of 23.37 sq km.

Summary

Coral reefs of Sudan comprise of a near-continuous, coastal fringing reef, an off-shore barrier reef system and the oceanic atoll of Sanganeb. The off-shore coral reef habitats comprise of fringing reefs, patch reef and coral pinnacles and atoll-like structures. Significant intra-reef geomorphic details could be delineated for the coastal fringing and the off-shore barrier reef. However, for detail mapping of the off-shore reefs consisting of fringing, patch, pinnacles and atoll-like structures, high resolution data is needed. Overall the Sudanese reefs show major reef zonation in terms of reef slope and reef flat zones. Exposure of well-defined reef crest is quite limited. However, well-defined, shore-parallel, linear moats separating the reef slope and reef flat zones and reef flat moats dividing the reef flat into outer and inner reef flats are characteristic features of Sudanese reefs. The status of coral reefs in Sudan has been reported to be in good condition (Kotb *et al.* 2008). In general, the offshore reefs remained unaffected in 1997-98 bleaching event while the near-shore reefs have shown patchy recovery (Kotb *et al.* 2004). Effects of COTS outbreak, damage by *Drupella* and coral diseases have been minimal on these reefs.

Coral reef habitats of Sudan face potential threats from the coastal and industrial development activities, recreational diving and growing tourism. Port Sudan and Suakin are the two major coastal cities. Expansion of port activities, coastal and urban developments have known to damage the coral reefs near Port Sudan and Suakin Harbour, especially as a result of increased sedimentation (Kotb *et al.* 2004). These effects are well apparent on the coral reef habitat maps. Two sq km of reef area was in fact reclaimed near Port Sudan (Kotb *et al.* 2004). Sewage pollution has been reported to be a problem close to both cities (Spalding *et al.* 2001). Sanganeb Atoll and Dungunab Bay have been declared as MPAs from Sudanese reefs with the former sharing a status of MNP since the year 1990 (Spalding *et al.* 2001). Coral reefs of Sudan as mapped from AWiFS data cover a total area of 1582.35 sq km and appear in *near-pristine* condition barring the localized impacts near Port Sudan and Suakin.

Table 6.1.2.1 Areal Extent of coral reefs of Sudan

Map No.	**Location**	**Reef Area (sq km)**
6.1.2.1	Coral reef habitats of Geziret Mirear and surroundings	123.53
6.1.2.2.	Coral reef habitats of Sudan Coast, Red Sea (segment 1)	81.81
6.1.2.3	Coral reef habitats of Sudan coast with offshore islands of Siyal and Rawabel	285.87
6.1.2.4	Coral reef habitats of Gezirat Halaib El-kebir and surroundings	89.27
6.1.2.5	Coral reef habitats of Sudan coast between Ras Hadarba and Ras Abu Shagara	138.07
6.1.2.6	Coral reef habitats of Dungunab Bay, Mukawwar, Maytib and Shambaya Islands	242.22
6.1.2.7	Coral reef habitats of Sudan coast near Ara Kiyai and surroundings	134.93
6.1.2.8	Coral reef habitats of Port Sudan, Sanganeb Atoll MNP and surroundings	87.99
6.1.2.9	Coral reef habitats of Sudan coast near Suakin and surroundings	96.13
6.1.2.10	Coral reef habitats of Suakin Archipelago (Seil Ada Kebir and surroundings)	23.37
6.1.2.11	Coral reef habitats of Sudan coast (Saqir Island and surroundings) and off-shore Green Reef	153.22
6.1.2.12	Coral reef habitats of Suakin Archipelago (Talla Talla Saghir, Talla Talla Kebir, Masamirit and Seven Islets)	28.25
6.1.2.13	Coral reef habitats of Er Rih Island and surroundings	97.67
	Total Area	**1582.35**

Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.1 represents Results > under **Basin 1. Red Sea**
6.1.2 represents Results > under Basin 1. Red Sea > for **Country 2. Sudan**
6.1.2.1 represents **Coral Reef Habitat Map** of **Sudan coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

1. Geziret Mirear and surroundings
2. Sudan coast, Red Sea (segment 1)
3. Sudan coast with offshore islands of Siyal and Rawabel
4. Gezirat Halaib El-kebir and surroundings
5. Sudan coast between Ras Hadarba and Ras Abu Shagara
6. Dungunab Bay, Mukawwar, Maytib and Shambaya Islands
7. Sudan coast near Ara Kiyai and surroundings
8. Port Sudan, Sanganeb Atoll MNP and surroundings
9. Sudan coast near Suakin and surroundings
10. Suakin Archipelago (Seil Ada Kebir and surroundings)
11. Sudan coast (Saqir Island and surroundings) and off-shore Green reef
12. Suakin Archipelago (Talla Talla Saghir, Talla Talla Kebir, Masamirit and Seven Islets)
13. Er Rih Island and surroundings

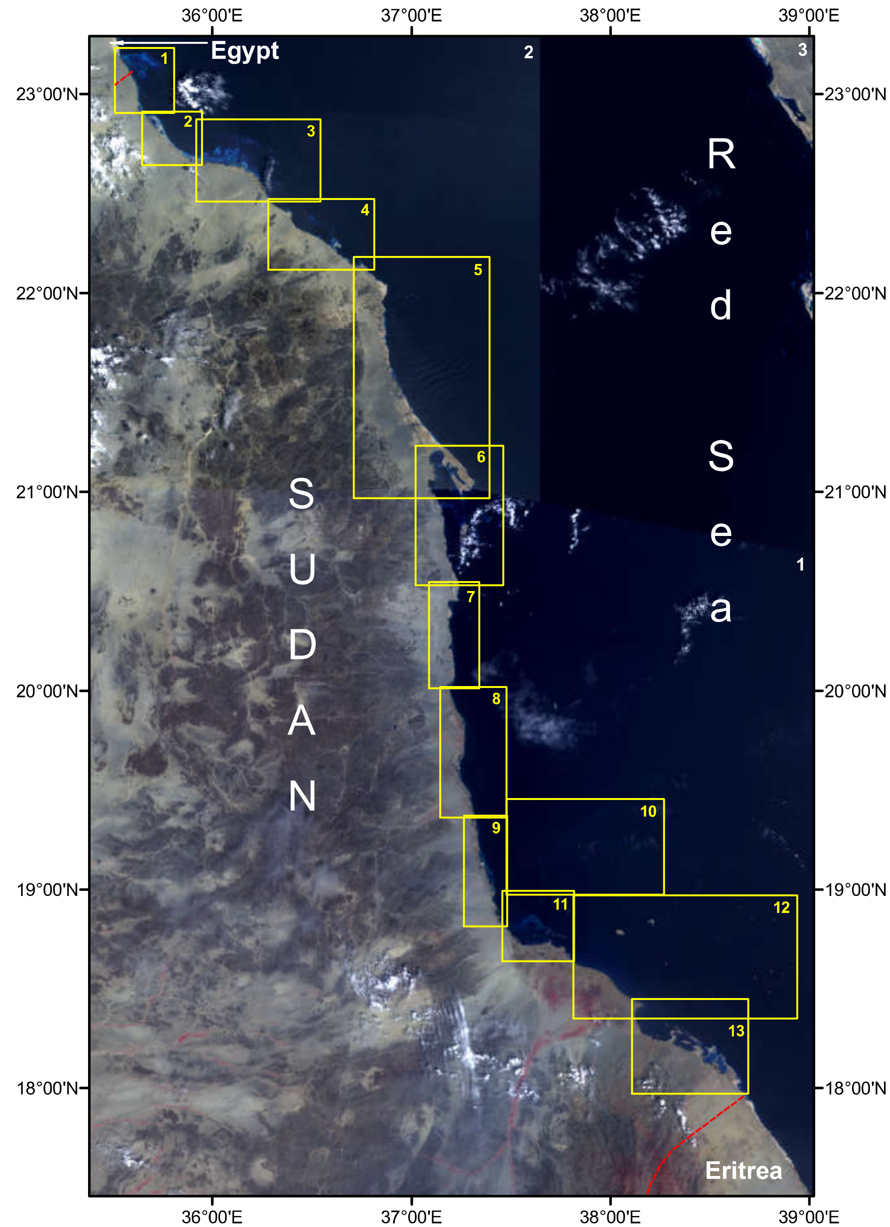
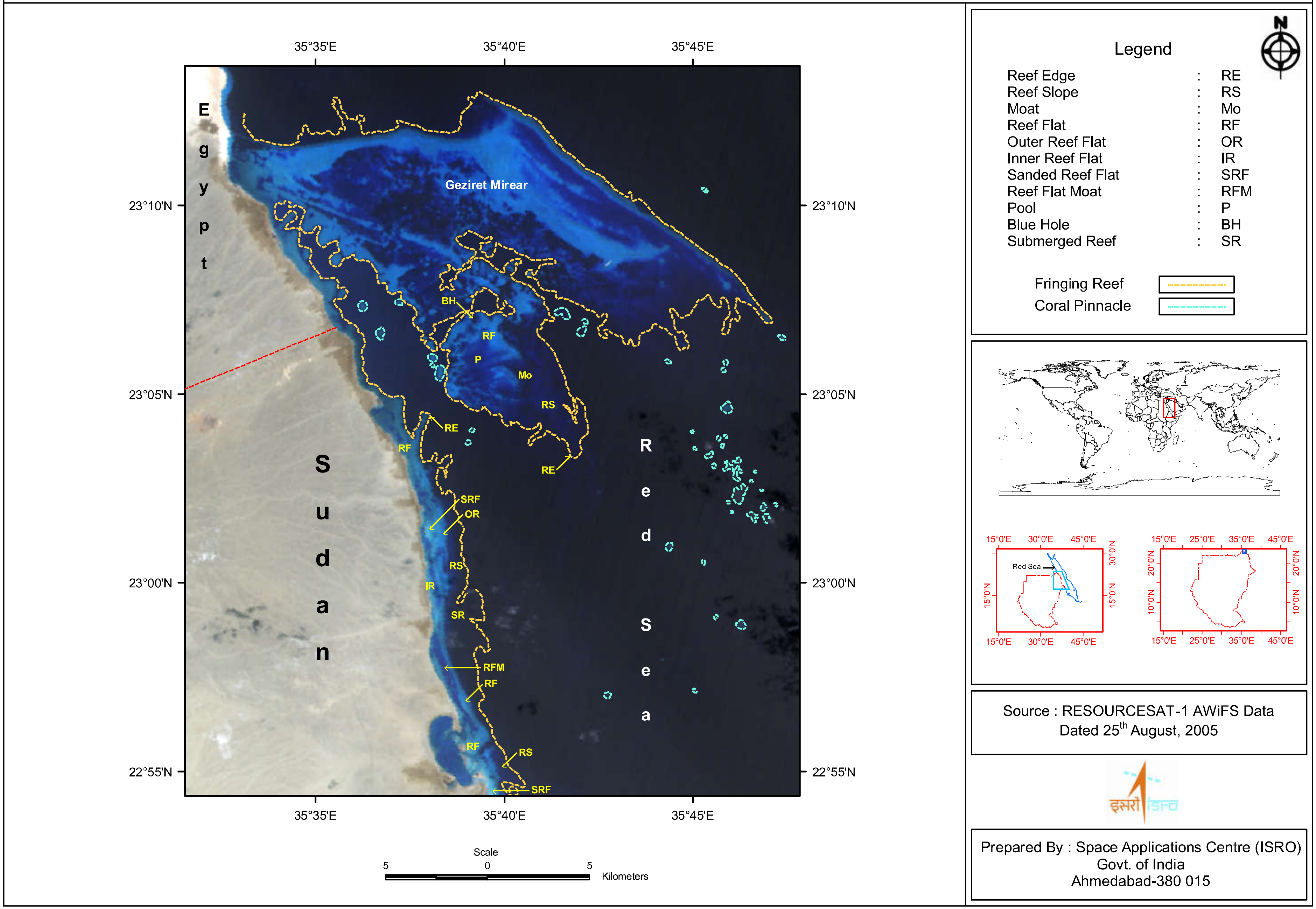


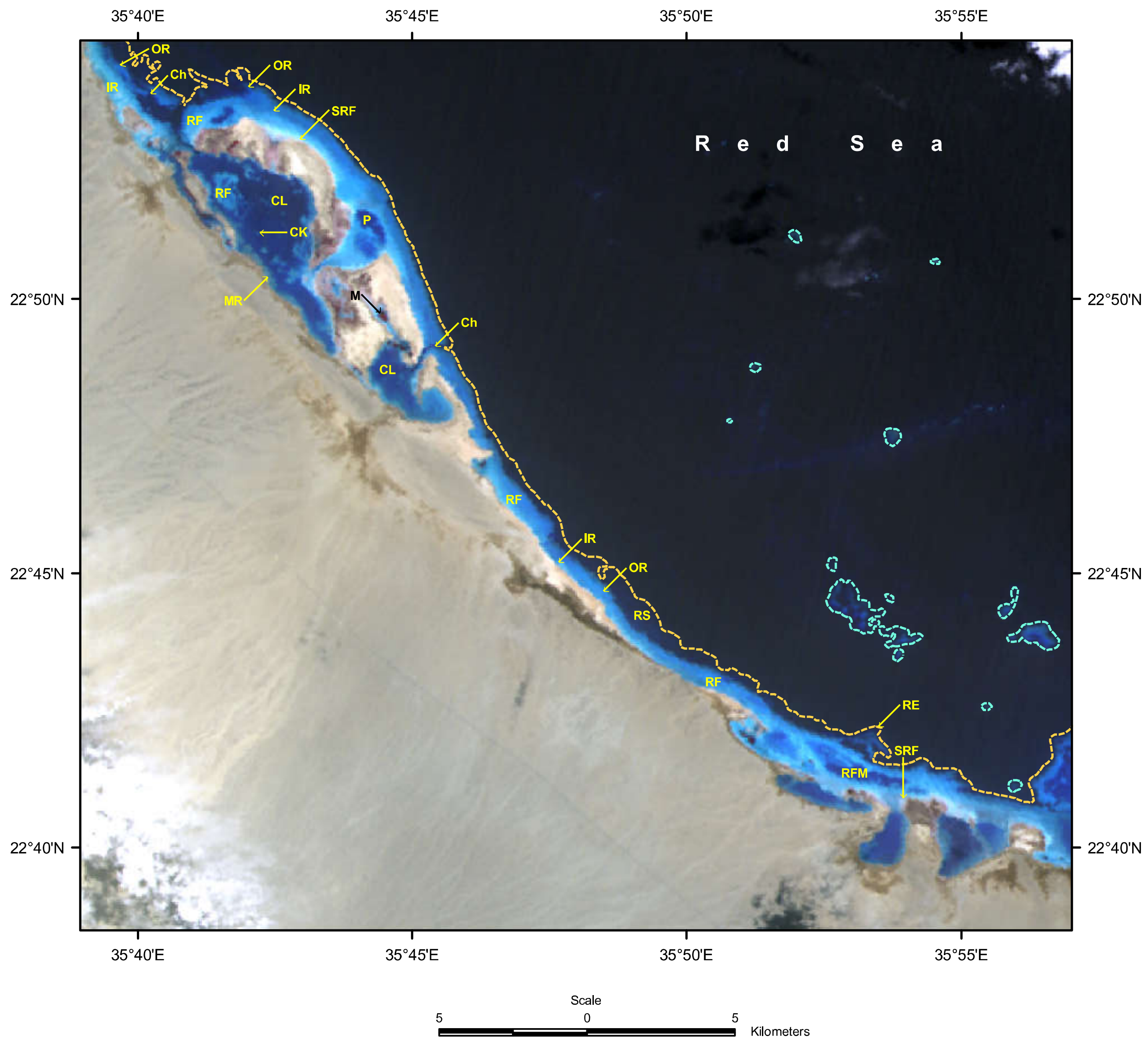
Figure 6.1.2 Index to coral reef habitat maps of Sudan

--- International boundary

Source: Resourcesat-1 AWiFS mosaic from data dated: 22nd September, 2008 (1) ; 25th August, 2005 (2) and 2nd August, 2005 (3)



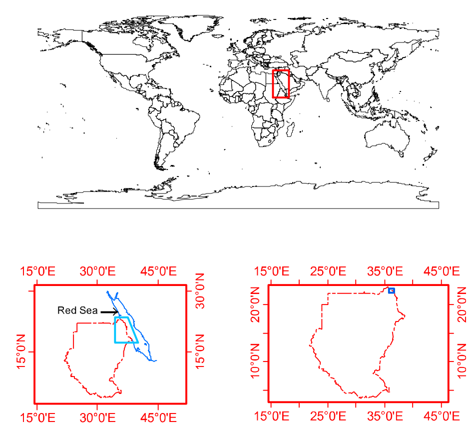
Map 6.1.2.1 : Coral reef habitats of Geziret Mirear and surroundings



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Muddy Reef Flat	:	MR
Reef Flat Moat	:	RFM
Pool	:	P
Coastal Lagoon	:	CL
Coral Knolls	:	CK
Mangrove	:	M

Fringing Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 25th August, 2005

Prepared By : Space Applications Centre (ISRO)
Govt. of India
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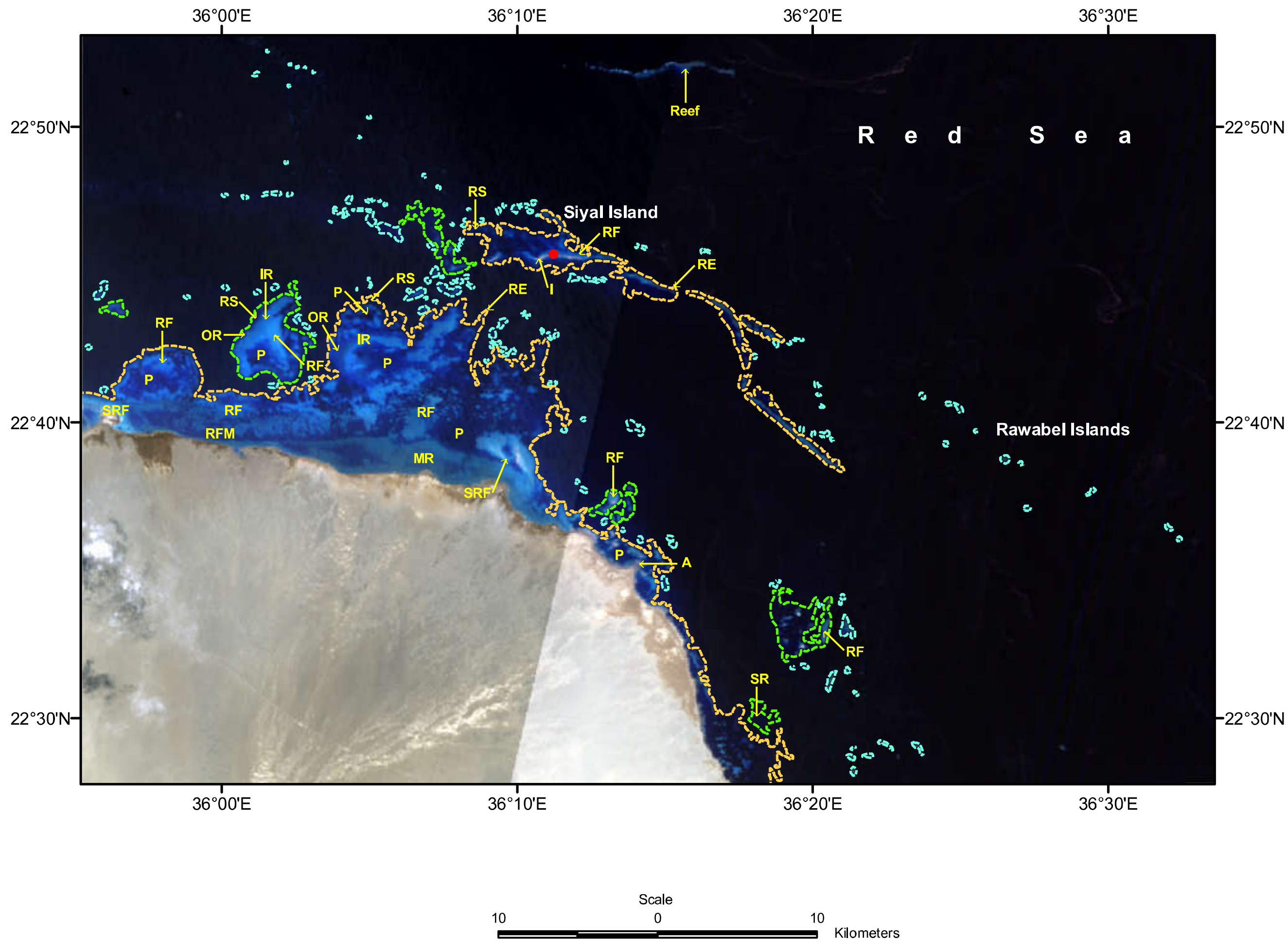
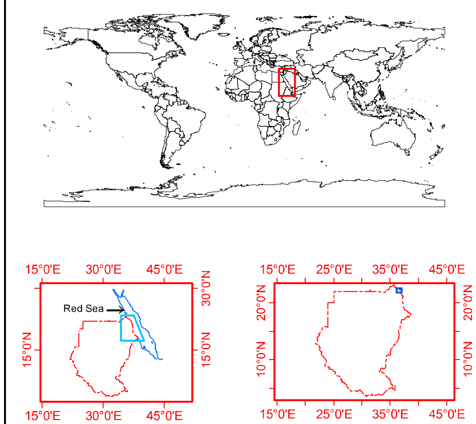
Map 6.1.2.2 : Coral reef habitats of Sudan coast, Red Sea (segment 1)



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Muddy Reef Flat	:	MR
Reef Flat Moat	:	RFM
Pool	:	P
Algae	:	A
Submerged Reef	:	SR
Island	:	I

Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 25th August, 2005 and 2nd August, 2005

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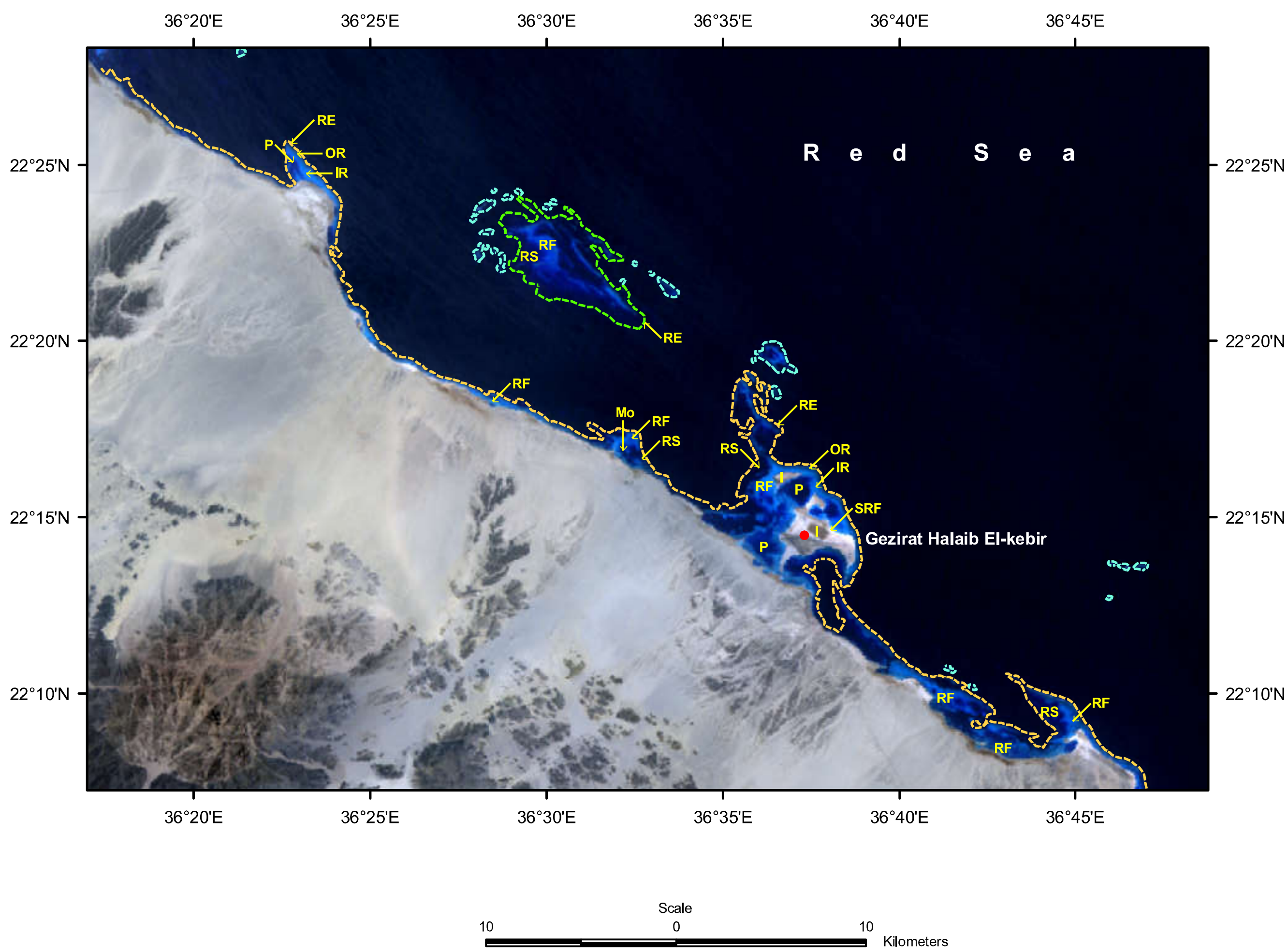
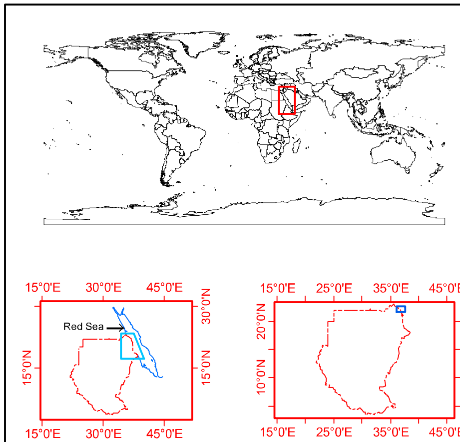
Map 6.1.2.3 : Coral reef habitats of Sudan coast with offshore islands of Siyal and Rawabel



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Pool	:	P
Island	:	I

Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 25th August, 2005

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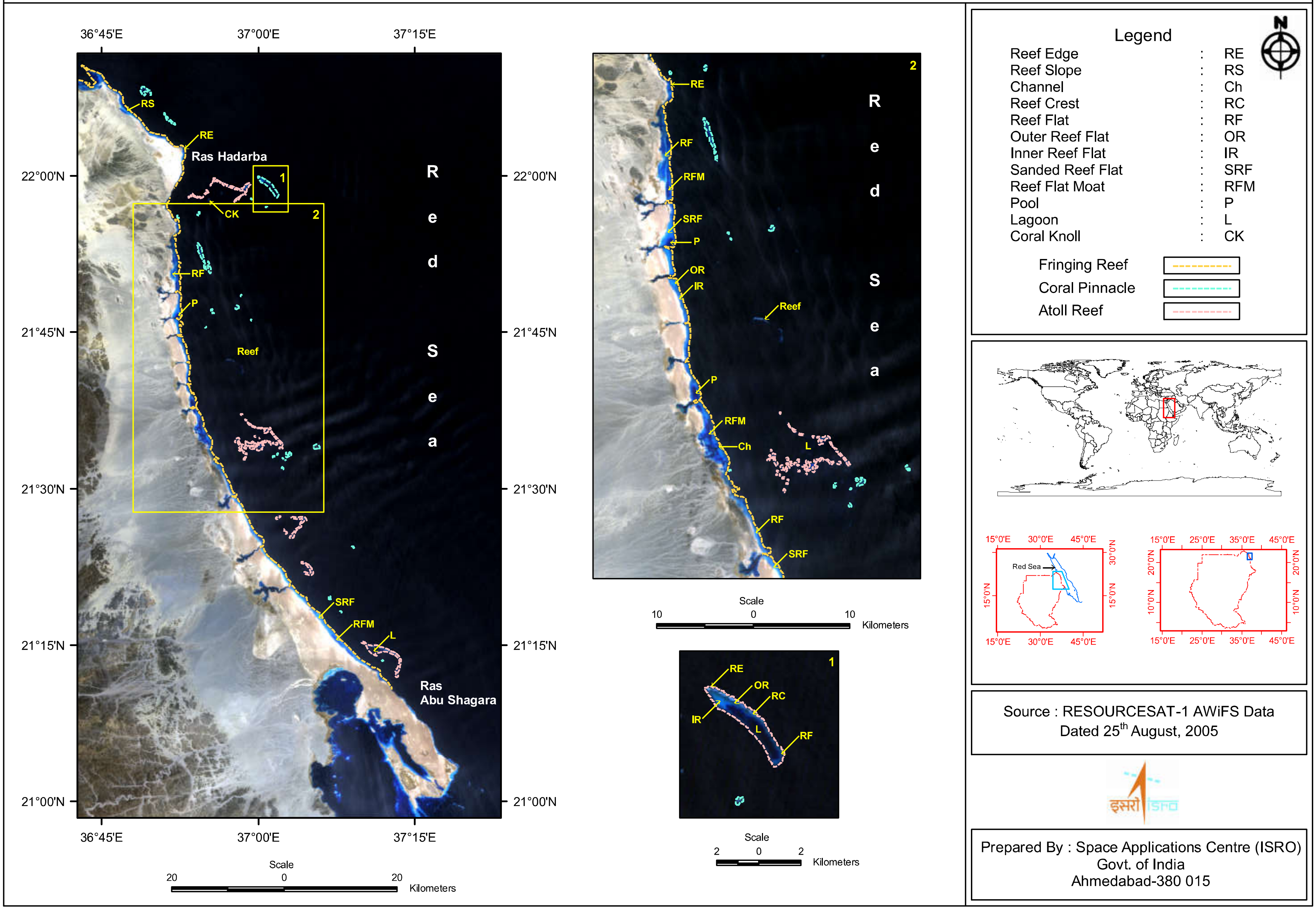
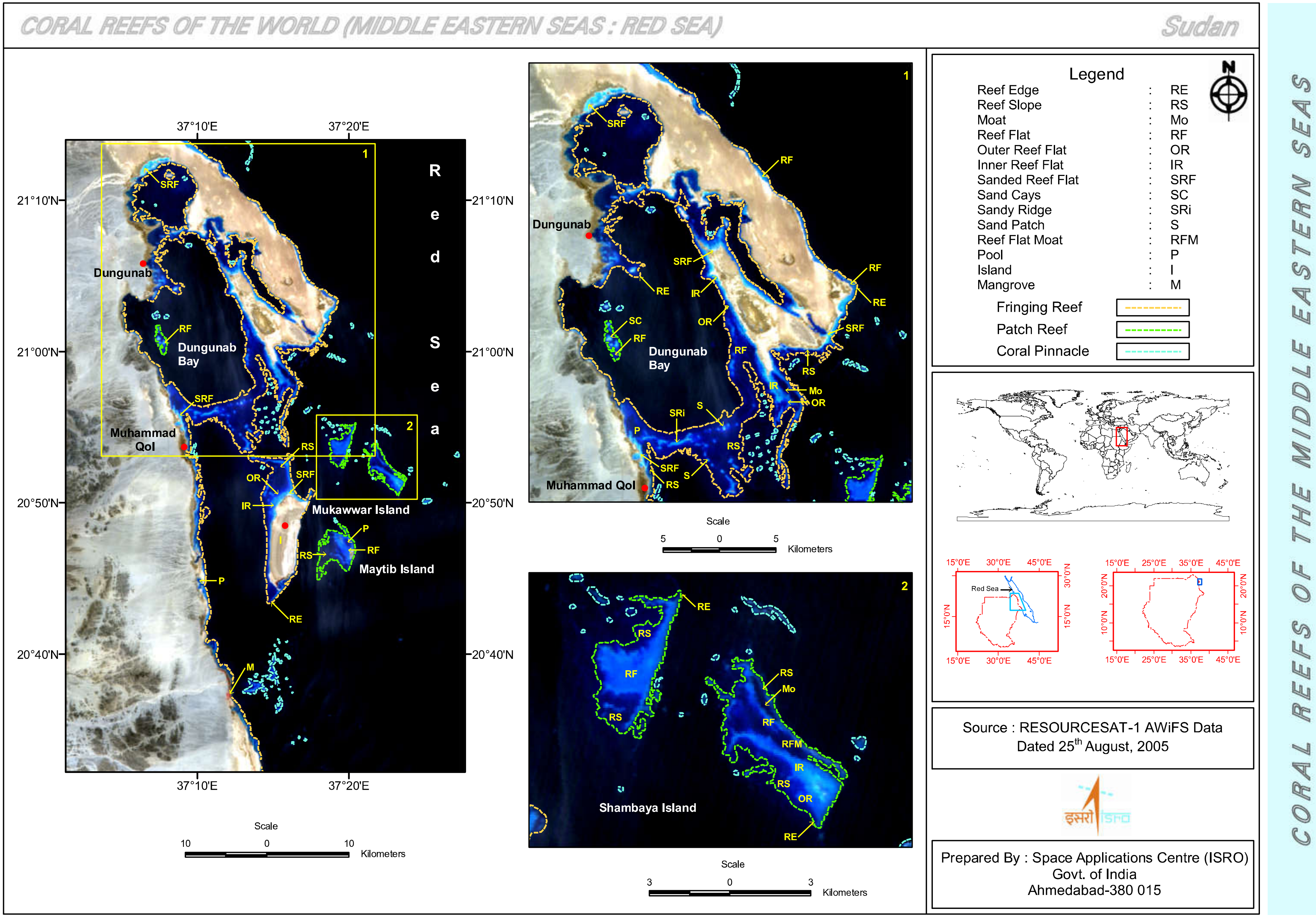
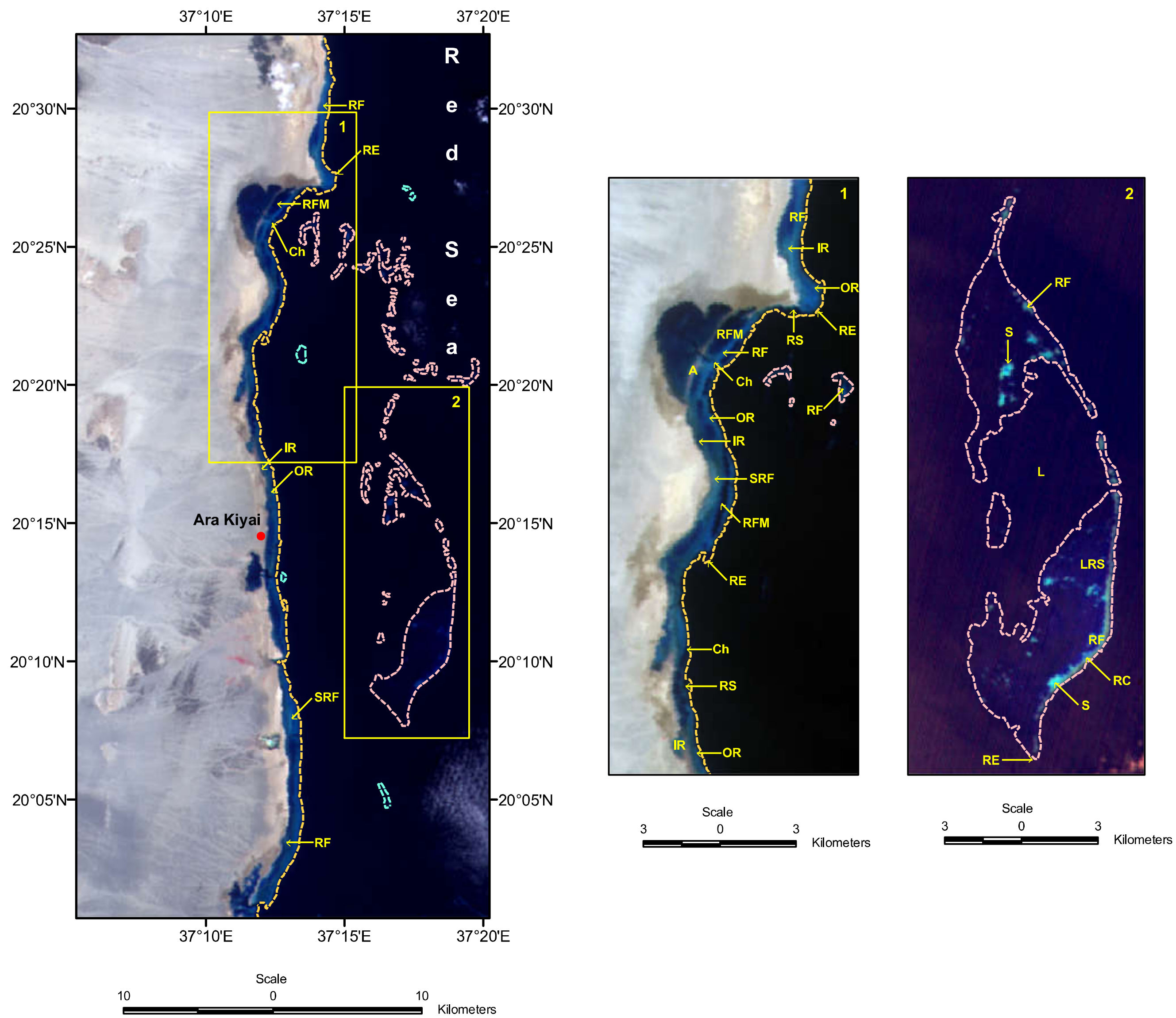
Map 6.1.2.4 : Coral reef habitats of Gezirat Halaib El-kebir and surroundings



Map 6.1.2.5 : Coral reef habitats of Sudan coast between Ras Hadarba and Ras Abu Shagara



Map 6.1.2.6 : Coral reef habitats of Dungunab Bay, Mukawwar, Maytib and Shambaya Islands



Legend

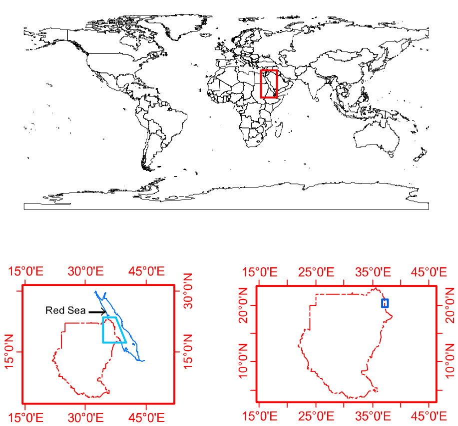
Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Reef Crest	:	RC
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Sand Patch	:	S
Reef Flat Moat	:	RFM
Algae	:	A
Lagoon	:	L
Lagoonal Reef Slope	:	LRS

Fringing Reef

Coral Pinnacle

Atoll

N



Source : RESOURCESAT-1 AWiFS Data
Dated 22nd September, 2008

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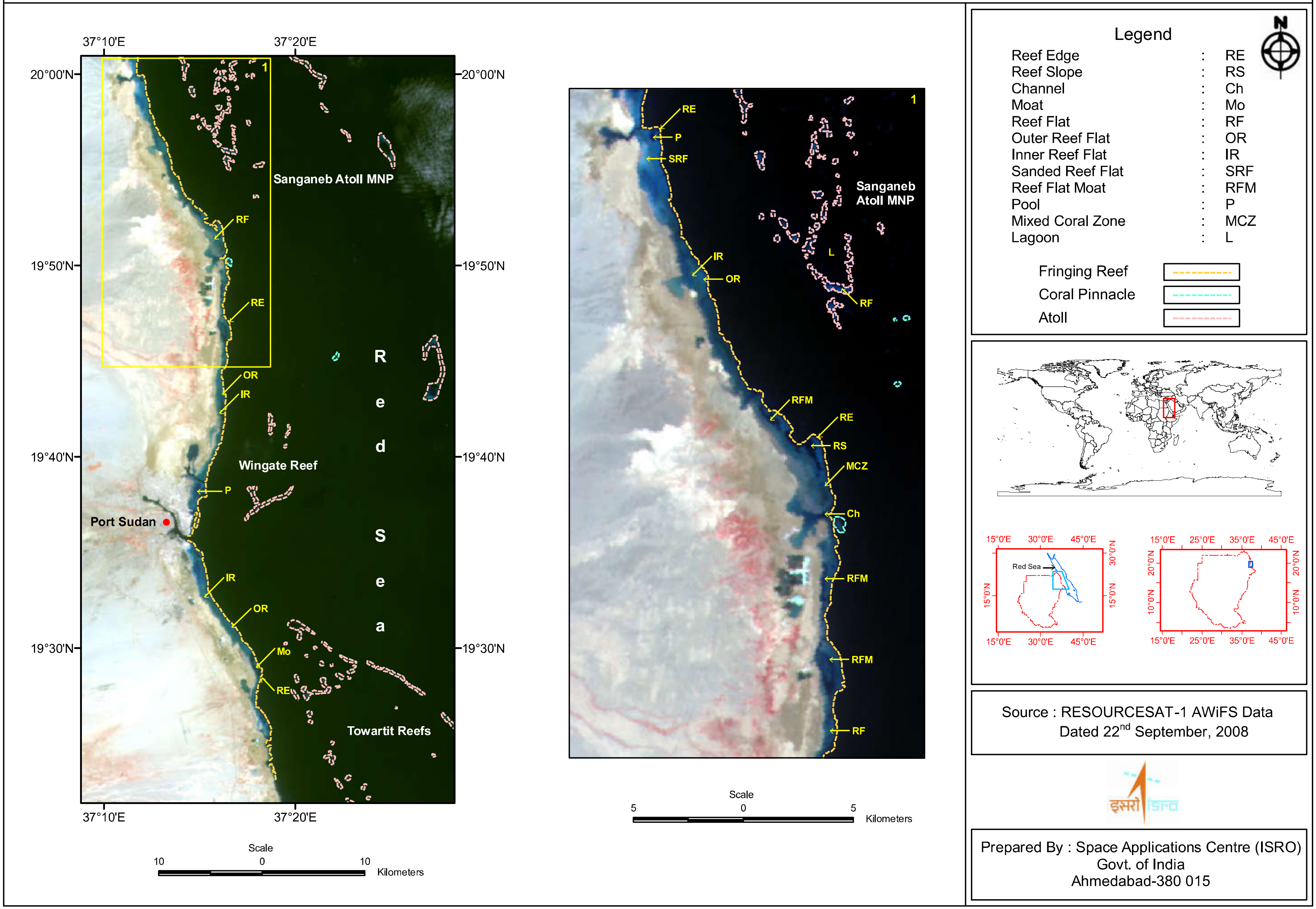
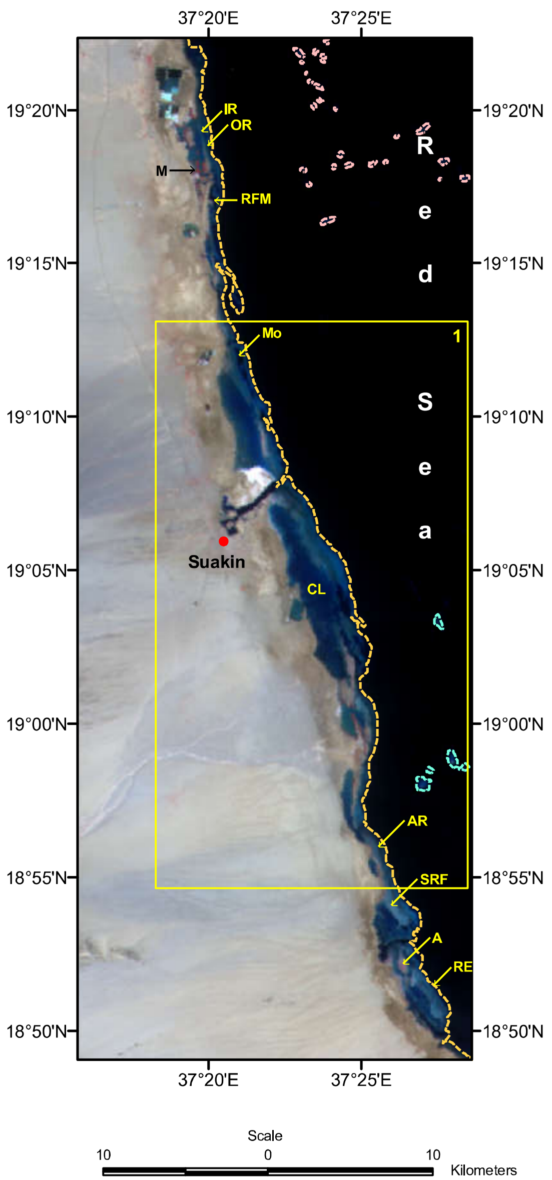
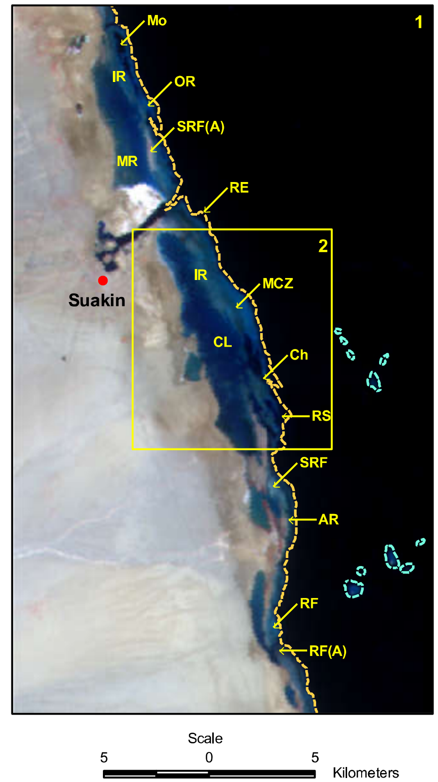
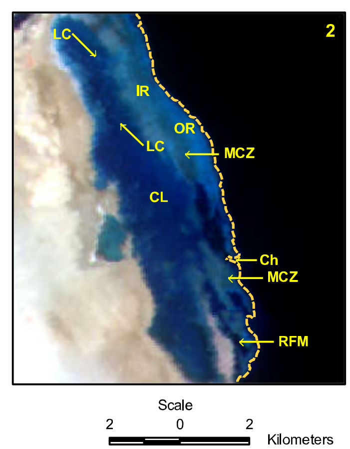
Map 6.1.2.7 : Coral reef habitats of Sudan coast near Ara Kiyai and surroundings



Map 6.1.2.8 : Coral reef habitats of Port Sudan, Sanganeb Atoll MNP and surroundings





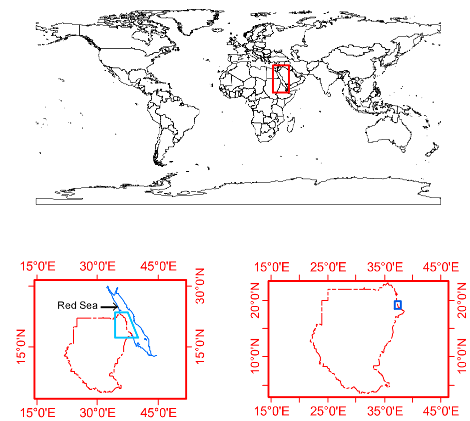


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Moat	:	Mo
Algal Ridge	:	AR
Reef Flat	:	RF
Reef Flat (Algae)	:	RF(A)
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Sanded Reef Flat (Algae)	:	SRF(A)
Muddy Reef Flat	:	MR
Reef Flat Moat	:	RFM
Mixed Coral Zone	:	MCZ
Live Coral	:	LC
Algae	:	A
Coastal Lagoon	:	CL
Mangrove	:	M

Fringing Reef
Coral Pinnacle
Atoll Reef

N



Source : RESOURCESAT-1 AWiFS Data
Dated 22nd September, 2008

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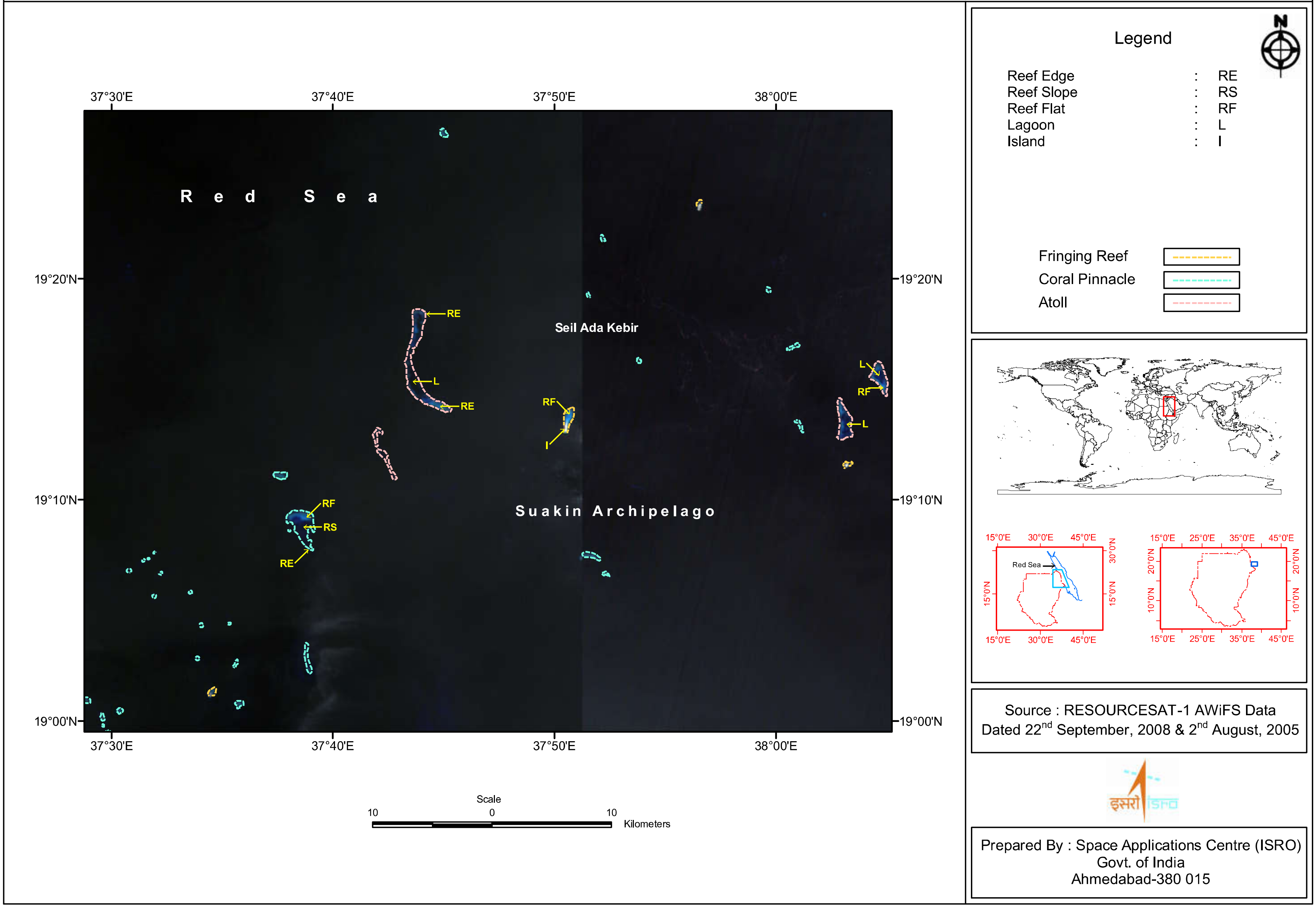
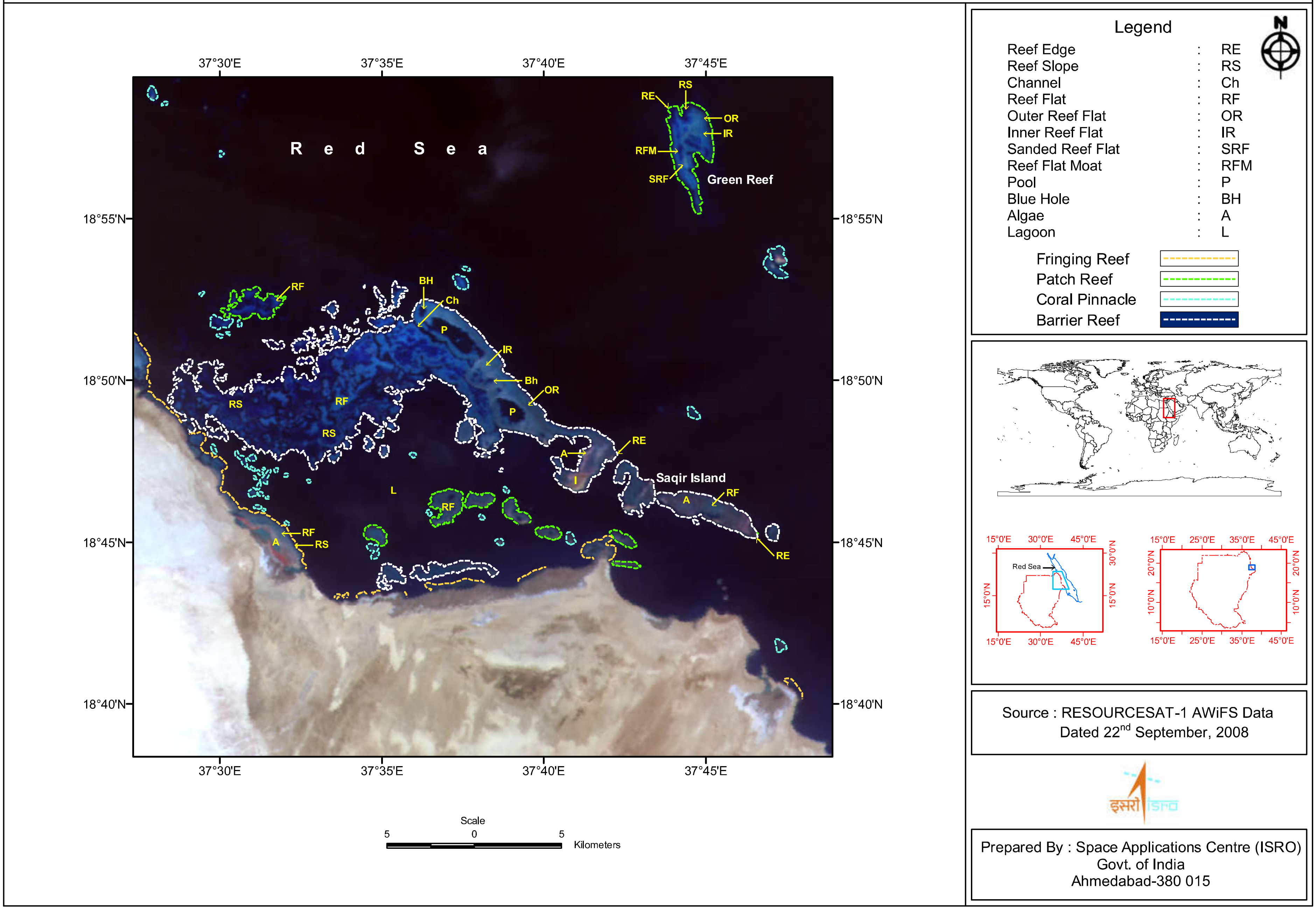
Ahmedabad-380 015

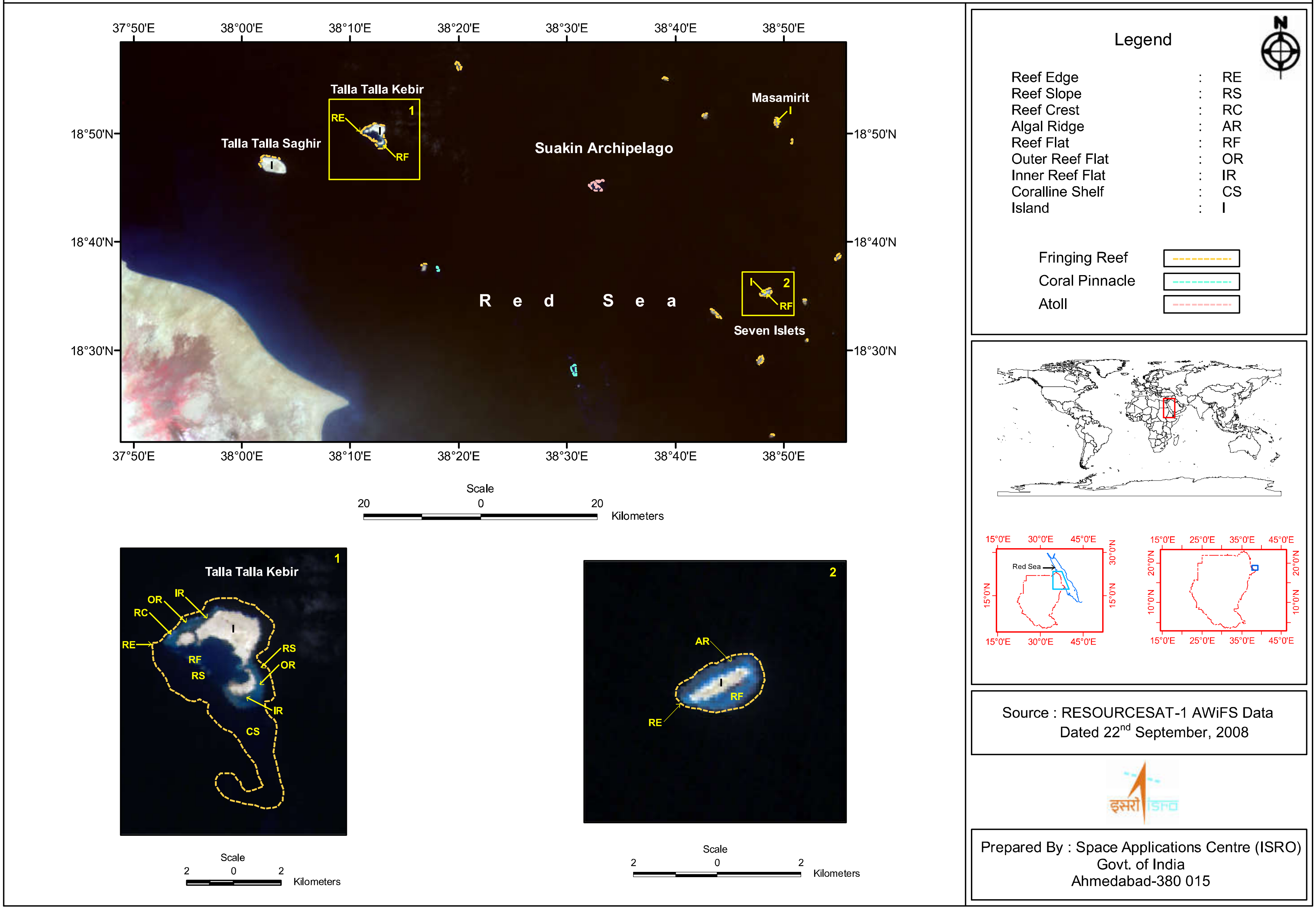
Map 6.1.2.9 : Coral reef habitats of Sudan coast near Suakin and surroundings



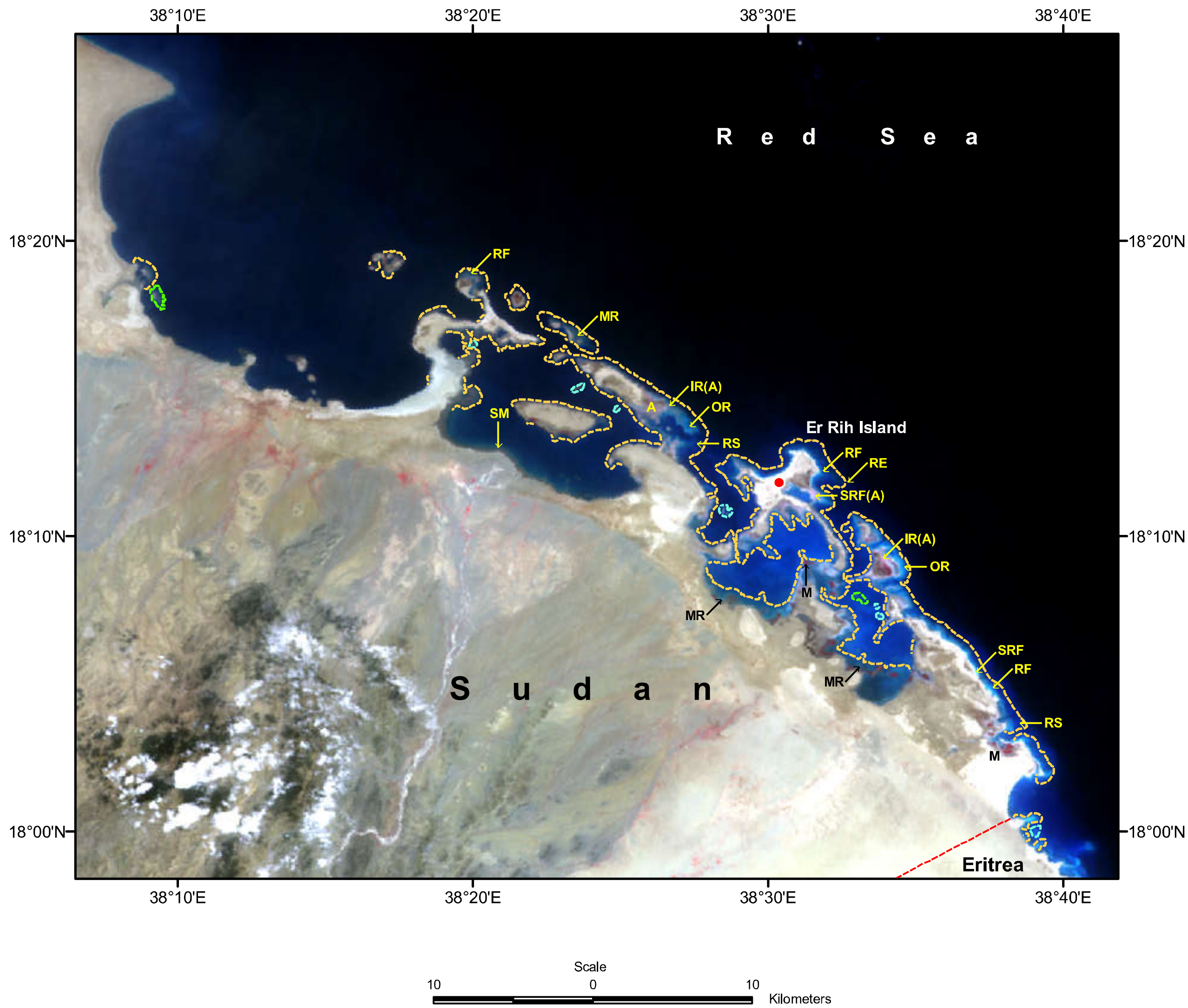
Map 6.1.2.10 : Coral reef habitats of Suakin Archipelago (Seil Ada Kebir and surroundings)



Map 6.1.2.11 : Coral reef habitats of Sudan coast (Saqir Island and surroundings) and off-shore Green reef



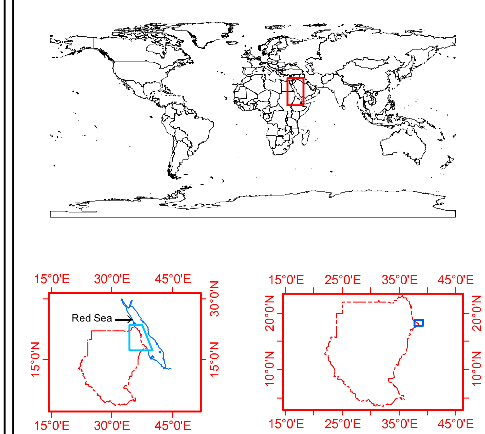
Map 6.1.2.12 : Coral reef habitats of Suakin Archipelago (Talla Talla Saghir, Talla Talla Kebir, Masamirit and Seven Islets)



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Inner Reef Flat (Algae)	:	IR(A)
Sanded Reef Flat	:	SRF
Sanded Reef Flat (Algae)	:	SRF(A)
Muddy Reef Flat	:	MR
Algae	:	A
Subtidal Mudflat	:	SM
Mangrove	:	M

Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 22nd September, 2008

Prepared By : Space Applications Centre (ISRO)
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Map 6.1.2.13 : Coral reef habitats of Er Rih Island and surroundings

6.1.3. Eritrea

Background

The 1350 km long Eritrean coastline extends from the Sudanese border in the north and shares border with Djibouti in the south. Eritrea's coastline occurs within the geographical limits of 12°42'- 18°00' N latitudes and 38°38' - 43°08'E longitudes in the southern Red Sea. The coastal plains comprise of 59% of Eritrea's national area (Pilcher and Alsuhaibany 2000). Extensive coral reefs fringe around 18% of the mainland coast and three hundred and fifty off-shore islands in the Red Sea. Among these islands, the Dahlak archipelago includes approximately two hundred and ten islands and represents a relict Pleistocene carbonate platform. The biodiversity of Eritrea's coral reefs is of global significance since this region contains globally important and unique assemblages of species with some of the most spectacular coral reefs of the world (Kotb *et al.* 2004; Kotb *et al.* 2008).

Two hundred and twenty coral species from 38 genera have been reported from Eritrea (Kotb *et al*. 2008) with *Porites*, *Montipora*, *Stylophora* and *Platygyra* being the most common genera. Eritrean corals flourish in warm waters with low rainfall. Eritrean corals are possibly resistant to wide temperature variations as local water temperature reaches to 37.5°C in summer at 10m depth. There has been limited bleaching damage (less than 1% in 1997-98 bleaching event) in Eritrean reefs (Pilcher and Alsuhaibany 2000; Kotb *et al.* 2008) probably due to their high thermal tolerance. The coral cover ranges from 20-50% at most sites in Dahlak Archipelago and occasionally reaches 100% at certain sites (Kotb *et al.* 2004). Crown-of-Thorns Starsfish (COTS) predation and coral diseases are known to be rare in Eritrean reefs, however, coral eating mollusc *Drupella* occurs in high densities in many reefs (Kotb *et al.* 2004).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Eritrea have been mapped with Resourcesat-1 AWiFS data (single scene) dated 12th October, 2008. Detailed habitat characteristics of these reefs are depicted in ten habitat maps (Maps: 6.1.3.1 to 6.1.3.10). In Eritrea the major reef formations include coastal fringing reefs and the off-shore fringing reefs of Dahlak Archipelago.

A narrow reef fringes the northern coast of Eritrea in discontinuous segments right from the Sudanese border to the coastal areas facing the off-shore island of Difnein (Maps: 6.1.3.1, 6.1.3.2). Near the Sudanese border, the reef crest could be detected along with reef flat, reef crest and reef edge (Map: 6.1.3.1). The reef flat can be distinguished into outer and inner reef flat in the reef segment just north to Mersa Teklay. In case of the off-shore reef of Difnein and another island the boundary of the reef could only be delineated (Map: 6.1.3.2). Mangroves are found as associated habitats in both the coastal segments.

The Dahlak archipelago (Map: 6.1.3.3, Map: 6.1.3.3A) is a magnificent reef structure on the Eritrean coast, off the port city of Massawa. The Dahlak archipelago includes approximately two hundred and ten islands and sits on a relict Pleistocene carbonate platform (Pilcher and

Alsuhaibany 2000). The carbonate platform has been uplifted and has undergone further modifications in its geological history (Spalding *et al.* 2001). Dahlak archipelago comprises of an intricate fringing reef structure in the centre and several other off-shore island fringing reefs in its periphery like Harat, Harmil, Aucan, etc. A constellation of semi-submerged patch reefs and submerged coral pinnacles occur in the northern part of Dahlak archipelago while a smaller group of patch reefs is found in the extreme south-eastern part as mapped from AWiFS data dated 12th October, 2008. Fourteen patch reefs and one hundred and twenty-five coral pinnacles have been detected from this data for Dahlak archipelago. The fringing reef structure in the central portion appears to be an intricate network of narrow, linear reef flats with relatively large but intermittent oceanic pools. Three selected areas from the Dahlak archipelago have been zoomed to show the intra-reef details (Map: 6.1.3.3A). The Harat island (Map: 6.1.3.3A, subset: 1) shows a classic reef zonation in terms of reef slope and reef flat, the latter being easily separated into outer and inner reef flats. A moat separating the coralline shelf and the reef slope can be detected in the northern part of this reef. Subset: 2 of Map: 6.1.3.3A zooms up the intricate network of the central reef structure of this archipelago. This area too shows the classic reef zonation in terms of moats separating the reef slopes from the reef flats. The narrow reef flats could be separated into outer and inner reef flats. Channels and submerged reefs are also noticed here. Subset 3 provides a sneak peek into the differential exposure of the island fringing reefs where the reef flat and the reef slope could be detected easily while the patch reefs in the vicinity appear in a relatively submerged condition. Formation of a sandy ridge is noticed in one of the patch reef. Associated habitat of mangrove vegetation appears extremely limited in Dahlak archipelago.

A narrow reef fringes the mainland coast of Eritrea near the port city of Massawa in discontinuous segments and continues in an embayment further little south of Dureli (Maps: 6.1.3.4, 6.1.3.5). Corals in general, around Massawa appear patchy and separated by sand or along the fringing reefs in about 6m depth (Pilcher and Alsuhaibany 2000). The fringing reef is narrow and the intra-reef details are limited to detection of reef flat, reef slope and reef edge categories from AWiFS data. Only to the south of Dureli, the reef flat broadens out and can be separated into outer and inner reef flats (Map: 6.1.3.5). For detailed habitat mapping of the reefs of this part of Eritrean reef, a high resolution data is needed. Coral cover in this portion of the reef has shown a massive decline since 1996 (Pilcher and Alsuhaibany 2000). Mangrove vegetation occurs in discontinuous pockets in this part of the Eritrean coast.

Coastal fringing reefs on the Eritrean coast faces the open waters of Red Sea near coastal sites of Gruta and Dluh along with off-shore fringing reefs and coral pinnacles (Map: 6.1.3.6). On the mainland coast, the reef flat is separated from the reef flat zone through a moat and in certain cases the reef flat can be separated into outer and inner reef flats. The prominent off-shore island fringing reef (Map: 6.1.3.6, subset: 1) shows a north-south linear extension where a submerged sandy ridge defines the central part of the reef. In this reef too, a small moat separates the reef flat from reef slope zone. To the north of this fringing reef, a coral pinnacle with a small sand patch is noticed. Mangrove vegetation occurs in small pockets on the mainland coast near Gruta.

Coastal and off-shore fringing reefs along with coral pinnacles border the Eritrean coast near Mersa Fatma (Map: 6.1.3.7). The reefs fringe the mainland coast from the headland (located to the north of Ghela' elo) to Mersa Fatma within an embayment. This part of the reef appears muddy along with few pockets of mangrove vegetation. The embayment is dotted with three major and ten minor island fringing off-shore reefs along with fifty-two coral pinnacles as detected from the AWiFS data. From Mersa Fatma to Miida the reef flat extends over a relatively broader width and show distinct separation from the reef slope zone. Near Mora and Miida the reef flat can be distinguished into outer and inner reef flats. Shore-perpendicular channels dissect the fringing reef near Mora. Some part of this reef, however, remains in submerged condition. Discontinuous patches of mangroves border the Eritrean coastline in this section.

After a considerable gap on the mainland coast of Eritrea, coastal fringing reefs start reappearing few kilometers north of Behld and continue upto Rehayto (Maps: 6.1.3.8, 6.1.3.9 and 6.1.3.10) close to the Djibouti border. The reef flat to the north of Behld appears in submerged condition at relatively higher depths as compared to the wider reef flat near Beraisole (Map: 6.1.3.8). Near Beraisole, mangrove vegetation frequents the coast as an associated habitat and accordingly a portion of the reef appears muddy. Another major associated habitat is that of beach on the mainland coast. The coastal fringing reef further down south (Map: 6.1.3.9) shows a classic zonation with a long, continuous reef flat moat separating the reef flat into outer and inner reef flats. In the northern part, a sand cay, located between the outer and inner reef flats extend northwards in the form of a shore-parallel sandy ridge. The inner reef flat appears muddy and shows association with mangrove vegetation. A mixed coral zone is detected in the inner reef flat, sheltered by the sand cay and the sandy ridge to its east. Down south the reef flat narrows down, however, frequented with three prominent but smaller reef flat moats. A high resolution data can bring out significant intra-reef details of this part of the coastal fringing reef. An off-shore coral pinnacle is detected in submerged condition in the north.

The coastal and off-shore fringing reefs of southern Eritrean coast near port cities of Assab and Rehayto (Maps: 6.1.3.10, 6.1.3.10A) rank next to Dahlak archipelago in importance. Here too the coral cover ranges between 20-50% and occasionally reaches 100% at some sites (Kotb *et al.* 2004). The off-shore fringing reefs and reefs adjacent to the headland near Kiloma show higher benthic diversity and strong association with mangrove vegetation. The coastal fringing reef near Assab is relatively very narrow and appears as a muddy reef. A jetty is located on the mainland coast to the south of Assab city. Two major reef areas have been zoomed (Map: 6.1.3.10A) to depict intra-reef geomorphic details. The off-shore fringing reef (Map: 6.1.3.10A, Subset: 1) has an elongated shape and show clear zonation in terms of reef slope, reef crest and reef flat zones. The reef flat is distinguished into outer and inner reef flats. The reef flat is separated by two large pools connected to the sea in northern and southern parts. The benthic diversity is high on the southern reef flat as indicated by mixed coral zones and algae-dominated reef flats. Lush mangrove vegetation occurs adjoining the reef islands both in the north and south. The reef adjacent to the headland near Kiloma (Map: 6.1.3.10A, Subset: 2) shows a classical reef profile with reef slope, reef crest, a long narrow, algal ridge and a wide reef flat. The reef flat is dotted with two small depression pools and significant proportion of the reef is covered with macroalgae. A mixed coral zone is also seen at the centre of the reef flat. A sandy ridge appears in the northern side of the reef.

The frequencies of the reef categories detected for Eritrean coral reefs are represented in Figure 6.1.3.1. Geomorphological zones like reef flat, sub-zones like reef edge and reef slope appear as the most commonly detected classes. Overall the reef flat of Eritrean reefs are relatively muddy rather than deposition of sand. However, in certain cases sandy ridge has been detected. Mixed coral zone is the only benthic zone detected among Eritrean coral reefs. Mangrove habitats show a one to one association with coral reefs here, a typical characteristic of southern Red Sea coast.

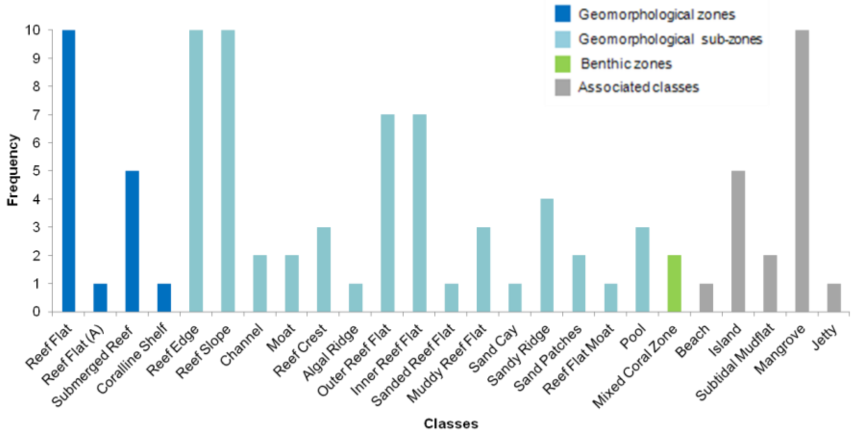


Figure 6.1.3.1 Frequency of classes detected for coral reef habitats of Eritrea

Areal Extent of Coral Reefs of Eritrea

The coral reef habitats of Eritrea as mapped from AWiFS data cover a total area of 5346.18 sq km. Reef area corresponding to each habitat map is summarized in Table No. 6.1.3.1. Dahlak archipelago occupies the highest reef area of 4036.78 sq km while coral reef habitats of Massawa and surroundings occupy the minimum area of 22.68 sq km.

Summary

Coral reef habitats of Eritrea are primarily coastal and off-shore fringing reefs. Among the off-shore fringing reefs Dahlak archipelago and the off-shore reefs near Assab represent some of the magnificent reef structures of the Eritrean coast. These archipelagos also include semi-submerged patch reefs and coral pinnacles along with the island fringing reefs. Most of the reefs show classical reef zonation pattern in terms of distinct reef slope, reef crest and reef flat zones. Eritrean coral reefs show a strong association with mangrove vegetation which is a typical characteristic of southern Red Sea coast. Eritrean coral reefs have maintained a good health condition despite moderate growth in tourism, coastal development and growth of commercial fisheries since its independence in 1993 (Spalding *et al.* 2001; Kotb *et al.* 2004). The majority of the coastline is sparsely populated with Massawa and Assab, the two main population centres on the coast while only four out of the three hundred and fifty islands are inhabited. Accordingly, the population pressure on coastal resources remained relatively low. The most important and diverse reefs, around the Dahlak archipelago still remain in good condition despite the lack of legal protection. Contrastingly some of the coastal reefs have rather suffered from land reclamation, sedimentation and resort developments in Massawa and coral reefs in vicinity. Eritrean corals represent thermally tolerant coral species of the world (Kotb *et al.* 2008). Coral reef habitats of Eritrea as mapped from AWiFS data dated 12th October, 2008 cover an area of 5346.18 sq km and appear in *near-pristine* condition.

Table 6.1.3.1 Areal Extent of coral reefs of Eritrea

Map No.	Location	Reef Area (sq km)
6.1.3.1	Coral reef habitats to the north of Mersa Teklay	64.19
6.1.3.2.	Coral reef habitats of the northern coast of Eritrea and off-shore reef off Difnein	47.05
6.1.3.3	Coral reef habitats of Dahlak Archipelago	4036.78
6.1.3.4	Coral reef habitats of Massawa and surroundings	22.68
6.1.3.5	Coral reef hyabitats of central Eritrea coast, Red Sea	49.95
6.1.3.6	Coral reef habitats near Gruta and Dluh	68.27
6.1.3.7	Coral reef habitats of Mersa Fatma, Mora, Miida and surroundings	605.60
6.1.3.8	Coral reef habitats of Behld, Beraisole and surroundings	244.14
6.1.3.9	Coral reef habitats of southern coast of Eritrea	25.02
6.13.10	Coral reef habitats between Assab and Rehayto	182.50
	Total Area	**5346.18**

Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.1 represents Results > under **Basin 1. Red Sea**
6.1.3 represents Results > under Basin 1. Red Sea > for **Country 3. Eritrea**
6.1.3.1 represents **Coral Reef Habitat Map** of **Eritrea coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

1. North of Mersa Teklay
2. Northern coast of Eritrea and off-shore reef of Difnein
3. Dahlak Archipelago
4. Massawa and surroundings
5. Central Eritrea coast, Red Sea
6. Near Gruta and Dluh
7. Mersa Fatma, Mora, Miida and surroundings
8. Behld, Beraisole and surroundings
9. Southern coast of Eritrea
10. Between Assab and Rehayto

--- International boundary

Source: Resourcesat-1 AWiFS mosaic from data dated: 12th October, 2008

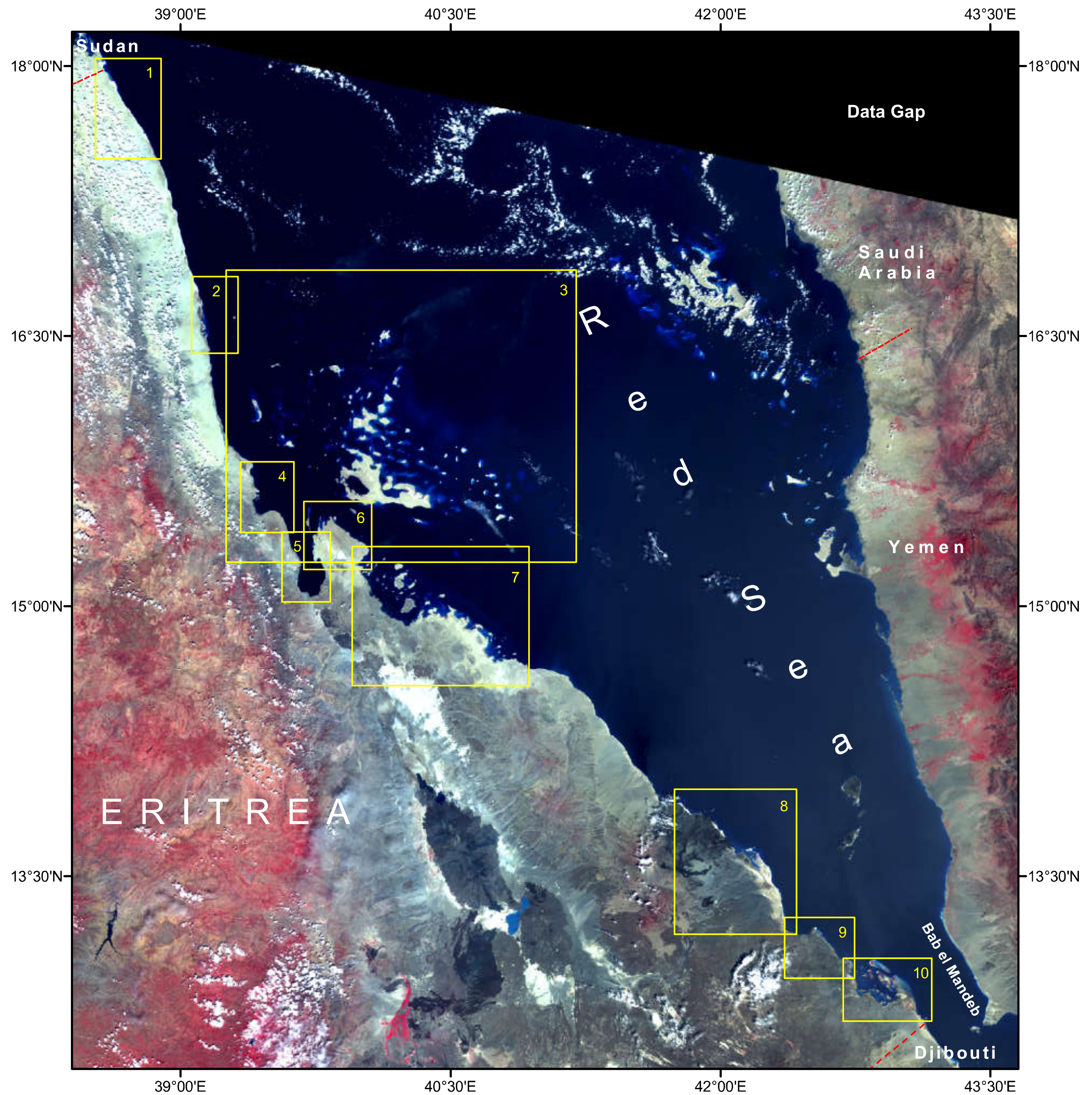
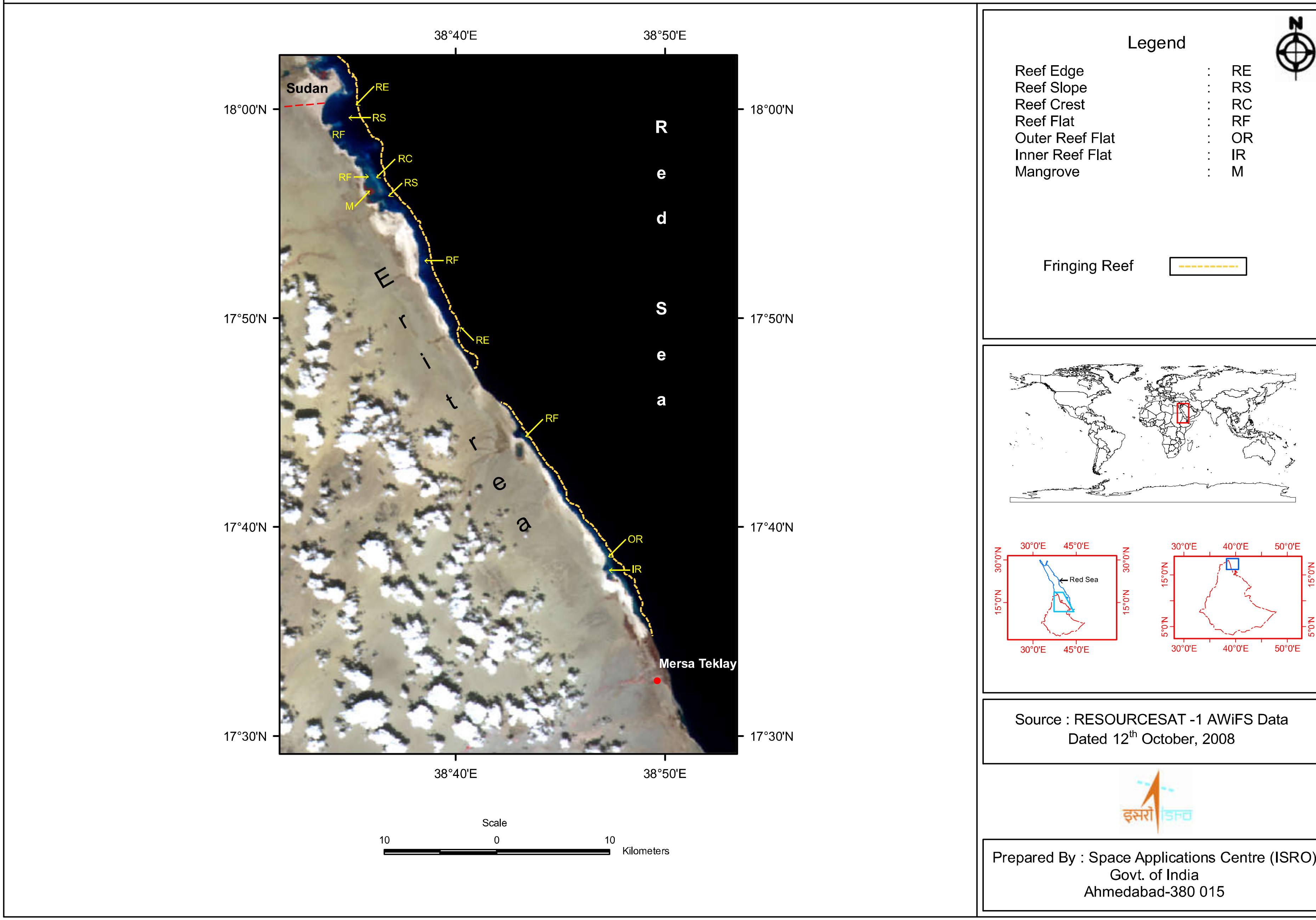
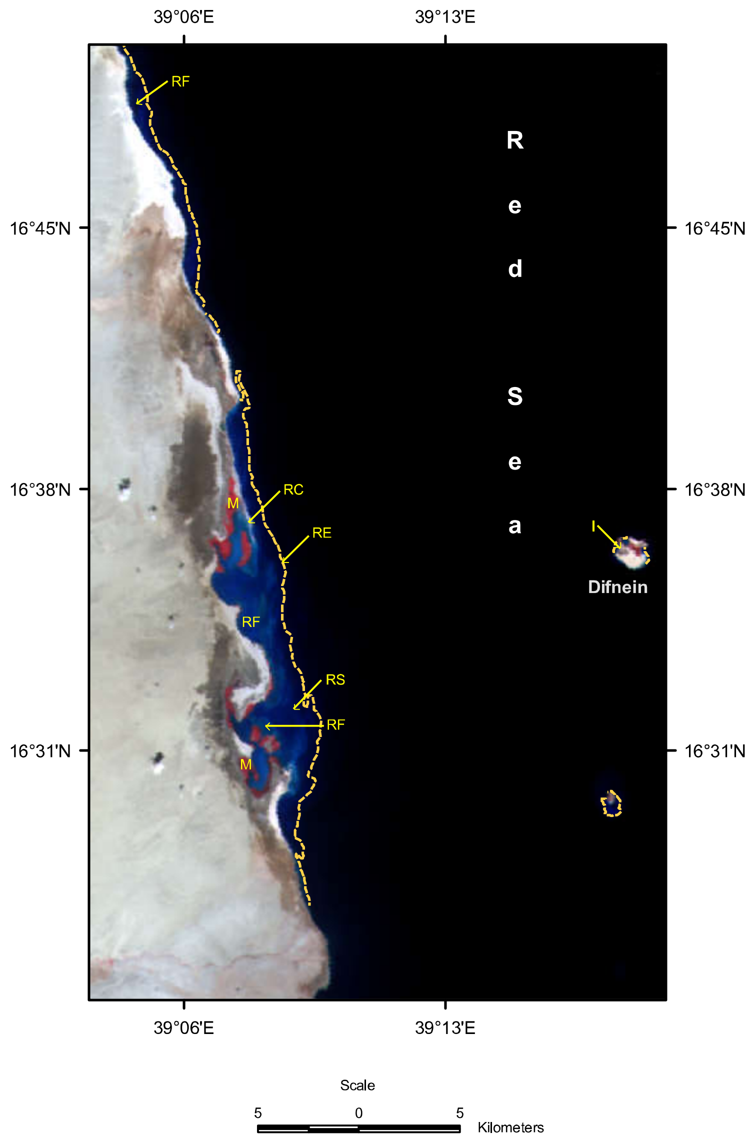


Figure 6.1.3 Index to coral reef habitat maps of Eritrea



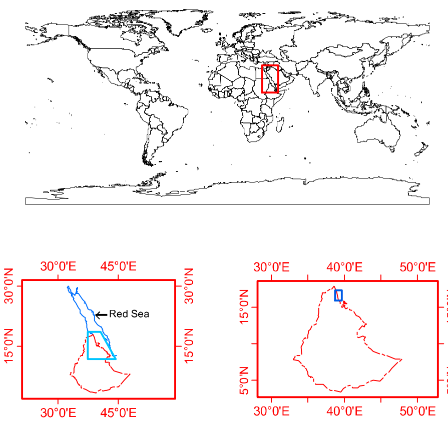
Map 6.1.3.1 : Coral reef habitats to the north of Mersa Teklay



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Crest	:	RC
Reef Flat	:	RF
Island	:	I
Mangrove	:	M

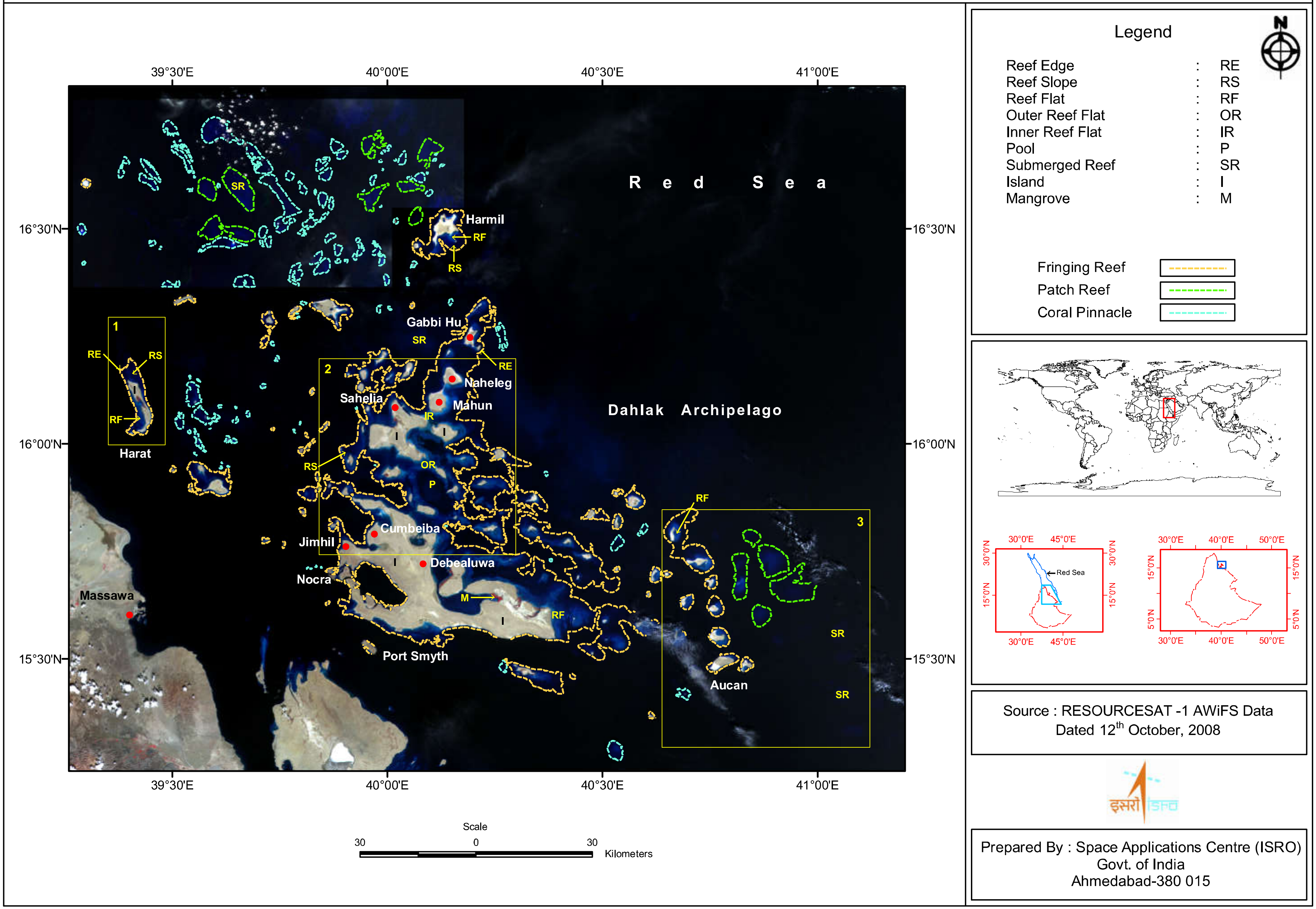
Fringing Reef



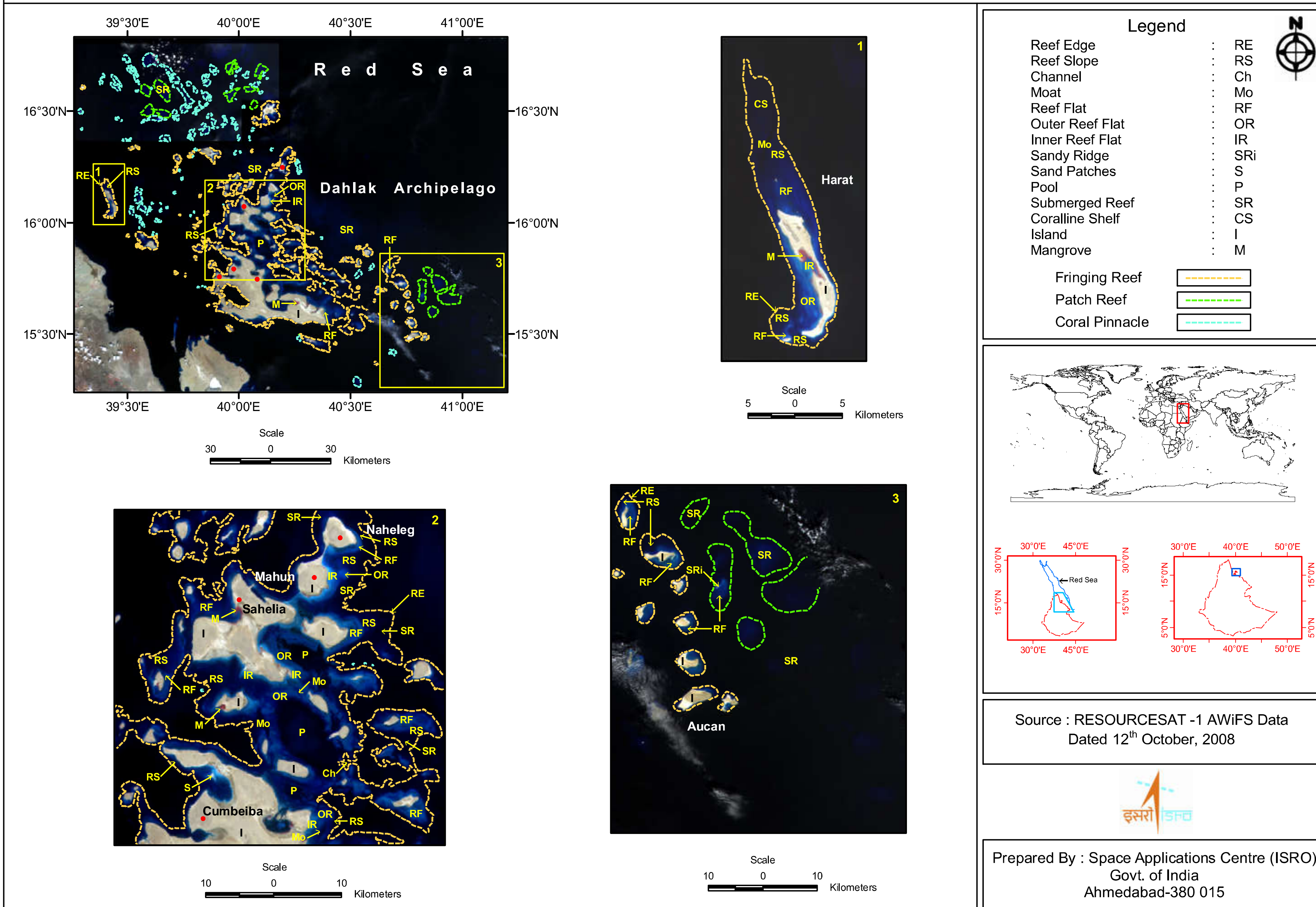
Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

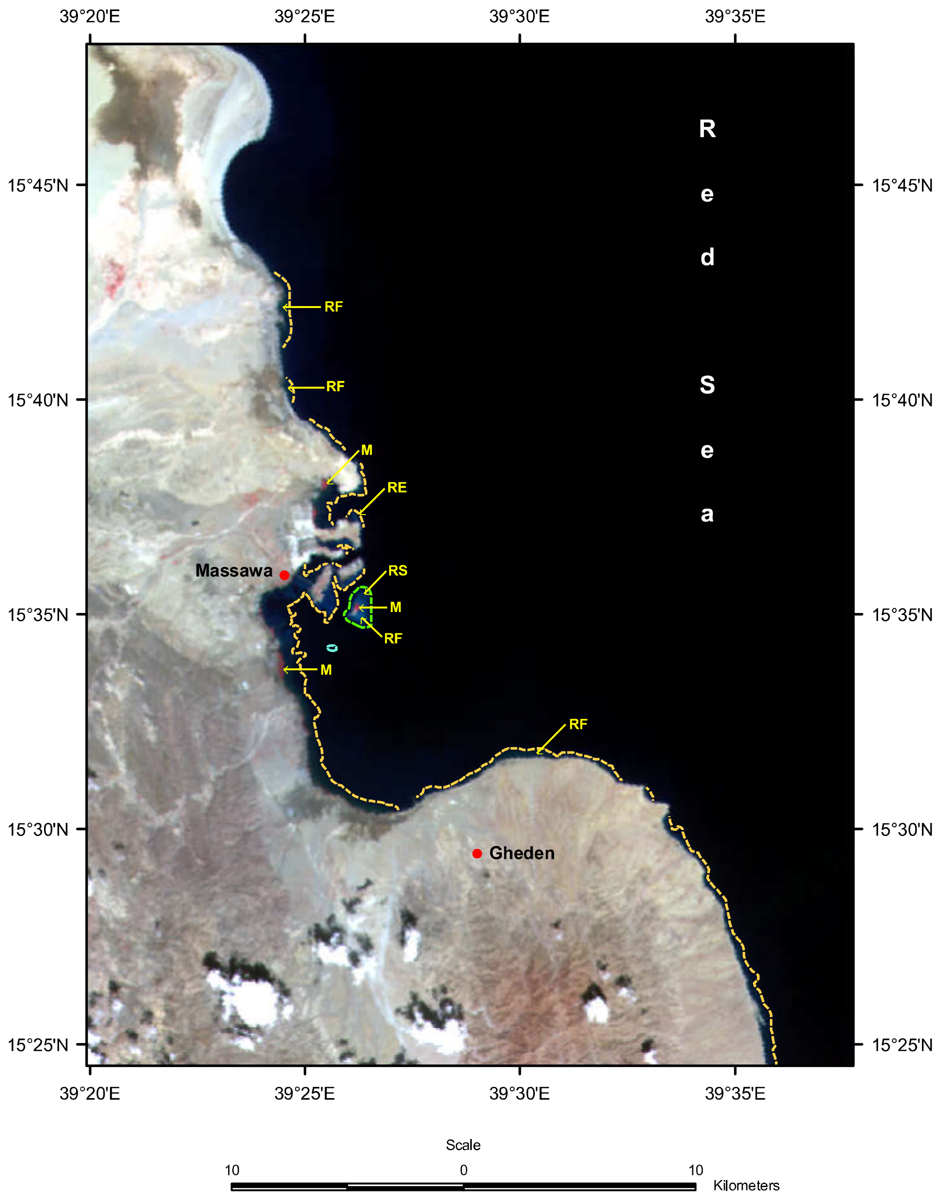
Map 6.1.3.2 : Coral reef habitats of northern coast of Eritrea and off-shore reef of Difnein



Map 6.1.3.3 : Coral reef habitats of Dahlak Archipelago



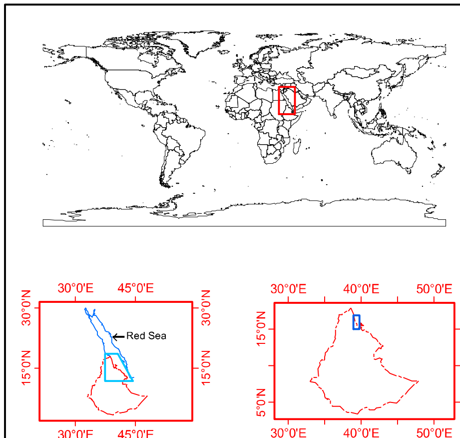
Map 6.1.3.3A : Selected coral reef habitats of Dahlak Archipelago



Legend

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF
Mangrove : M

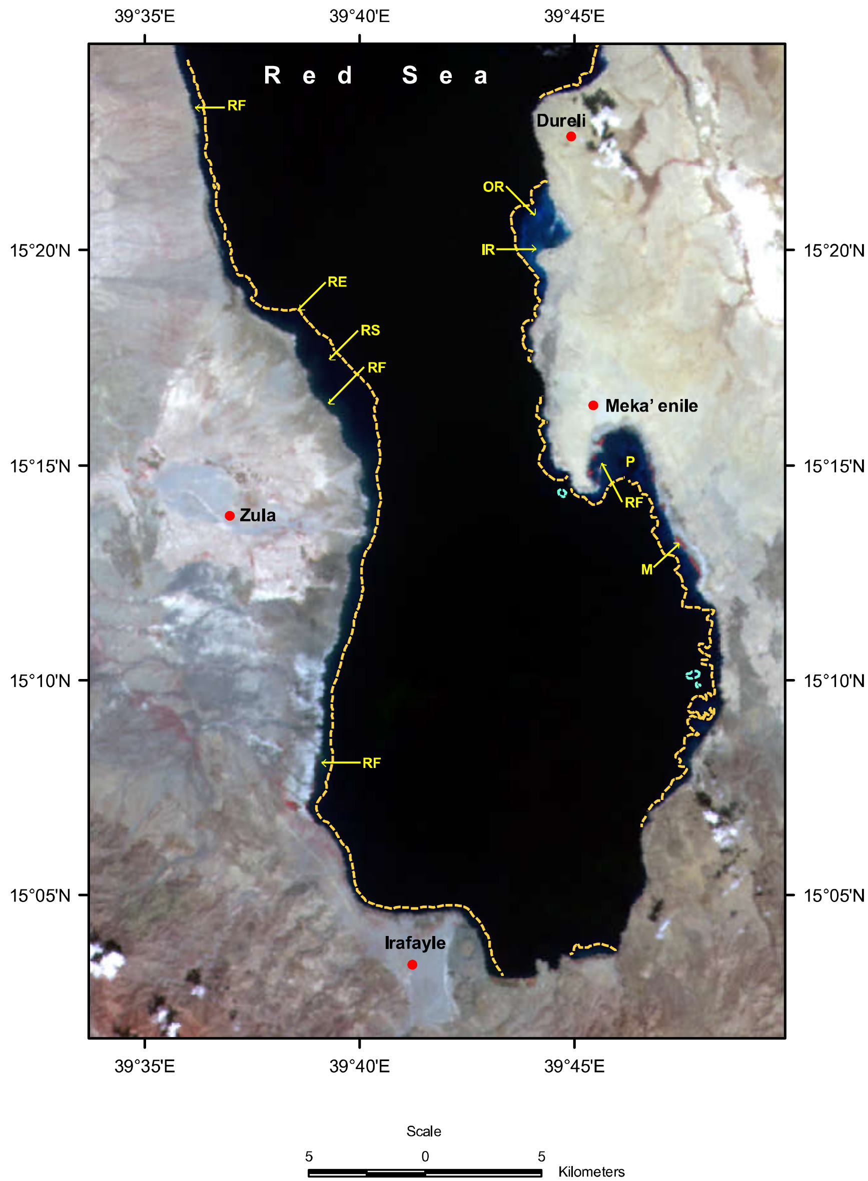
Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

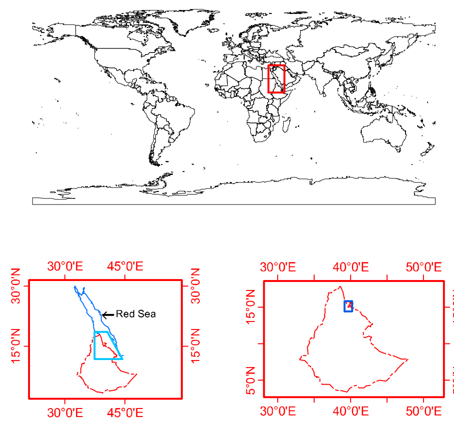
Map 6.1.3.4 : Coral reef habitats of Massawa and surroundings



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Pool	:	P
Mangrove	:	M

Fringing Reef
Coral Pinnacle



Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
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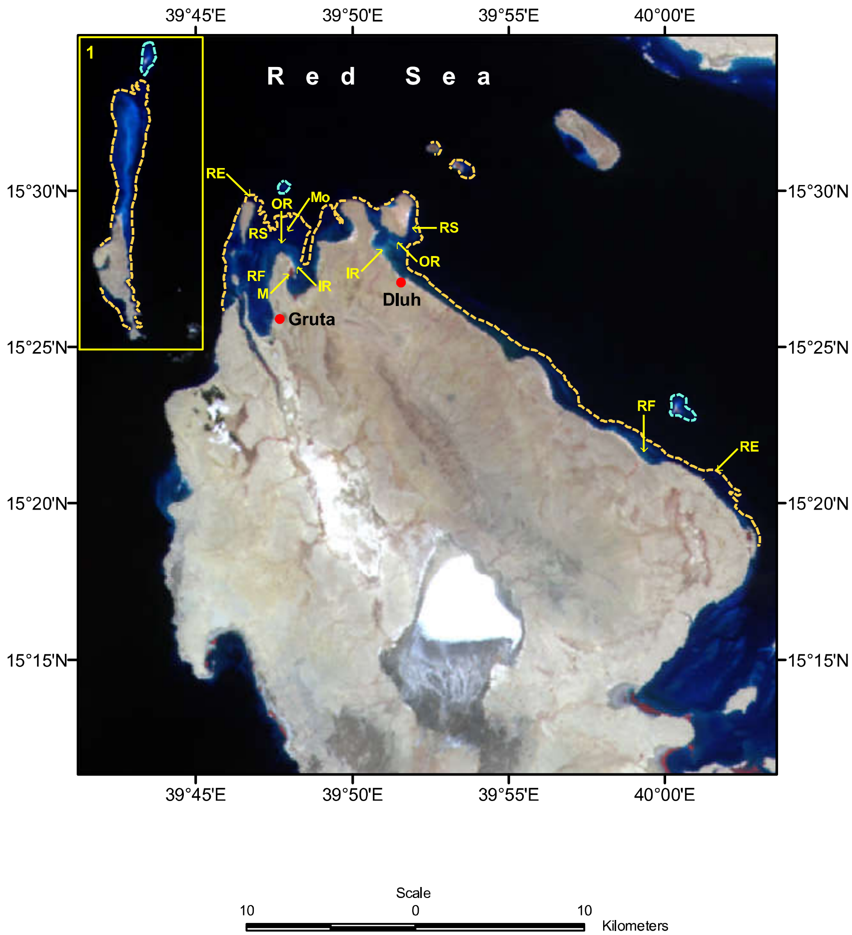
Ahmedabad-380 015

Map 6.1.1.5 : Coral reef habitats of central Eritrea coast, Red Sea

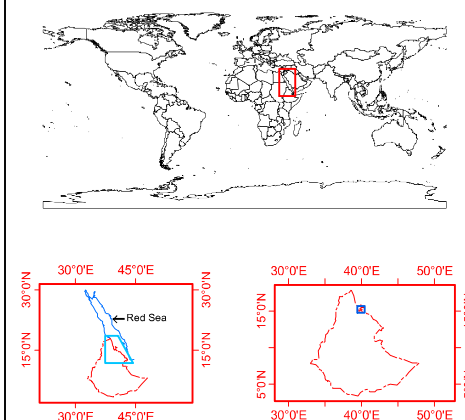


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sandy Ridge	:	SRi
Sand Patches	:	S
Island	:	I
Mangrove	:	M

Fringing Reef

Coral Pinnacle



Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
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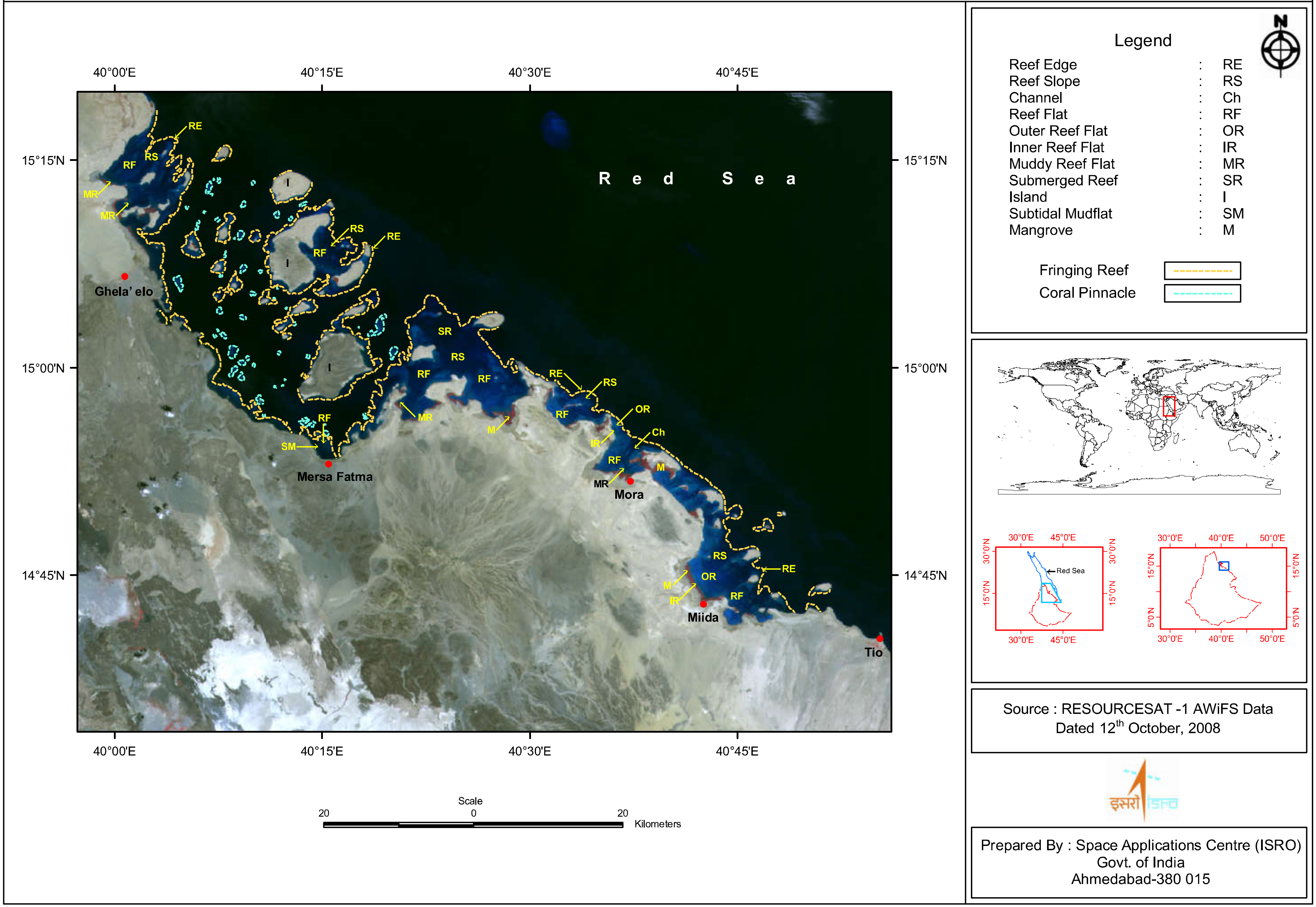
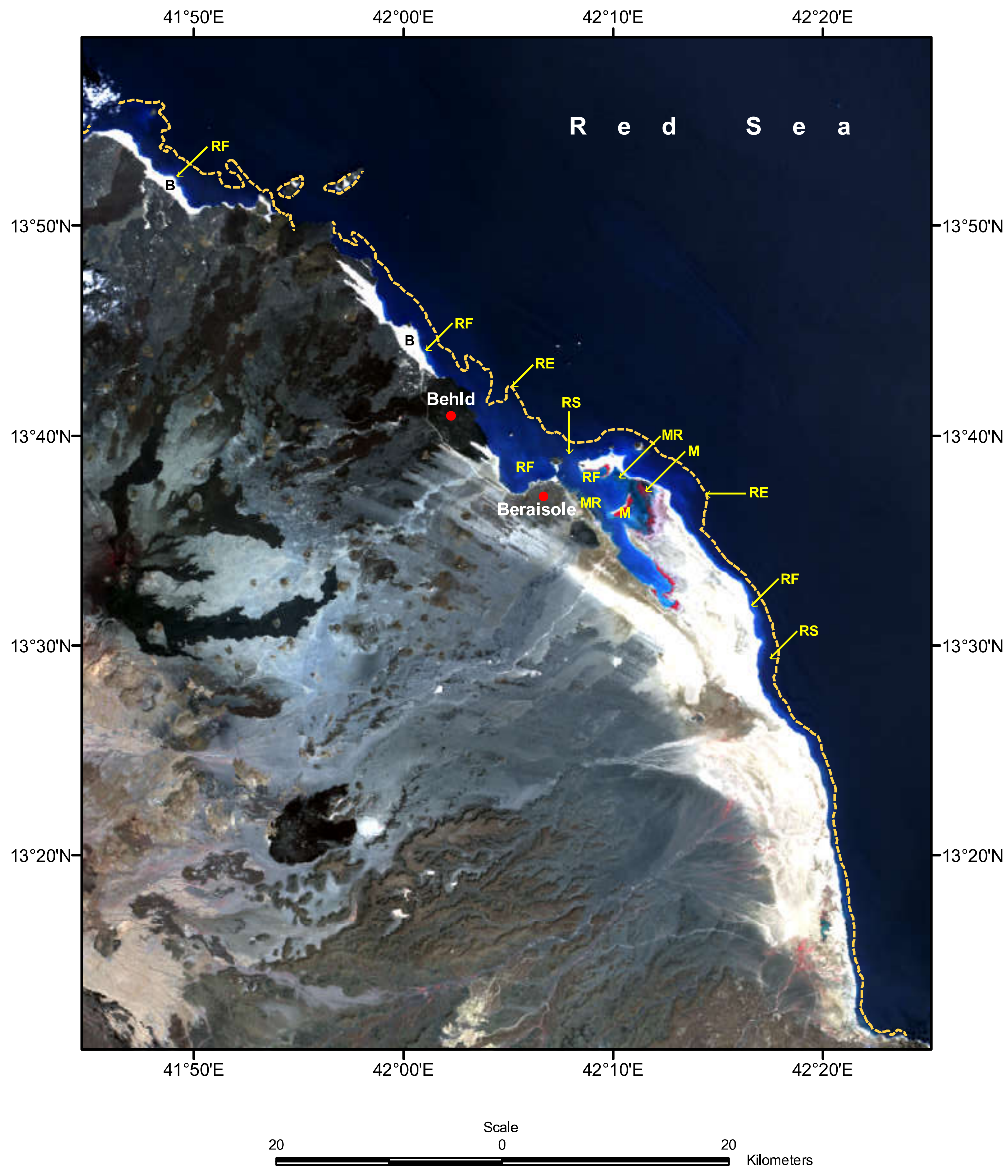
Map 6.1.3.6 : Coral reef habitats near Gruta and Dluh



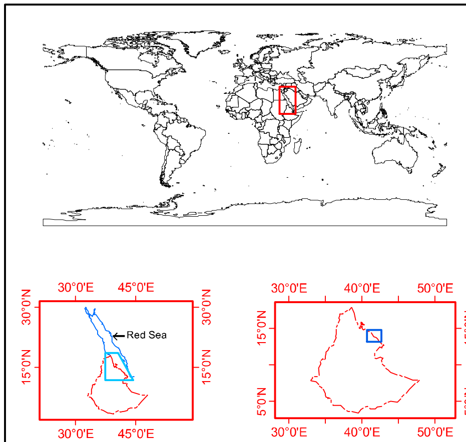
Map 6.1.3.7 : Coral reef habitats of Mersa Fatma, Mora, Miida and surroundings



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Muddy Reef Flat	:	MR
Beach	:	B
Mangrove	:	M

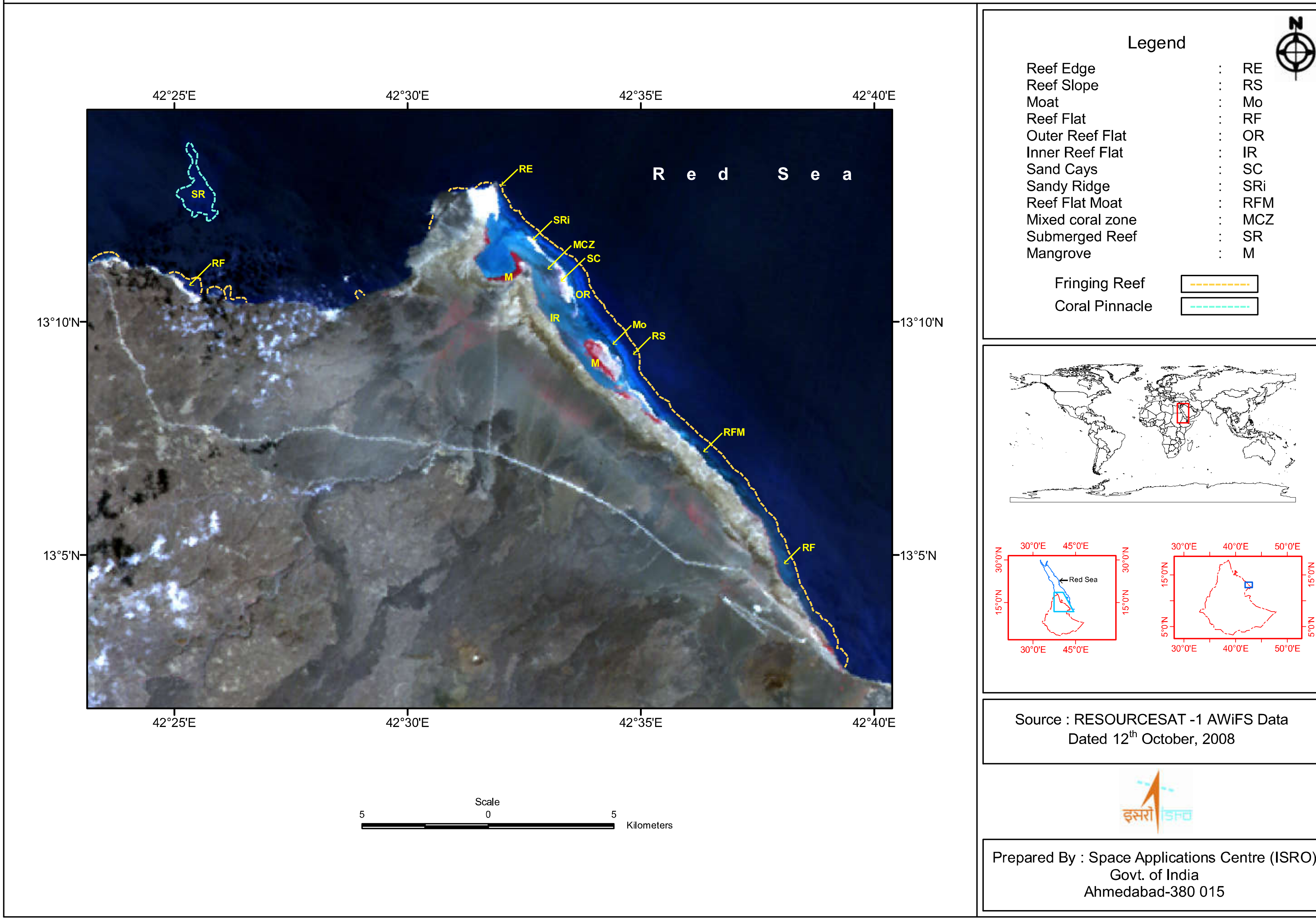
Fringing Reef



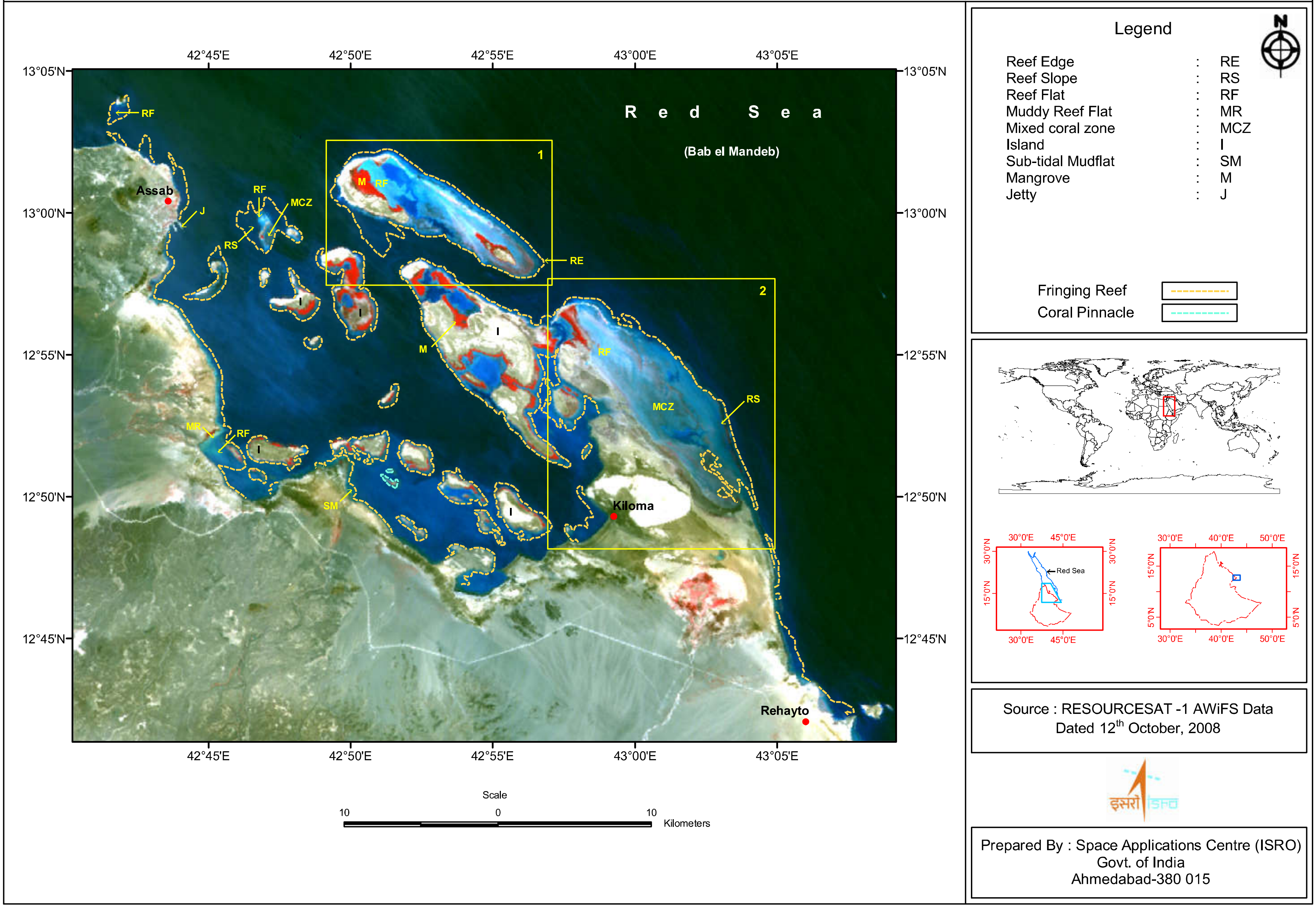
Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

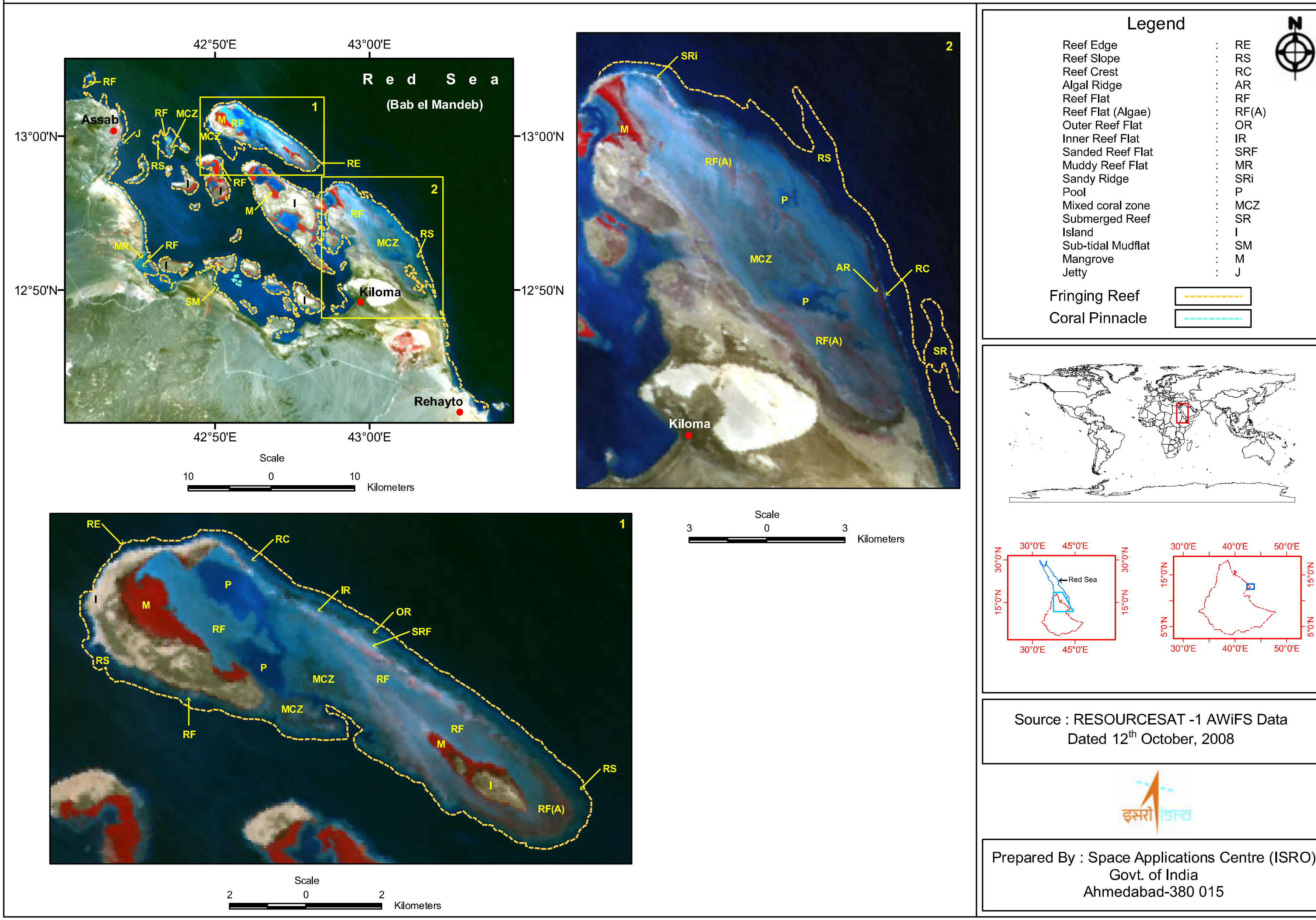
Map 6.1.3.8 : Coral reef habitats of Behld, Beraisole and surroundings



Map 6.1.3.9 : Coral reef habitats of southern coast of Eritrea



Map 6.1.1.10 : Coral reef habitats between Assab and Rehayto



Map 6.1.3.10A : Selected coral reef habitats between Assab and Rehayto

6.1.4. Jordan

Background

The Gulf of Aqaba coastline of Jordan extends for a short length of 27 km within the geographical co-ordinates of 29°20’ to 29°33’ N latitudes and 34°58’ to 34°59’ E longitudes. The Gulf of Aqaba is a semi-enclosed system with limited water circulation (residence time of two to three years) and the Jordanian coast shares an arid regional climate (Pilcher and Al-Moghrabi 2003). The coastline has considerable urban and industrial development in the north due to port location which accounts for thirty per cent of the coastline (Kotb *et al.* 2008).

Fringing reefs border 50% of Jordan’s coast with a high diversity of corals and associated fauna (about 180 coral and 512 fish species, Kotb *et al.* 2008). Overall Jordan’s coral reefs have been reported to be in good condition supporting 90% scleractinian coral cover in certain areas. There is approximately 45% of living coral cover consisting of 30% hard corals and 15% soft corals (Kotb *et al.* 2008). No bleaching events (following 1997-98 warming) were recorded in these cooler water reefs of Gulf of Aqaba, possibly due to their location in the extreme northern latitude (Pilcher and Al-Moghrabi 2003).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Jordan coast have been mapped with AWiFS data (single scene) dated 8th June, 2007. The coral reef habitat map (Map. 6.1.4.1) depicts narrow fringing reefs on Jordan coast to the south of Port Aqaba. The spatial resolution of AWiFS data proves to be too coarse to bring out any significant intra-reef details of these narrow fringing reefs. AWiFS data could detect only two reef categories: reef flat and reef edge. The frequency of the detected reef categories is represented in Figure 6.1.4.1.

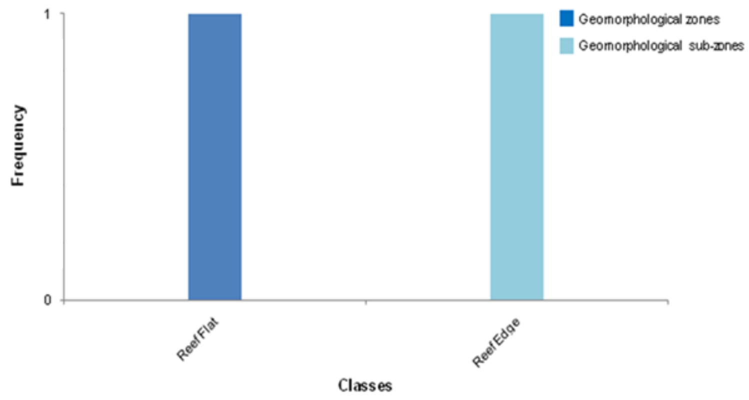


Figure 6.1.4.1 Frequency of classes detected for coral reef habitats of Jordan

Areal Extent of Coral Reefs of Jordan

Coral reefs of Jordan as detected and mapped from AWiFS data occupy a total area of 1.05 sq km.

Table 6.1.4.1 Areal Extent of coral reefs in Jordan

Map No.	Location	Reef Area (sq km)
6.1.4.1	Coral reef habitats to the south of Aqaba Port	1.05
	Total Area	**1.05**

Summary

Coral reef habitats of Jordan are coastal fringing reefs which occupy 1.05 sq km area. However, detailed mapping of these reef habitats requires high resolution (spatial) data. Jordan has one 7 km long MPA (the Marine Peace Park) and the coral reefs have been reported to be in overall good condition (Kotb *et al.* 2008). The major sources of threats to Jordan coral reefs include: COTS outbreaks, diseases from aquaculture and anthropogenic pressures from urban, industrial, port and tourism developmental activities (Spalding *et al.* 2001; Kotb *et al.* 2004, 2008). Gulf of Aqaba is susceptible to pollution including oil spills and industrial discharges, municipal and ship-based sewage and solid waste (Al-Moghrabi 2003; Pilcher and Kotb *et al.* 2008). However, Jordan's reef health condition can not be commented in detail due to the coarse resolution of AWiFS data.

Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.1 represents Results > under **Basin 1. Red Sea**
6.1.4 represents Results > under Basin 1. Red Sea > for **Country 4. Jordan**
6.1.4.1 represents **Coral Reef Habitat Map** of **Jordan coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

1. South of Aqaba Port

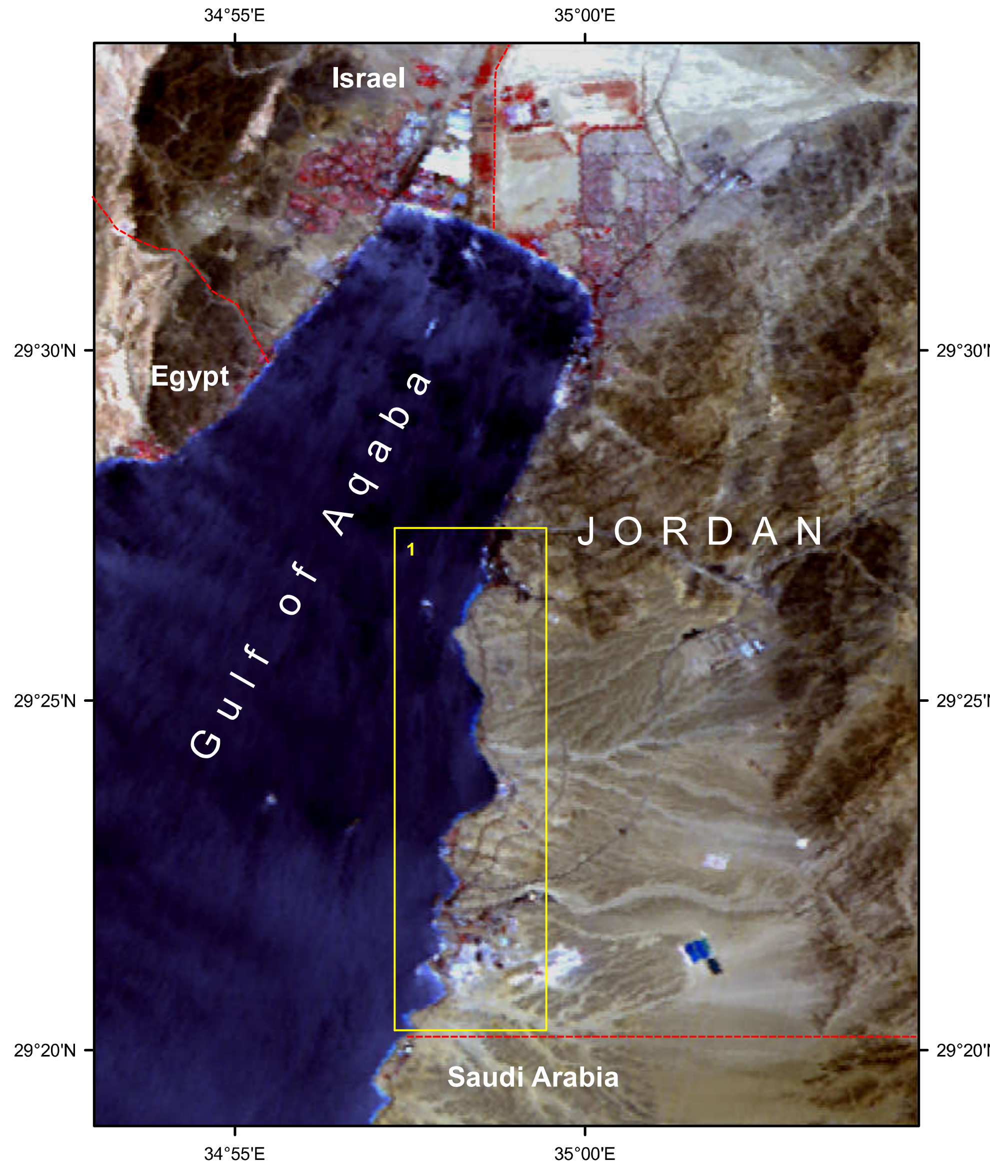
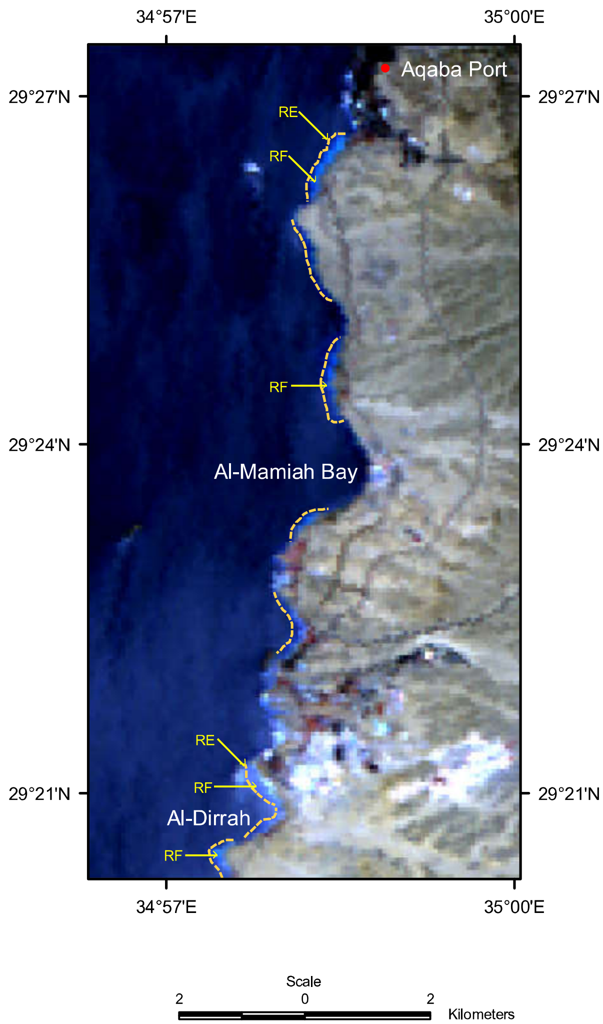


Figure 6.1.4 Index to coral reef habitat maps of Jordan

--- International boundary

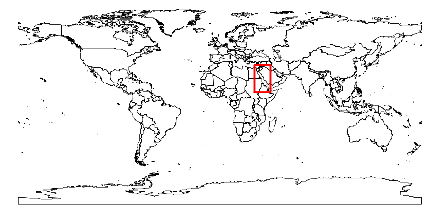
Source: Resourcesat-1 AWiFS mosaic from data dated: 8th June, 2007

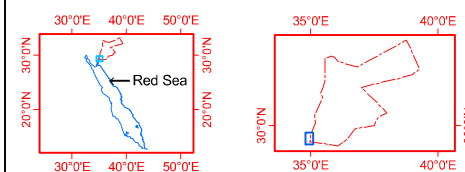


Legend

Reef Edge : RE
Reef Flat : RF

Fringing Reef





Source : RESOURCESAT-1 AWiFS Data
Dated 8th June, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.4.1 : Coral reef habitats to the south of Aqaba Port

6.1.5. Saudi Arabia

Background

Saudi Arabia's Red Sea coast runs for a length of 1840 km and represents the east coast of northern and central Red Sea. The Saudi Arabian coast shares the border with Jordan in the northern Gulf of Aqaba and with Yemen in the southern Red Sea. This coastline extends within the geographical co-ordinates of 16°22' to 29°25' N latitudes and 34°51' to 42°48' E longitudes. The coastal region is arid and dominated by high relief along much of its length (Spalding *et al.* 2001). The continental shelf extends for a narrow width (less than a kilometer) in Gulf of Aqaba and gradually widens down south; in far south, near Farasan Bank it extends over hundreds of kilometers (Pilcher and DeVantier 2003). Saudi Arabia's Red Sea coast and islands support a variety of coastal and marine habitats including coral reefs, seagrass beds and mangroves related largely to different oceanographic regimes, degree of exposure and topographic features.

Saudi Arabia's Red Sea coast is fringed with a near continuous reef along with platform, patch, pinnacles and barrier kind of reefs (Kotb *et al.* 2008). This region has a complex tectonic history of uplift and subsidence related to the Red Sea rift development from the movements of the Arabian and the African tectonic plates. The present series of living coral reefs are the latest in chronological sequence of the raised and submerged reefs that have developed at various times over the past several hundred millennia (Pilcher and DeVantier 2003). In many cases, the present reefs have developed on earlier reef structures.

Saudi Arabia's Red Sea coast can be divided into three relatively homogenous areas in terms of the distribution and variety of coral reefs and other coastal and marine habitats: i) the Gulf of Aqaba in the north, ii) the northern-central section from the southern end of Aqaba to Jeddah, and iii) the central-southern region from south of Jeddah to the border of Yemen including Farasan Bank and Islands (Pilcher and DeVantier 2003). In Gulf of Aqaba, the coral reefs are typically narrow, fringing the mainland coast. The northern-central section has a much higher diversity of coral reefs and other coastal habitats than Gulf of Aqaba. Fringing reefs are present on the mainland coast while platform, patch and barrier reefs are located off-shore. The area is renowned for the presence of Al Wadj Bank, a large, shallow area bordered by a barrier reef system in its seaward edge incorporating many islands and reefs. The central-southern area including the Farasan Bank and Islands have different geomorphological and bio-physical characteristics as compared to the other two regions. This region experiences highest sea surface temperatures and accordingly reef development gets restricted. This area contains the reef-species locally adapted to grow on the wide, extensively shallow, coastal shelf allowing mixing of sea-waters with turbid, inshore waters (Spalding *et al.* 2001; Pilcher and DeVantier 2003).

In terms of biodiversity, this coastline incorporates the complete wealth of Red Sea species, including those endemic to northern regions as well as the ones abundant in south. Two hundred and sixty species of hard corals have been reported from the field surveys carried out during 1997-

99 (Spalding *et al.* 2001). Most of the coral reefs of Saudi Arabia's Red Sea coastline are generally in good condition with high coral cover, often exceeding 50%, except near major cities (Kotb *et al.* 2004, Kotb *et al.* 2008). The 1997-1998 bleaching event had resulted in localized losses of coral cover and diversity of some reefs particularly in south (Kotb *et al.* 2004). Isolated Crown-of- Thorns Starfish (COTS) outbreaks have also been reported, however, most of the northern reefs remained in good health condition (Kotb *et al.* 2004).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Saudi Arabia's Red Sea coast have been mapped with Resourcesat-1 AWiFS data (3 scenes; dated: 2nd August, 2005, 25th February, 2006 and 19th March, 2007). An additional LISS- III scene dated 25th February, 2006 has been used for mapping selected coral reefs of the Farasan Islands. Detailed habitat characteristics of these reefs have been depicted in twenty-two reef habitat maps (Map No. 6.1.5.1 to 6.1.5.22). The entire coastline of Saudi Arabia is fringed with near-continuous, coastal fringing reefs along with off-shore platform, patch, pinnacle types of reefs and barrier reefs. Habitat characteristics of Saudi Arabia's coral reefs are discussed here, under three major coastal segments, as mentioned in the preceding section.

i) Coral reefs of Gulf of Aqaba:

In Gulf of Aqaba, there is little or no continental shelf, the coral reefs are typically narrow with narrow reef flats and have steep to vertical reef profiles (Spalding *et al.* 2001). The same is evident in Map No. 6.1.5.1 to 6.1.5.3. AWiFS data could detect the extremely narrow, coastal fringing reefs and only the reef edge and the reef flat categories could be identified. South of Al Maqnah (Map. 6.1.5.3), however, pools and benthic zone of algae could be detected. A significant coral reef area occurs at the southern end or the entrance of Gulf of Aqaba as the Tiran-Senafir National Park, Ras al Qasbah and Sinafir Island (Map. 6.1.5.4). This region forms a unique reef complex with a variety of biotopes (coral reefs, seagrass beds and intertidal sand flats) having high zoogeographical significance (Pilcher and DeVantier 2003; Kotb *et al.* 2004). AWiFS data dated 19th March, 2007 helped in distinguishing the reef slope, reef crest and reef flat zones of the coastal fringing reef. At certain locations moats separate the reef flat from the reef slope zones. On the mainland coast the reef areas adjacent to mudflats appear muddy. The reef fringing the Sinafir Island (Map. 6.1.5.4; subset: 1) has been zoomed to show the intra-reef features. The moat separates the reef flat from the reef slope zones and the reef flat can be separated into outer and inner reef flats. A prominent algal ridge and algal patches are detected on this reef. Two patch reefs and three coral pinnacles are detected in this part of the Saudi Arabian coast.

The narrow contour reefs, less than 50 m wide, fringing the steep coastal slopes in Gulf of Aqaba are among the most species-rich of the entire region (Pilcher and DeVantier 2003). The high species diversity is extremely significant given the restricted reef area, cool sea temperatures and Gulf of Aqaba's remote location at the north-westernmost extent of Indo-Pacific reef development region. New species of hard corals have been reported from this area (Kotb *et al.* 2004).

ii) Northern-central section (from southern end of Gulf of Aqaba to Jeddah):

The northern-central section of Saudi Arabian coastline hosts near-continuous fringing reef along with off-shore platform, patch reefs and sometimes complex barrier reefs. Coral reef habitats near Ash Sharmah and off-shore reefs of Al Muwaylih (Map. 6.1.5.5, 6.1.5.5A) show typical distribution of coastal fringing reefs, a barrier reef structure, along with off-shore fringing reefs and elongated patch reefs. The narrow coastal fringing reef widens and extends off-shore from the coastal headland to the west of Al Sharmah and fringe an off-shore island. This part of the reef has been selectively zoomed (Map. 6.1.5.5A; subset: 1) to view the intra-reef details. The reef can be distinguished into reef slope, reef crest and reef flat zones. A moat is found to separate the reef flat and the reef slope zones. To the north of the island a sanded reef flat extends on the reef flat while another sanded reef flat juts out from the headland in northward direction. Existence of dune vegetation is noticed on this sanded reef flat. On the eastern side, the reef adjacent to the mainland coast appears muddy. Opposite to this coastal fringing reef, a barrier reef structure emerges with a wide reef slope, clear reef crest and reef flat features. Moats and pools are also detected within the reef structure. A sandy ridge is also detected. The reef area surrounding the island appears muddy. The off-shore reefs near Al Muwaylih (Map. 6.1.5.5A; subset: 2) show classic distribution of platform reef along with elongated fringing and patch reefs which are generally widespread in off-shore waters less than 50 m deep (Pilcher and DeVantier 2003). The platform reef shows an intricate 'reticulate' structure composed of interconnected reef matrix separated by sand. A prominent sandy ridge is seen at the center of the reef flat which branches out on the reef flat rimmed by a deep reef slope zone. The patch reefs and coral pinnacles are elongated with clear zonation between reef slope and reef flats. Algal ridge, sanded reef flat and coralline shelf are also detected on these coral reefs. One patch reef and twenty submerged coral pinnacles have been detected in this part of the Saudi Arabian coast.

The narrow coastal fringing reef continues further south, crosses Duba and widens out near Abu Salama (Map. 6.1.5.6). Near Abu Salama, an algal ridge separates the submerged reef slope zone from the reef flat which shows influence of the adjacent mudflats and small pockets of mangrove vegetation. Off-shore, a major island fringing reef An Nu'man is located with a shore-parallel orientation. A prominent reef crest is detected in the north while an algal ridge is seen in the western and south-western rims of the reef. The outer and inner reef flats can be distinguished while a sanded reef flat is detected on the western side of the narrow reef flat. Dune vegetation rims the island. Eight coral pinnacles are detected from AWiFS data dated 19th March, 2007 in this segment of Saudi Arabian coast. However, AWiFS data proves coarse to depict intra-reef details of the coastal fringing reef.

These reef complexes support a high reef species diversity including Red Sea endemic corals, undescribed coral species and rare coral species with restricted distribution in the Red Sea (Pilcher and DeVantier 2003).

The coastal fringing reef continues south of Abu Salama on the mainland coast (Map. 6.1.5.7) while elongated patch reefs and submerged coral pinnacles are found off-shore, near Al Uwaynidhiyah. A part of the coastal fringing reef (Map. 6.1.5.7; subset: 1) and off-shore patch reefs (Map. 6.1.5.7; subset: 2) have been selectively zoomed to show the intra-reef details. The coast fringing reef could be zoned into reef slope and reef flat. An algal ridge is detected on the seaward margin of the reef. Dune vegetation is also noticed around the island adjacent to the coast. Off-shore, the elongated patch reefs have irregular boundaries. The reefs show clear distinction between reef slope and reef flat zones. Prominent algal ridge could also be detected for individual patch reefs. Pool and sand patches are also noticed on the patch reefs. Three patch reefs and twenty-nine coral pinnacles have been detected from the AWiFS data for this part of the Saudi Arabian coast.

The narrow reef continues to fringe the mainland coast of Saudi Arabia down south and converge with the more complex reef systems near the Al Wadj Bank. To the north of Al Wadj Bank, an off-shore fringing reef occurs (Map. 6.1.5.8) resembling the shape of a fish. The reef could be distinguished into reef slope and reef flat zones. The reef fringes an island to its western part and an algal ridge is detected rimming the reef and the island. A large pool separates the reef flat adjacent to the island and the reef flat in the central portion of the reef. A sanded reef flat is noticed in the central reef flat which is covered with dune vegetation.

The northern-central coast of Saudi Arabia is renowned for the presence of Al-Wadj Bank (Map. 6.1.5.9, 6.1.5.9.A) a large, relatively shallow area bordered by a barrier reef system on its seaward edge. This area also incorporates complex series of fringing and patch reefs along with many reef islands and houses important and extensive seagrass and mangrove communities. Barrier reef structure is developed further offshore, on the edge of the continental slope where water depths increase from less than 50 m to greater than 200 m (Pilcher and DeVantier 2003). The barrier is composed of a continuous line of reefs stretching for about 100 km and separated by several narrow (< 200 m wide) channels. AWiFS data dated 19th March, 2007 show the well developed barrier reef structure with wide reef flat exposed at different depths on the seaward side. The barrier reef encloses a lagoon with one major fringing reef, seven patch reefs and twenty-one coral pinnacles. The lagoon is connected to the open sea through a narrow conduit in the north. In the northern portion, the near shore, coastal fringing reef shows reef edge, reef slope zones with very narrow reef flat. On the barrier arm five major reef islands have developed with shore-parallel orientation in NW-SE direction. Mashabih is one such major island. Most of these islands are rimmed with mangrove vegetation in their sheltered, landward sides while have a line of dune vegetation on their seaward edges. Submerged reefs are seen within the lagoon.

Three areas of Al Wadj Bank have been selectively zoomed (Map. 6.1.5.9.A) to show the intra-reef details. The hooked-arm of the barrier reef in the northern portion of the Al Wadj Bank with Umm Urumah and Mashabih islands (Map. 6.1.5.9A; subset: 1) show a classic reef zonation with reef front and reef flat zones being discerned with their respective sub-zones. The reef front area shows clear zonation of reef edge, reef slope sub-zones in both northern and southern parts of the selected subset. A channel is detected near Umm Urumah islands while spur and groove could be detected in the southern portion of the barrier reef. This is the only case where spur and groove features have been detected with AWiFS data in the entire Red Sea and Gulf of Aden. A discontinuous algal ridge is seen in the central and southern parts. Very clear exposure of reef crest is found in the southern portion. The reef flat could be distinguished into outer and inner reef flats. The lagoonal reef slope is relatively narrow in the northern portion and culminates into lagoonal patch reefs or submerged portions of the reef. Pools are found in both the barrier and the coast fringing reef. The lagoon is dotted with patch reefs and coral pinnacles as described earlier.

The second subset (Map. 6.1.5.9A; subset: 2) shows a single off-shore reef developed parallel to this barrier reef system. On its seaward edge, a long, linear, narrow algal ridge rims the reef with well developed moats separating the reef slope and the ridge or the ridge and the reef flat. The reef flat has a narrow outer reef flat and a relatively wide inner reef flat with a sand patch on it. Dune vegetation is prominent on the sand patch. Onto the eastern side of this reef, major portion of the reef appears submerged. The third subset (Map. 6.1.5.9A; subset: 3) shows a cluster of fringing, patch and pinnacle reefs within the lagoon. In case of the fringing reef, reef slope and reef flat can be detected and the reef flat can be further distinguished into outer and inner reef flats. In case of other fringing and patch reefs, the reef flats are dotted with small islands surrounded by sanded reef flats. Here, circular or elongated patch reefs are widespread in off-shore waters having depth more than 50m **(**Pilcher and DeVantier 2003). As evident from the satellite data, patch reef supports sand-coral islands (or sand cays), while others are submerged and resemble coral carpets (Riegl and Piller 1999).

This bank supports the greatest range of reef types and other marine and coastal habitats in this region (Pilcher and DeVantier 2003). Al Wadj Bank hosts Red Sea endemic corals, undescribed coral species and species with apparently restricted distributions. The size of the bank, the diversity of the reef habitats and likely high level of ecological connection in terms of larval dispersal in ocean currents, both within the bank and with other parts of the Red Sea attach great conservation significance to this bank. The Al Wadj Bank happened to be the best reef of Saudi Arabia during 2002 (with an average 40% coral cover at 5 m; Kotb *et al.* 2004). Being away from the influence zone of coastal, urban settlements, this bank still continues to remain in pristine condition. The bank is unique in several respects and had been a prime focus of MPA planning by Saudi Arabia's National Commission for Wildlife Conservation and Development (NCWCD; Pilcher and DeVantier 2003).

Just south of Al Wadj Bank, near Umm Lajj and surroundings (Map. 6.1.5.10), an interconnected, coast fringing reef system runs with elongated and reticulate patch reefs. Reticulate patch reefs, composed of interconnected networks of reef matrix separated by sand, form intricate patterns and are well developed in shallow waters with an approximate depth of 10 m (Pilcher and DeVantier 2003). This pattern is evident in AWiFS data dated 19th March, 2007. The reef flat zones along with sanded reef flats and sandy ridges stand out as compared to the reef slope zones which rather culminate into submerged reefs. In certain places algal ridge and dune vegetation have been detected. The submerged reefs here actually represent the subsurface patch reefs with virtually no reef flat. Elongated coral pinnacles are found in off-shore waters.

South of Al Wadj Bank to Jeddah (Map. 6.1.5.11 to Map. 6.1.5.17), a discontinuous, barrier reef structure runs along the Saudi Arabian coastline which is known as 'Little Barrier Reef' (Spalding *et al.* 2001). This barrier reef system is however of a different gross geomorphological structure and occurs further south near Yanbu (Pilcher and DeVantier 2003; Map.6.1.5.13). Map 6.1.5.11 and 6.1.5.12 show the discontinuous, fringing reef on the Saudi Arabian coast along with circular to elongated off-shore, coral pinnacles. In the southern part of Map 6.1.5.11, where the coast fringing reef widens to a considerable proportion, reef slope and reef flats could be detected along with pools and moat. An algal ridge is also detected on the seaward edge while dune vegetation is seen on the reef flat. Reef flats could be detected for most of the coral pinnacles. Near Sharm al Khaur (Map. 6.1.5.12), the gross, geomorphology of the reefs remains the same other than some parts of the reef flat which appear muddy.

Coast fringing and discontinuous, off-shore barrier reef structure continues further south near Yanbu (Map. 6.1.5.13). Reef flat moats and dune vegetation could be detected on the fringing reef to the north of Yanbu while towards the south the reef flat is dotted with pools and reef flat moat. An algal ridge rimming the seaward boundary of the reef is also seen. Just near the Yanbu city and Yanbu Al Bahr Dive Center, parts of the fringing reef, adjacent to the coastal lagoon appear muddy. Algae category is also detected on the reef flat. Jetties have also been constructed on the coast. The off-shore pinnacle reefs however appear submerged. Coral reefs around Yanbu are known to support higher coral diversity and benthic assemblages reported previously from any other parts of the Red Sea (Pilcher and DeVantier 2003). Coral reefs near Yanbu and to its north experienced intense bleaching and high coral mortality during 1997-98 (Pilcher and DeVantier 2003). However, due to urban and industrial influence, coral reefs near Yanbu are experiencing degradation due to oil and sewage pollution and land reclamation (Spalding *et al.* 2001; Pilcher and DeVantier 2003; Kotb *et al.* 2008).

Similar reef structure continues down south, between Rayyis and Masturah (Map. 6.1.5.14). The reef flat, fringing the coast, widens to the south of Rayyis. The reef flat is alternated with exposures of reef slope and sanded reef flat. The sand deposition in the vicinity of the reef is covered with green algae. Signatures of algae have been detected on the reef towards the south of Masturah. The off-shore coral pinnacles however appear partially submerged on the satellite image.

The mainland fringing reef, off-shore patch and pinnacle reefs continue on the Saudi Arabian coast upto Rabigh and beyond south (Map. 6.1.5.15). There is a major coastal lagoon towards the north of Rabigh. The mainland fringing reef has a well defined, narrow reef flat and an algal ridge on the seaward side. The reef flat widens near Rabigh and has a pool within. In the southern part of the coast, the reef flat partially appears as sandy reef flat with a line of dune vegetation. Exposure of reef slope is seen only in one place. The off-shore coral pinnacles are mostly elongated in shape, resembling submerged reefs and coral carpets (Pilcher and DeVantier 2003; Riegl and Piller 1999). Coral reefs running between Yanbu and Rabigh are unique reefs of Red Sea representing high species diversity and density.

The fringing, patch and pinnacle types of reefs continue to dot the Saudi Arabian coast from Tuwwal to Ras Hatiba (Map 6.1.5.16), a prime site for environmental and education programmes (Pilcher and DeVantier 2003). There is a large shallow coastal lagoon, covering around 450 sq km near Ras Hatiba marked by sandy and coralline spits, small mangrove stands and extensive off-shore reefs (Pilcher and DeVantier 2003). Two areas have been selectively zoomed to view the intra-reef details. The fringing reef near Tuwwal and surroundings (Map 6.1.5.16; subset 1) show reef flat rimmed by an algal ridge on the seaward side and dune vegetation on the landward margin. The reef flat can be distinguished into outer and inner reef flats. Algae dominance is observed on the reef flat. The fringing reef near Ras Hatiba (Map 6.1.5.16; subset 2) shows classic intra-reef zonation with reef edge, followed by algal ridge and reef flat. A channel separates the reef from the coastal lagoon. Dune vegetation predominate the sandy part of the coast fringing reef. Reef flat with deep centralized pools are observed within the off-shore patch reefs while the reef flat remains submerged in case of coral pinnacles.

iii) Central-southern section (from south of Jeddah to Yemen border including Farasan Bank and Islands)

South of Jeddah, the coral reefs are less well developed along the mainland coast. The continental shelf widens here and further south becomes very wide, extensive and provide shallow depth with turbid inshore waters. Differences in the topography, sediments and turbidity restrict the coral reef growth towards the Yemen border (Spalding *et al.* 2001; Pilcher and DeVantier 2003). Further south however, complex reef structures have been developed on the Farasan Bank and the islands.

South of Jeddah, the mainland fringing reef becomes considerably narrow (Map 6.1.5.17). Near Jeddah, clusters of off-shore coral pinnacles are also seen in the AWiFS image dated 2nd August, 2005 (Map 6.1.5.16; subset 1). Reef flat moat is found on the reef flat while algae and dune vegetation appear as major ecological categories. Near Mastabah (Map 6.1.5.16; subset 2), the nature of the reef remains same with channels and pools being detected in this subset. Jeddah reefs have been reported to have 20% coral cover at a depth of 5m from a survey conducted in 2002 while reefs off Jeddah had an average cover of 30% (Kotb *et al.* 2004, Kotb *et al.* 2008). Jeddah is the largest Red Sea port and reefs near Jeddah are continuously affected by the influence of the growing city (Spalding *et al.* 2001; Kotb *et al.* 2004). Jeddah port has experienced massive expansion in the last decades including large amount of reclamation and construction activities directly on the reef flat. Coastal areas along the Jeddah Corniche have been reported to be in-filled and dredged extensively (Kotb *et al.* 2008). Many of the near-shore reefs have experienced severe degradation due to the growing influence of urban and industrial development including effects of reclamation. Industrial pollution, domestic and industrial sewage dumping, construction, dredging, siltation and effluents from desalination plants: all these factors are resulting in extreme environmental stress along the Jeddah coast. Fishing and tourism including marine sports complicate the anthropogenic stresses on reefs around Jeddah.

Down south on the Saudi Arabian coast (Map 6.1.5.18), the coastal fringing reef co-occur with three off-shore fringing reefs. An off-shore platform reef and string of patch reefs appear in the extreme south while numerous coral pinnacles dot the coastline. Three areas have been selectively zoomed to view the intra-reef details as depicted in Map 6.1.5.18A. Near Al Lith on the Saudi Arabian Coast (Map 6.1.5.18A, Subset: 1), exposures of reef slope and reef flat could only be detected. Al Lith to Yemen border the Saudi Arabian coast is reported to be a productive coast with high fish landings (Pilcher and DeVantier 2003). Near Ras al Askar (Map 6.1.5.18A, Subset: 2), reef flat and at times reef slope can be seen on the image data. A cluster of coral pinnacles is located here. A major off-shore fringing reef occurs in Sirrayn Island. Reef slope, reef flat and sanded reef flat are major geomorphological categories detected while dune vegetation and a small patch of mangrove are the ecological categories detected. Near Ras Morwiya (Map 6.1.5.18A, Subset: 3), a long, off-shore, coast-parallel fringing reef occurs with many small islands along with the mainland fringing reef. Pool and coastal lagoon are seen within the reef flat of coast fringing reef. The off-shore fringing reef consists of Shafiq Island, Long Island, Fara Island and Pelican Island and show a classic geomorphological zonation. The reef flat can be separated into outer and inner reef flats while in its southern part the reef flat has considerable sand deposition. A long, narrow sandy ridge runs from the south of Long Island to the north of Pelican Island. Dune vegetation is also seen in Fara Island while Mangrove is seen in Pelican

Island. In case of the patch reefs and coral pinnacles, the reef surface appears submerged.

The fringing reef continues down south on the Saudi Arabian coast near Al Birk and Al Qahmah while platform, patch and pinnacle type of reefs are found off-shore (Map 6.1.5.19). Three areas have been selectively zoomed to view the intra-reef details (Map 6.1.5.19A). Subset: 1 from Map 6.1.5.19A shows one off-shore platform reef. The reef has a broad exposure of reef slope on the eastern side while a moat is present on to its western margin. The reef flat could be separated between outer and inner reef flats, with the latter being prominent due to its sandy nature. There is a small island too on the inner reef flat. Pools are also seen here. Off-shore islands of Katina and Hadarat (Map 6.1.5.19A, Subset: 2) are surrounded by platform reefs. Both the reefs show exposures of wide reef slope areas and the reef flat could be separated into outer and inner reef flat. Sanded reef flats border the islands with a sandy ridge extending southwards in case of the Katina Island. In case of Hadarat Island, reef crest is also noticed in the southern part. Reef flats of the coral pinnacles in vicinity are also seen. Near Al Birk and Al Qahmah and surroundings (Map 6.1.5.19A, Subset: 3), the reef flat is predominantly sandy while down south it becomes muddy. Sanded reef flat is seen within the inner reef flats. In this part of the coast, mangrove patches are also found in association with coral reefs.

The coral reefs of Farasan Bank (Map 6.1.5.20) lie off-shore to the Saudi Arabian coast, parallel to the stretch between Hamdanah and Al Birk. The reefs could only be detected with AWiFS data dated 2nd August, 2005. In this part of the Saudi Arabian coast, the continental shelf widens beyond 100 km in stretch and allows the growth of coral species suited to more turbid environment (Pilcher and DeVantier 2003). High sea water temperatures and sediment loading inhibit coral reef growth in this region. Farasan Bank hosts special type of reefs: the “tower reefs” similar to atolls in morphology other than fringing reefs and shallow coralline banks. The sequential subsets as drawn from the main AWiFS image show the tower reef structures with atoll rims and lagoons (Map 6.1.5.20; Subsets: 1 to 6). Submerged banks and tower reefs or atoll structures become more dominant in the southern part of Farasan Bank. For detail intra-reef geomorphology, a much finer resolution data is required for this case. Down south of Al Birk and north of Jizan, the narrow fringing reef continues on the Saudi Arabian coast (Map 6.1.5.21). The major categories of reef edge, reef slope and reef flat could only be seen with mangrove vegetation on AWiFS data dated 2nd August, 2005.

Farasan Islands (Map 6.1.5.22) represent one of the important off-shore reefs and Protected Areas (PA) of Saudi Arabia. The Farasan Islands represent an archipelago composed of fringing, submerged patch reefs and coral pinnacles. Fringing reef borders the mainland coast along with five small fringing reefs which lie in between the mainland coast and the Farasan Island group. Three areas (Map 6.1.5.22A) have been selectively zoomed to view the intra-reef details of Farasan Islands. Subset 1 extracted from LISS III data dated 25th February, 2006 depicts the classic submerged patch reefs of this area. Many of these reefs have remained uncharted in hydrographic charts (Pilcher and DeVantier 2003). Some of these patch reefs grow to just below the sea surface and the dominant coral species here has been reported as *Porites sp*. The reef flats are associated with reef flat moats, pools and coral knolls. In the northern patch reef sandy ridge and live coral could be seen based on the textural properties of the pixel. Subset 2 highlights northern portion of the main Farasan Island. Reef flat and reef slope area could be differentiated. The reef flat is dissected with deep pools while moats separate the reef slope from the reef flat. The reef flat is further separated into outer and inner reef flats. Sandy ridge is seen on the reef flat. Marginal areas of the reef however appear submerged. Subset 3 shows Dawharab Island which has a fringing reef. A channel separates the reef slope and the reef flat in the south eastern part while the reef flat could be separated into outer and inner reef flats. Subtidal mudflat, mangrove and jetty occur as associated classes on the mainland coast.

The frequencies of classes detected for coral reef habitats of Saudi Arabia are represented in Figure: 6.1.5.1. The geomorphological class: reef flat is the commonly detected class followed by submerged reefs. Reef edge, reef slope and pool are the common geomorphological sub-zones detected within the Saudi Arabian reefs. Coastal lagoons and lagoons have also been detected in association with barrier, fringing and atoll or tower type of reef structures. Many of the coral reefs are rimmed with algal ridges on their seaward margins. Dune vegetation records the highest frequency followed by algae and live coral (only once) among the benthic categories. Mangroves show moderate association with coral reef habitats on the Saudi Arabian coast.

Areal Extent of Coral Reefs of Saudi Arabia

The coral reef habitats of Saudi Arabia as mapped from AWiFS data cover a total area of 5832.91 sq km inclusive of coralline shelf, lagoons and coastal lagoons. Reef area corresponding to each habitat map is summarized in Table No. 6.1.5.1. Coral reef habitats of Al Wadj Bank occupy the maximum coral reef area of 1614.42 sq km while coral reef habitats near Al Humaydah occupy the minimum reef area of 1.47 sq km in the Red Sea coast of Saudi Arabia.

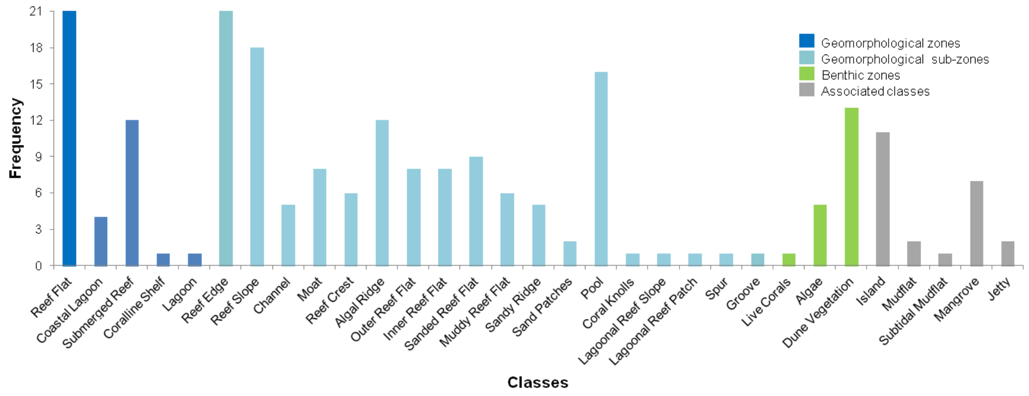


Figure 6.1.5.1 Frequency of classes detected for coral reef habitats of Saudi Arabia

Table 6.1.5.1 Areal Extent of coral reefs of Saudi Arabia

Map No.	Location	Reef Area (sq km)
6.1.5.1	Coral reef habitats near Al Humaydah	1.47
6.1.5.2.	Coral reef habitats of part of Saudi Arabian Coast in Gulf of Aqaba	4.14
6.1.5.3	Coral reef habitats of Saudi Arabian coast (to the south of Al Maqnah)	8.88
6.1.5.4	Coral reef habitats of Tiran-Senafir National Park, Ras al Qasbah and Sinafir Island	189.95
6.1.5.5	Coral reef habitats near Ash Sharmah and offshore reefs of Al Muwaylih	212.57
6.1.5.6	Coral reef habitats near Abu Salama and An Nu'man	43.88
6.1.5.7	Coral reef habitats of Saudi Arabian coast to the north of offshore reefs of Al Uwaynidhiyah	42.51
6.1.5.8	Coral reef habitats off Al Wadj and surroundings	36.92
6.1.5.9	Coral reef habitats of Al Wadj Bank	1614.42
6.1.5.10	Coral reef habitats near Umm Lajj and surroundings	399.62
6.1.5.11	Coral reef habitats of Saudi Arabian coast to the south of Umm Lajj	53.99
6.1.5.12	Coral reef habitats near Sharmal al Khaur and surroundings	53.33
6.1.5.13	Coral reef habitats of Yanbu Al Bhar Dive Center and surroundings	75.80
6.1.5.14	Coral reef habitats of Saudi Arabian coast near Rayyis and Masturah	215.91
6.1.5.15	Coastal and off-shore coral reef habitats of Saudi Arabia near Rabigh	127.25
6.1.5.16	Coral reef habitats of Tuwwal, Ras Hatiba and surroundings	219.16
6.1.5.17	Coral reef habitats of Saudi Arabian coast near Jeddah and Mastabah	168.04
6.1.5.18	Coral reef habitats near Al Lith, Al Qunfidhah, Umm al-Qamari islands PA and surroundings	537.32
6.1.5.19	Off-shore coral reef habitats of Ras Abu kalb and coastal reefs of Al Birk and surroundings	331.42
6.1.5.20	Coral reef habitats of Farasan Bank	Not Mapped
6.1.5.21	Coral reef habitats of Saudi Arabian coast to the north of Jizan	27.23
6.1.5.22	Coral reef habitats of Saudi Arabian coast near Jizan and off-shore reefs of Farasan Islands PA	1469.10
	Total Area	**5832.91**

Summary

Coral reefs of Saudi Arabia's Red Sea coast comprise of a near-continuous fringing reef with all its subtypes: platform, patch and pinnacle reefs occurring off-shore. Barrier and atoll or tower reef structures are also found in the Saudi Arabian coast. Significant intra-reef geomorphic details could be delineated for the coastal fringing and barrier reef. However, for detail mapping of the off-shore pinnacle reefs and atoll-like structures located on the Farasan Bank, high resolution data is needed. Overall the Saudi Arabian reefs show intricate reef structures with reef flats traversed by deep oceanic pools. Exposure of well-defined reef crest is limited but more than fifty percent of the reefs have algal ridges on their seaward margins. The status of coral reefs in Saudi Arabia has been reported to be in good condition with high living coral cover, other than those under the potential urban influence (Kotb *et al.* 2008). In general, the Saudi Arabian coral reefs in the north remained unaffected in 1997-98 bleaching event while the southern reefs had localized losses in terms of coral cover and diversity (Kotb *et al.* 2004). Effects of COTS outbreak have been minimal on these reefs.

Coral reef habitats of Saudi Arabia face potential threats from the growing urban and industrial development activities centered on the major cities of Jeddah, Yanbu and Jizan. Intensive fishing practices, land reclamation, dredging and growing tourism are major threats on the reefs near Jeddah. Sediment discharge, petroleum products, oil spill, industrial pollution and poorly treated sewage have been reported to damage the reefs nearby Jeddah (Kotb *et al.* 2008). It has been established that impacts of industrial and urban development along Saudi Arabia's Red Sea coast extends over more than 100 kilometers in length and have severely degraded many of the near-shore reefs and associated seagrass and mangrove habitats (Spalding *et al.* 2001). However, away from these urban centers, the impact of coastal development remains limited and the coral reefs are in overall good condition. Farasan Islands, Umm al-Qamari Islands have been declared as Protected Areas since 1989 and 1978 respectively (Spalding *et al.* 2001). Coral reefs of Saudi Arabia as mapped from AWiFS data cover a total area of 5832.91 sq km and appear in good condition barring the localized impacts near Jeddah, Yanbu and Jizan.

Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.1 represents Results > under **Basin 1. Red Sea**
6.1.5 represents Results > under Basin 1. Red Sea > for **Country 2. Saudi Arabia**
6.1.5.1 represents **Coral Reef Habitat Map** of **Saudi Arabia coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

1. Near Al Humaydah
2. Part of Saudi Arabian coast in Gulf of Aqaba
3. Saudi Arabian coast (to the south of Al Maqnah)
4. Tiran-Senafir National Park, Ras al Qasbah and Sinafir Island
5. Al Sharmah and offshore reefs of Al Muwaylih
6. Abu Salama and An Nu’man
7. Saudi Arabian coast to the north of offshore reefs of Al Uwaynidhiyah
8. Off Al Wadj and surroundings
9. Little Barrier Reef (Al Wadj Bank)
10. Umm Lajj and surroundings
11. Saudi Arabian coast to the south of Umm Lajj
12. Sharmal al Khaur and surroundings
13. Yanbu Al Bahr Dive Center and surroundings
14. Saudi Arabian coast near Rayyis and Masturah
15. Coastal and off-shore coral reef habitats of Saudi Arabia near Rabigh
16. Tuwwal, Ra´s Hatiba and surroundings
17. Jeddah and Mastabah
18. Al Lith, Al Qunfidhah, Umm al-Qamari Islands PA and surroundings
19. Ra´s Abu kalb and coastal reefs of Al Birk and surroundings
20. Farasan Bank
21. North of Jizan
22. Jizan and off-shore reefs of Farasan Islands PA

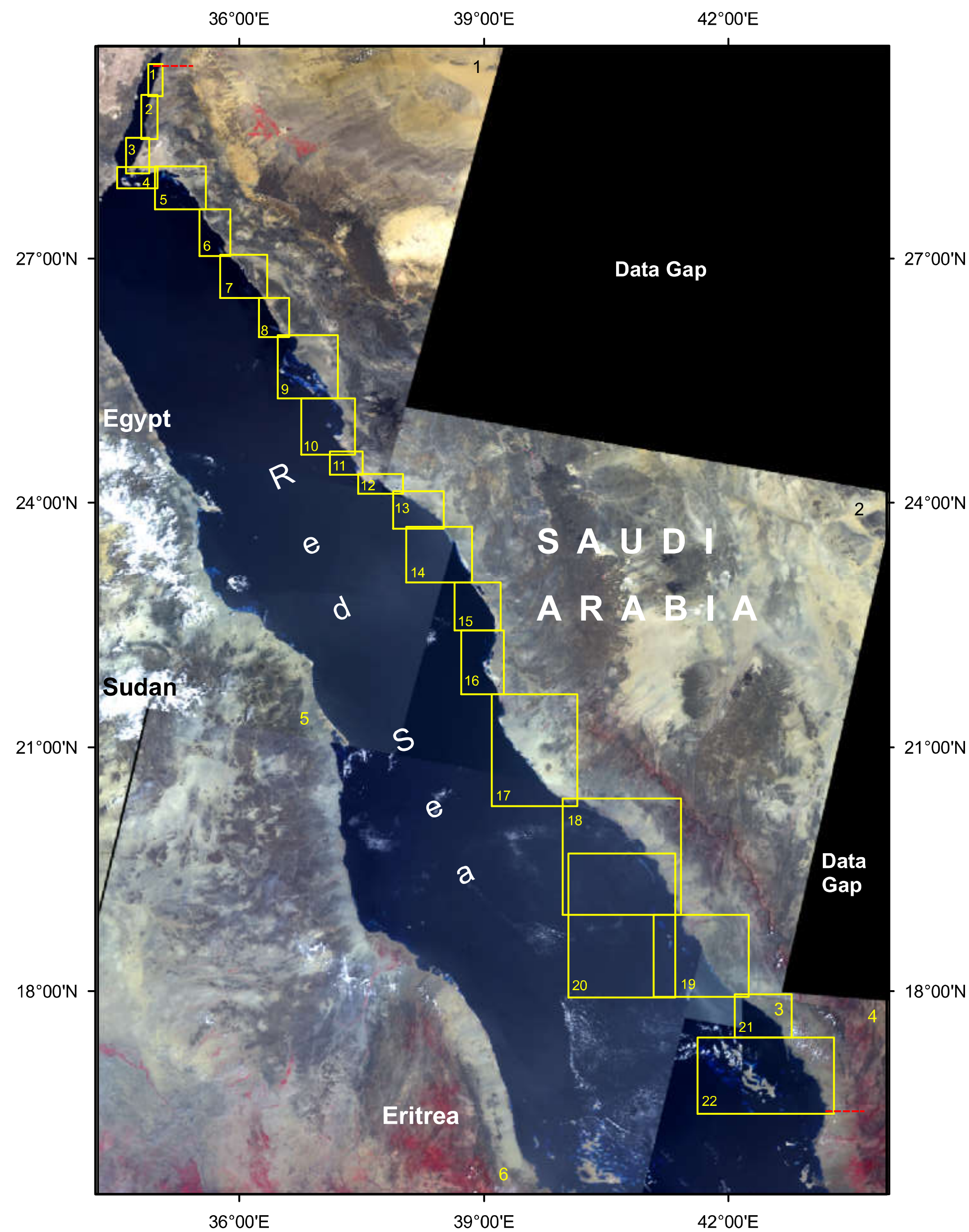
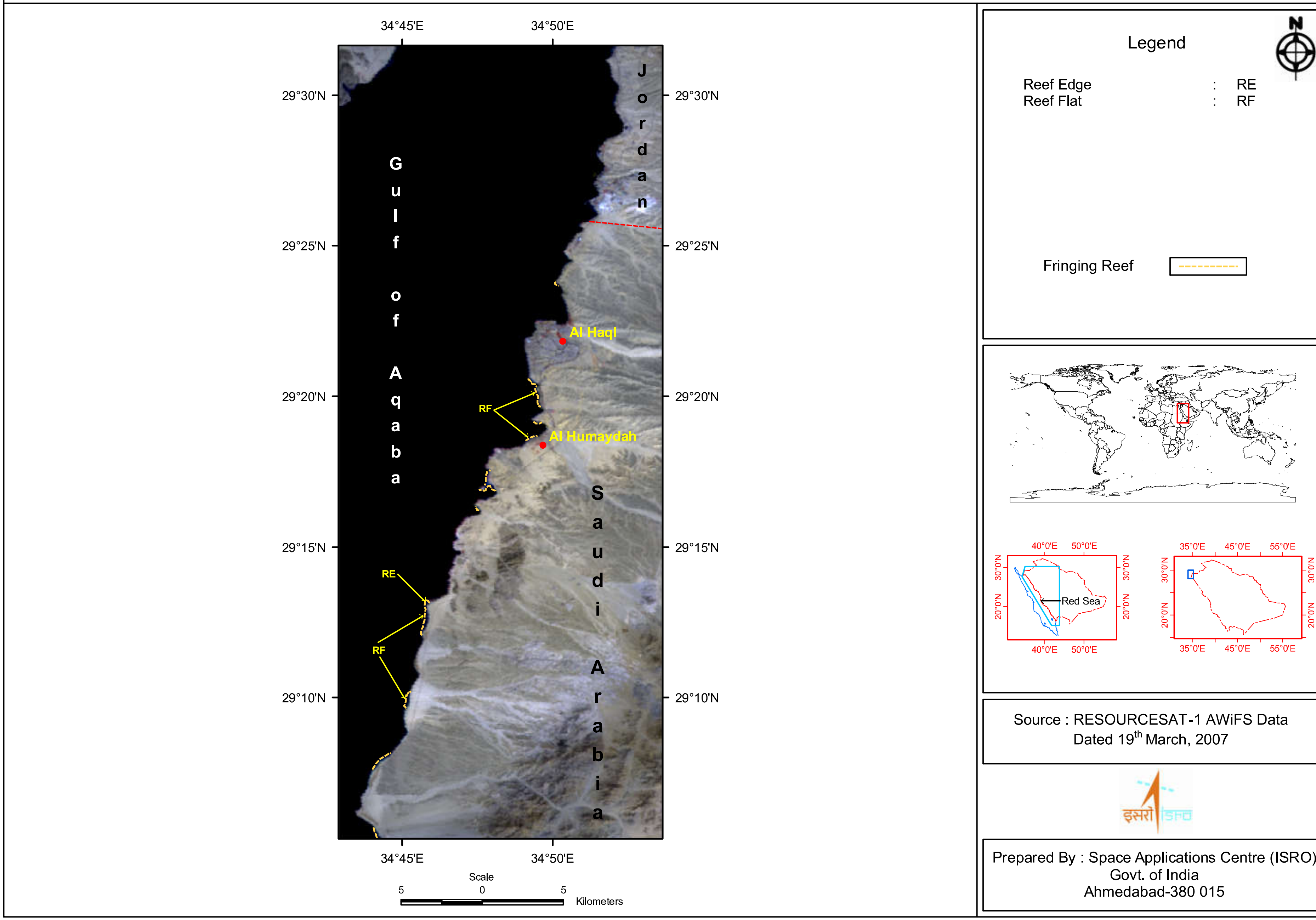


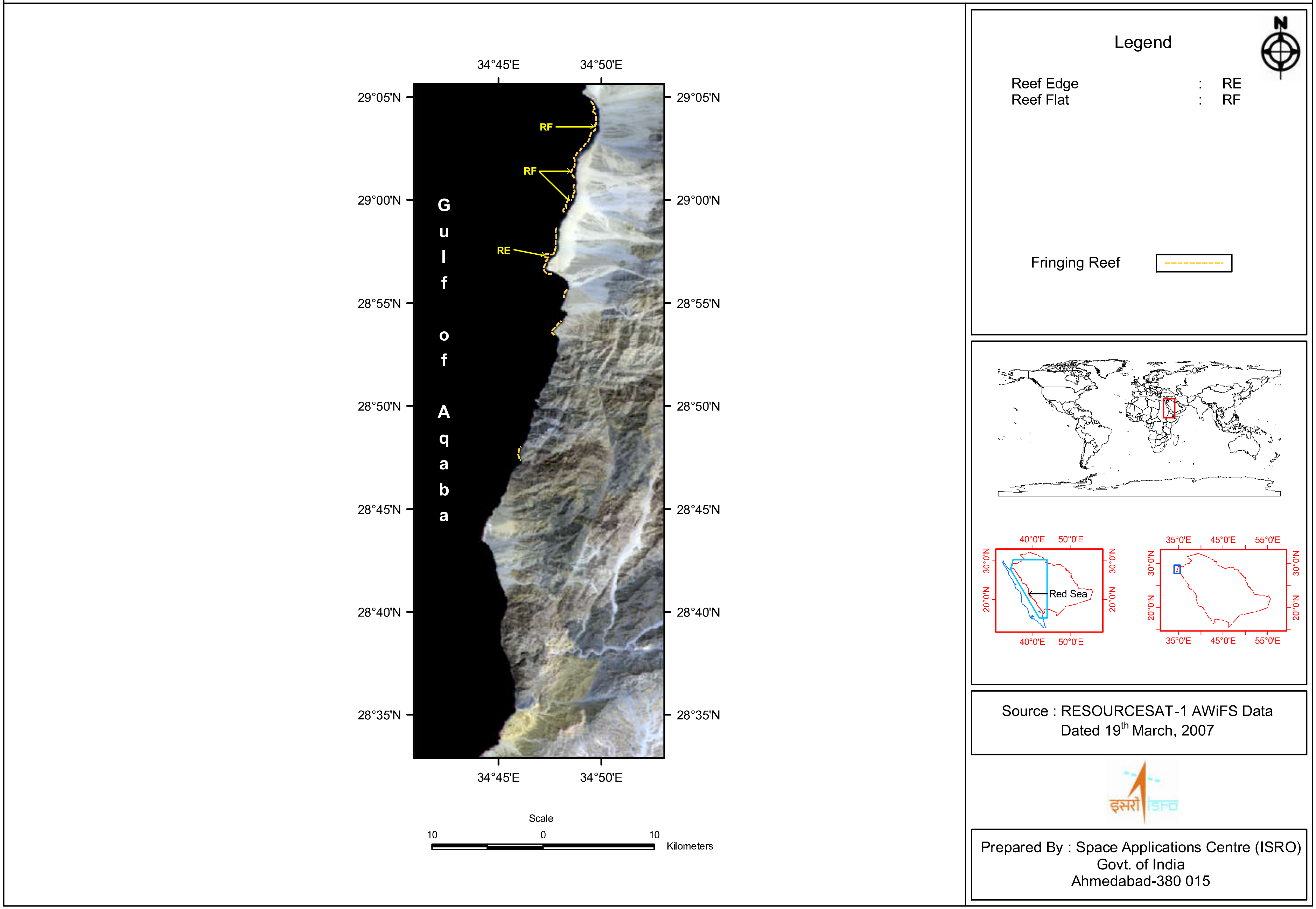
Figure 6.1.5 Index to coral reef habitat maps of Saudi Arabia

--- International boundary

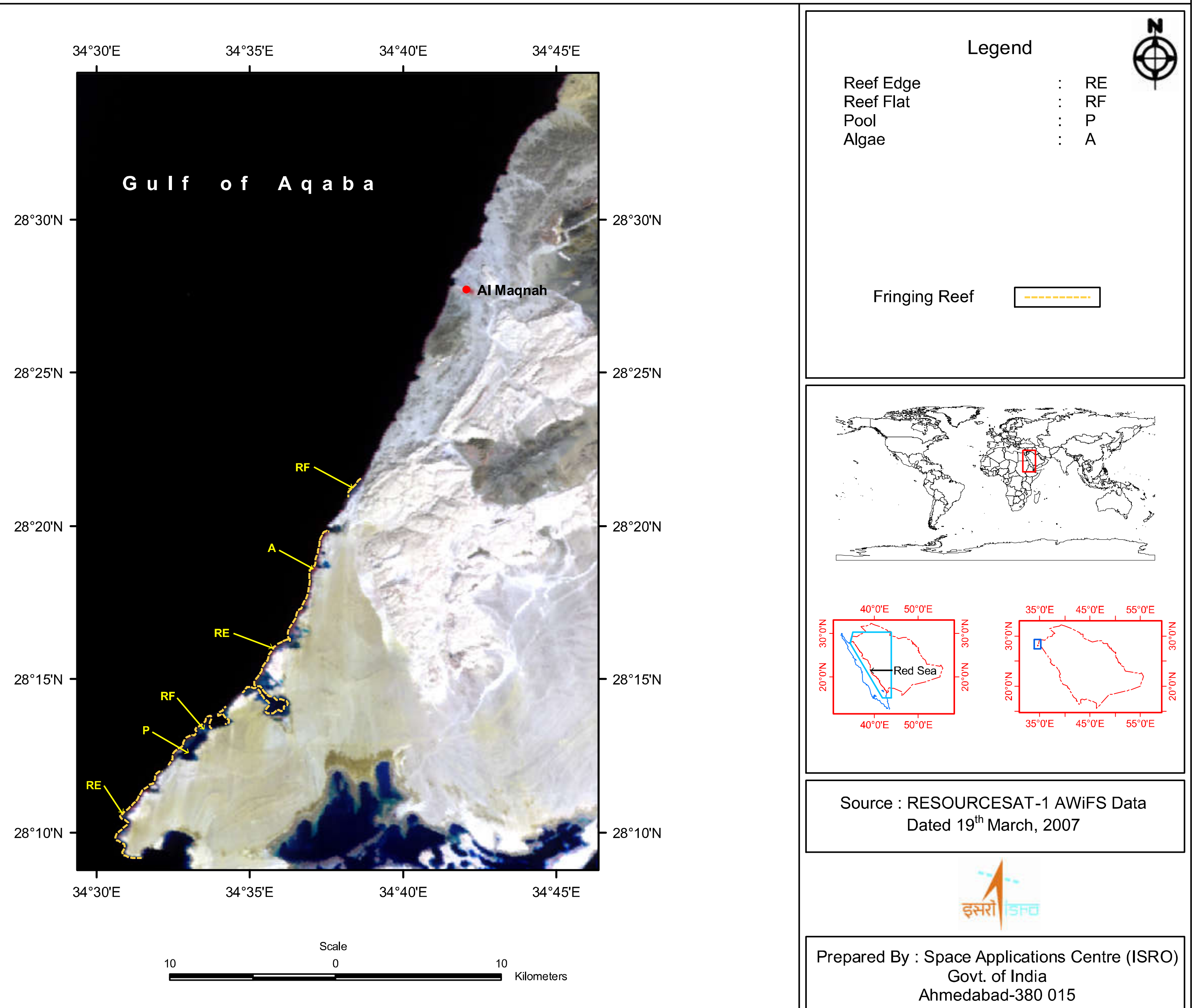
Source: Resourcesat-1 AWiFS mosaic from data dated: 19th March, 2007 (1); 2nd August, 2005 (2); 25th February, 2006 (3); 12th October, 2008 (4); 25th August, 2005 (5); 22nd September, 2008 (6)



Map 6.1.5.1 : Coral reef habitats near Al Humaydah



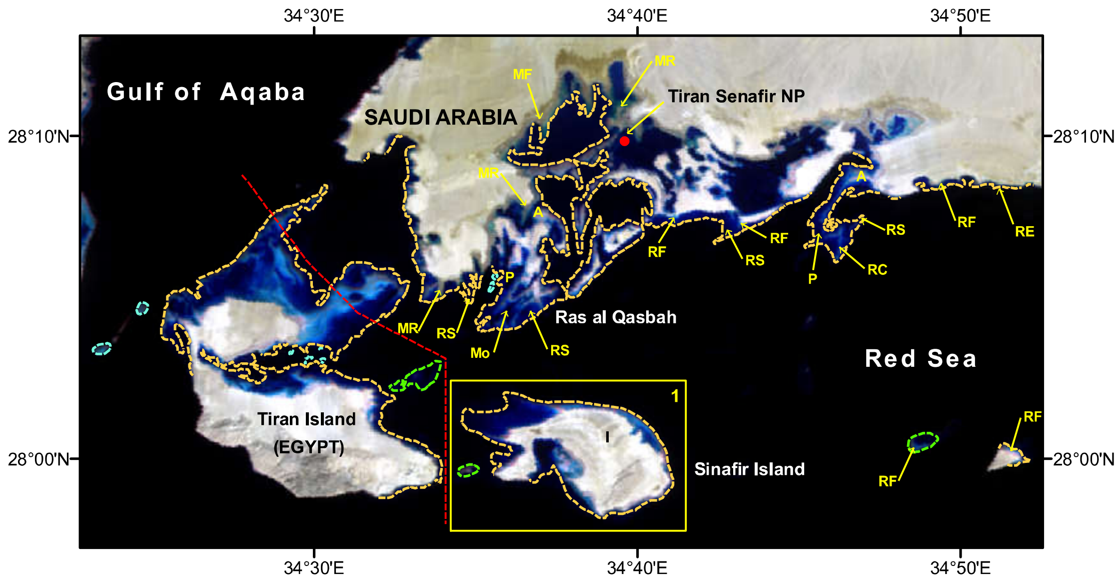
Map 6.1.5.2 : Coral reef habitats of part of Saudi Arabian coast in Gulf of Aqaba



Source : RESOURCESAT-1 AWiFS Data
Dated 19th March, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.5.3 : Coral reef habitats of Saudi Arabian coast (to the south of Al Maqnah)



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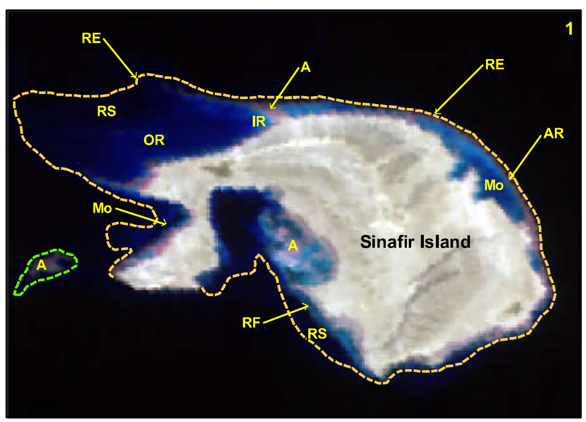


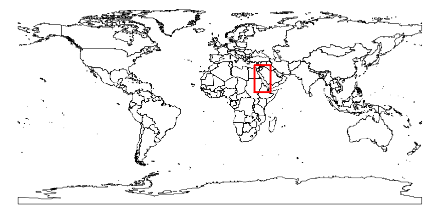
Scale
3 0 3 Kilometers

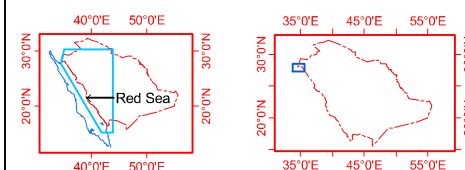
Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Crest	:	RC
Algal Ridge	:	AR
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Muddy Reef Flat	:	MR
Pool	:	P
Algae	:	A
Island	:	I
Mudflat	:	MF

Fringing Reef
Patch Reef
Coral Pinnacle

N





Source : RESOURCESAT-1 AWiFS Data
Dated 19th March, 2007

Prepared By : Space Applications Centre (ISRO)
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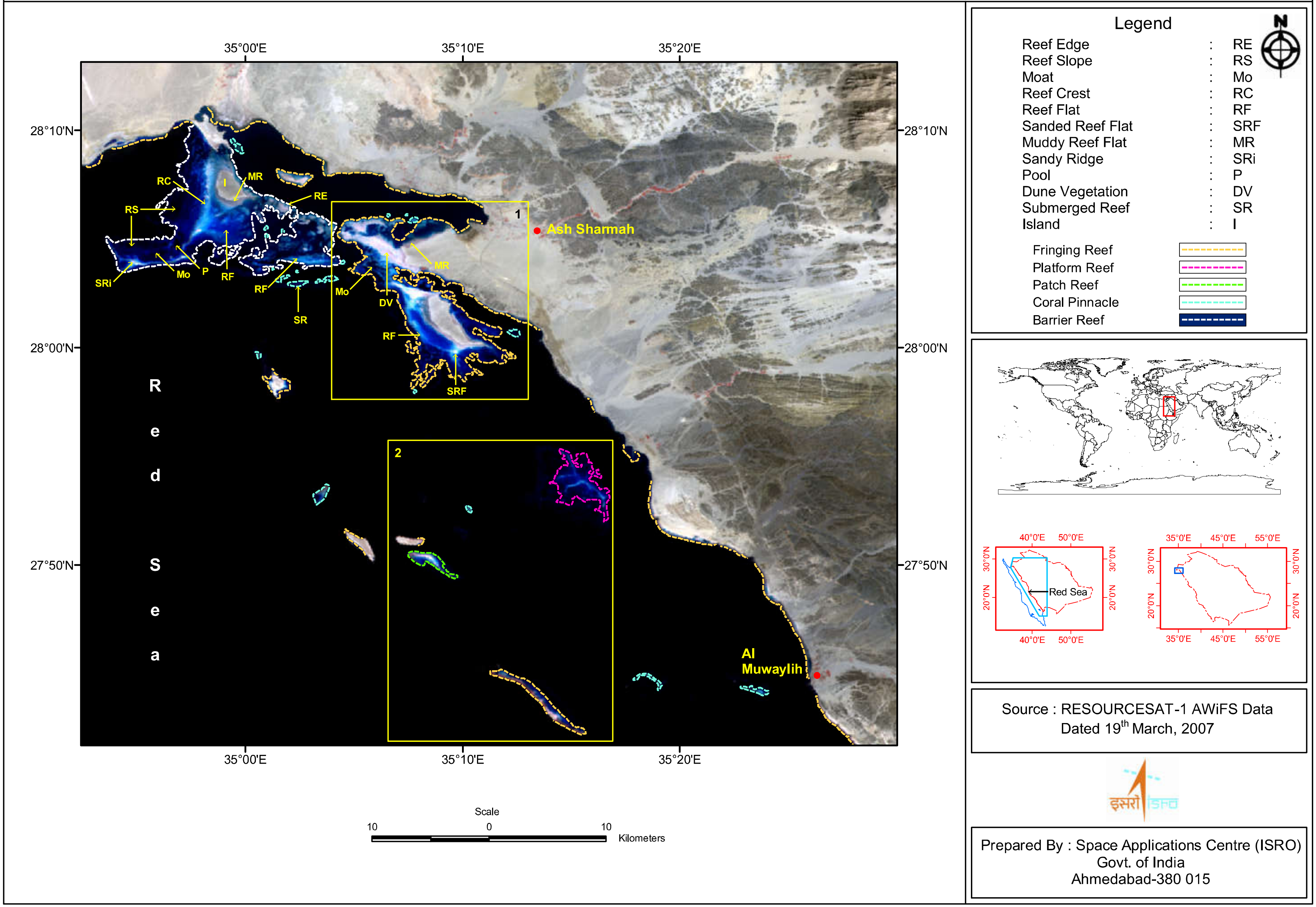
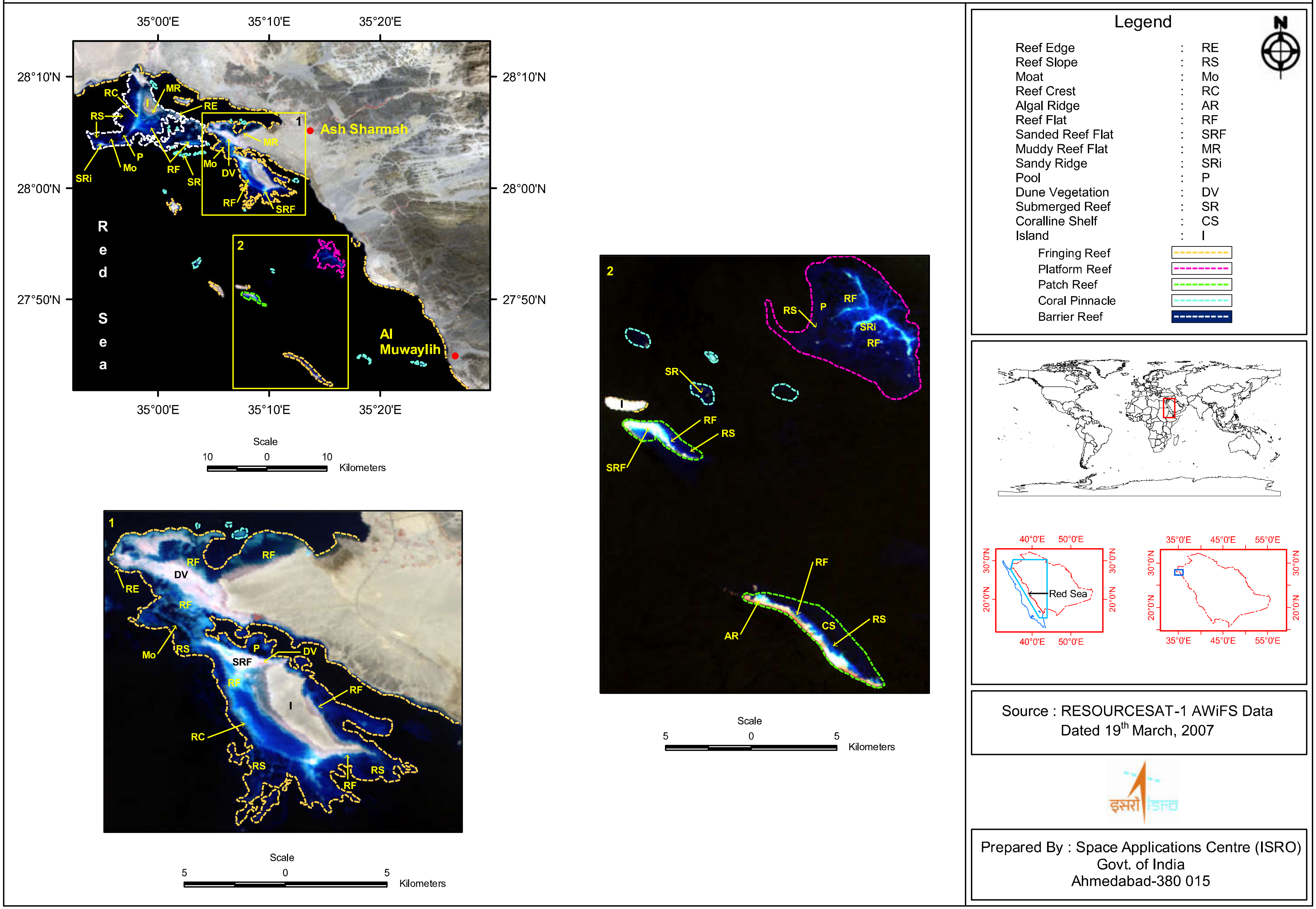
Ahmedabad-380 015

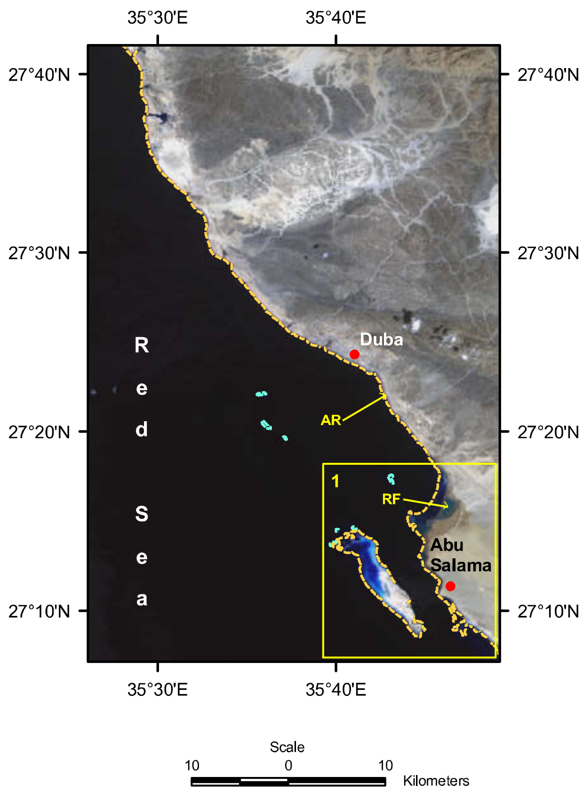
Map 6.1.5.4 : Coral reef habitats of Tiran-Senafir National Park, Ras al Qasbah and Sinafir Island

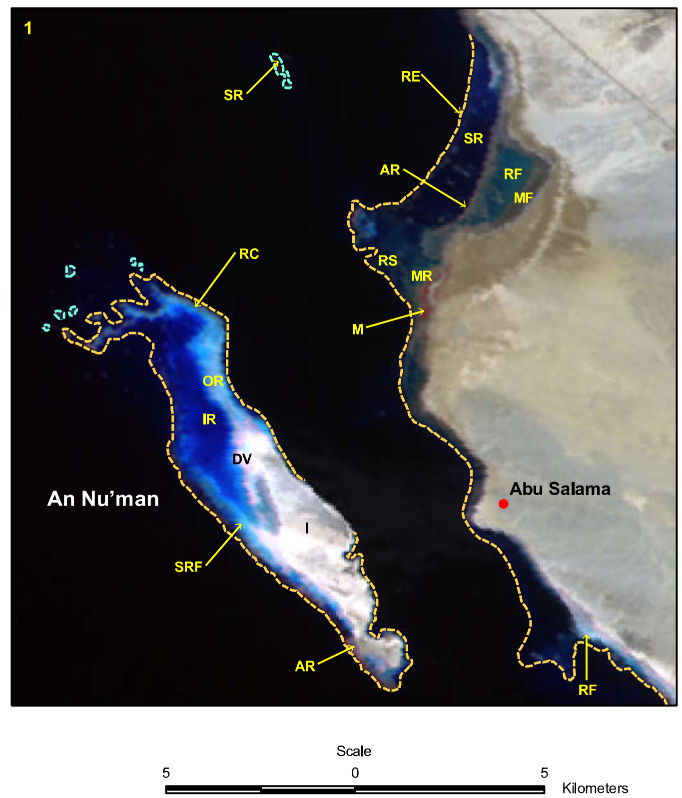


Map 6.1.5.5 : Coral reef habitats near Al Sharmah and offshore reefs of Al Muwaylih



Map 6.1.5.5A : Coral reef habitats near Al Sharmah and offshore reefs of Al Muwaylih





Legend

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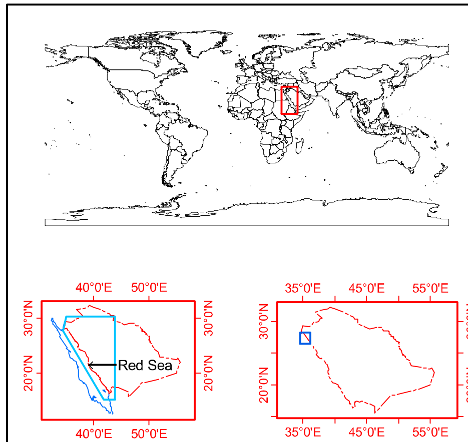
Reef Slope	:	RS
Reef Crest	:	RC
Algal Ridge	:	AR
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Muddy Reef Flat	:	MR
Dune Vegetation	:	DV
Submerged Reef	:	SR
Island	:	I
Mudflat	:	MF
Mangrove	:	M

Fringing Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 19th March, 2007

Prepared By : Space Applications Centre (ISRO)
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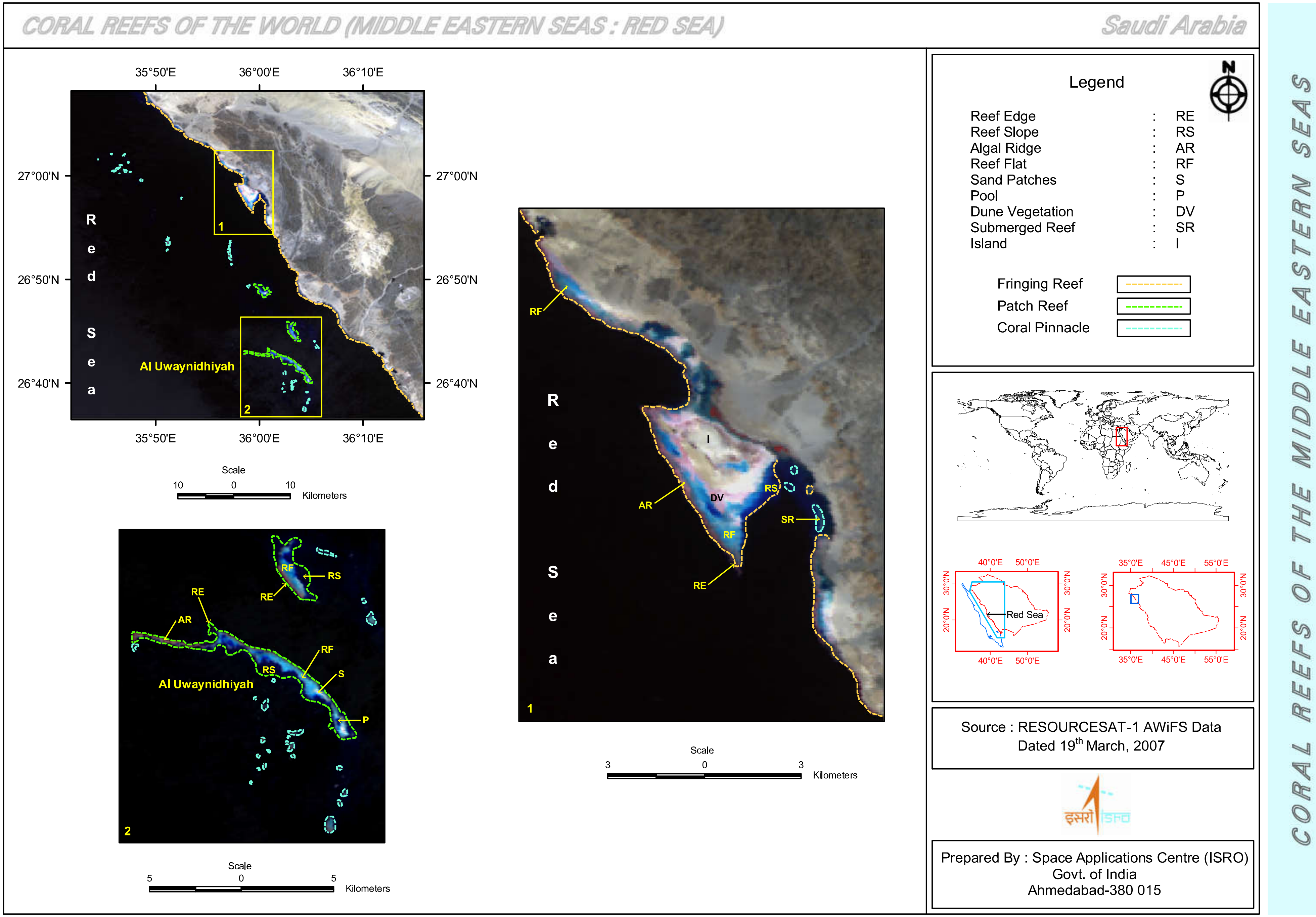
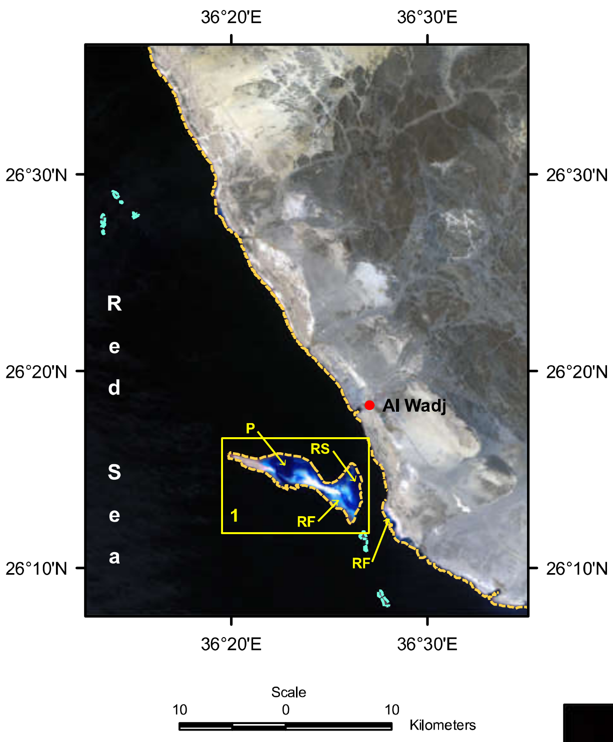
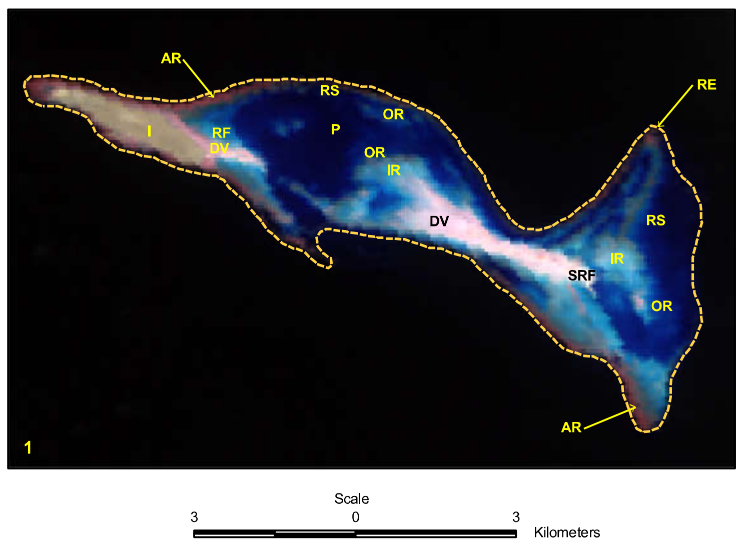
Ahmedabad-380 015

Map 6.1.5.6 : Coral reef habitats near Abu Salama and An Nu'man



Map 6.1.5.7 : Coral reef habitats of Saudi Arabian coast to the north of offshore reefs of Al Uwaynidhiyah



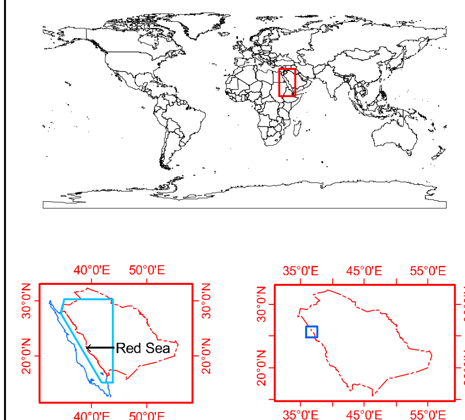


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Algal Ridge	:	AR
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Pool	:	P
Dune Vegetation	:	DV
Island	:	I

Fringing Reef

Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 19th March, 2007

Prepared By : Space Applications Centre (ISRO)
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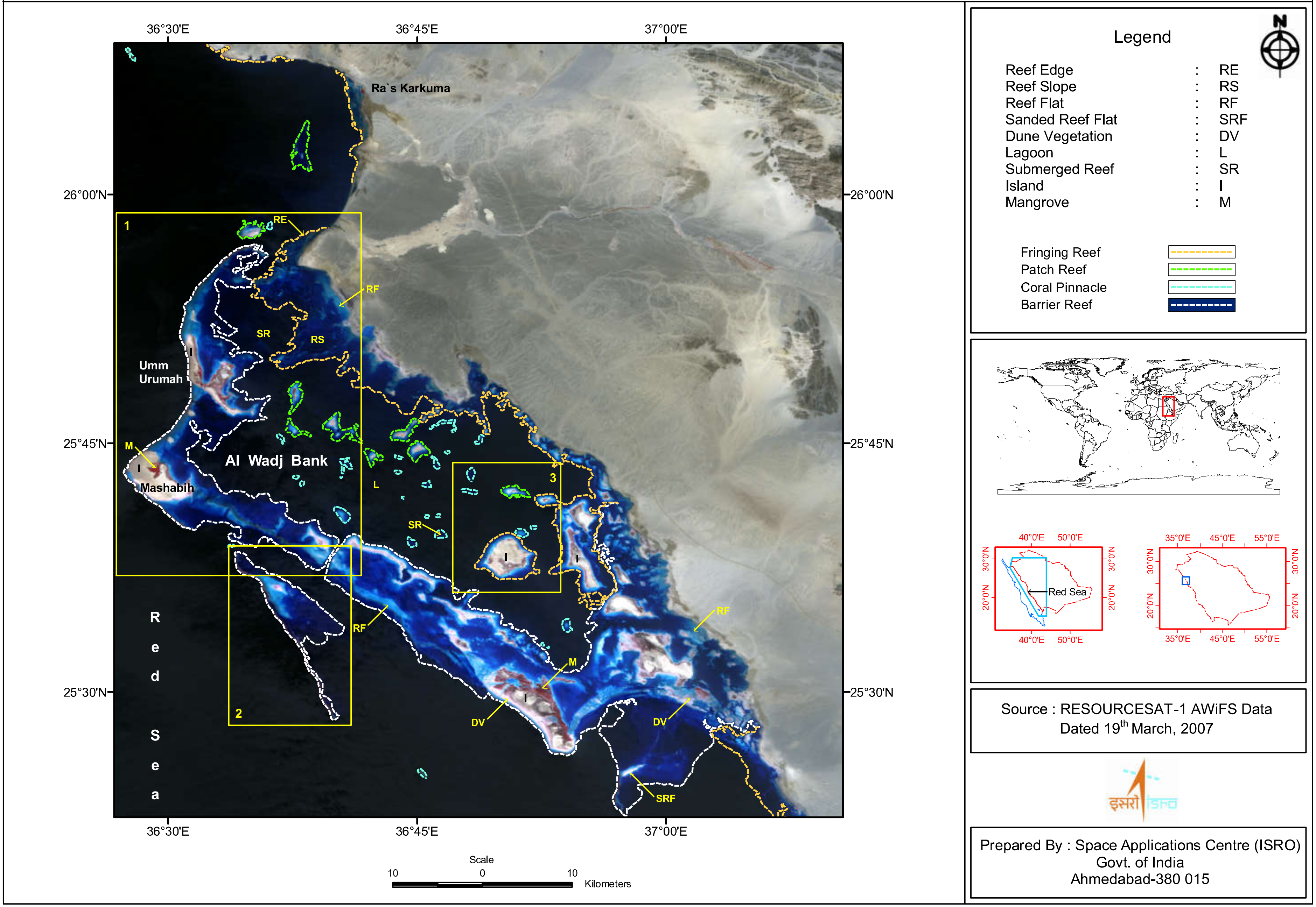
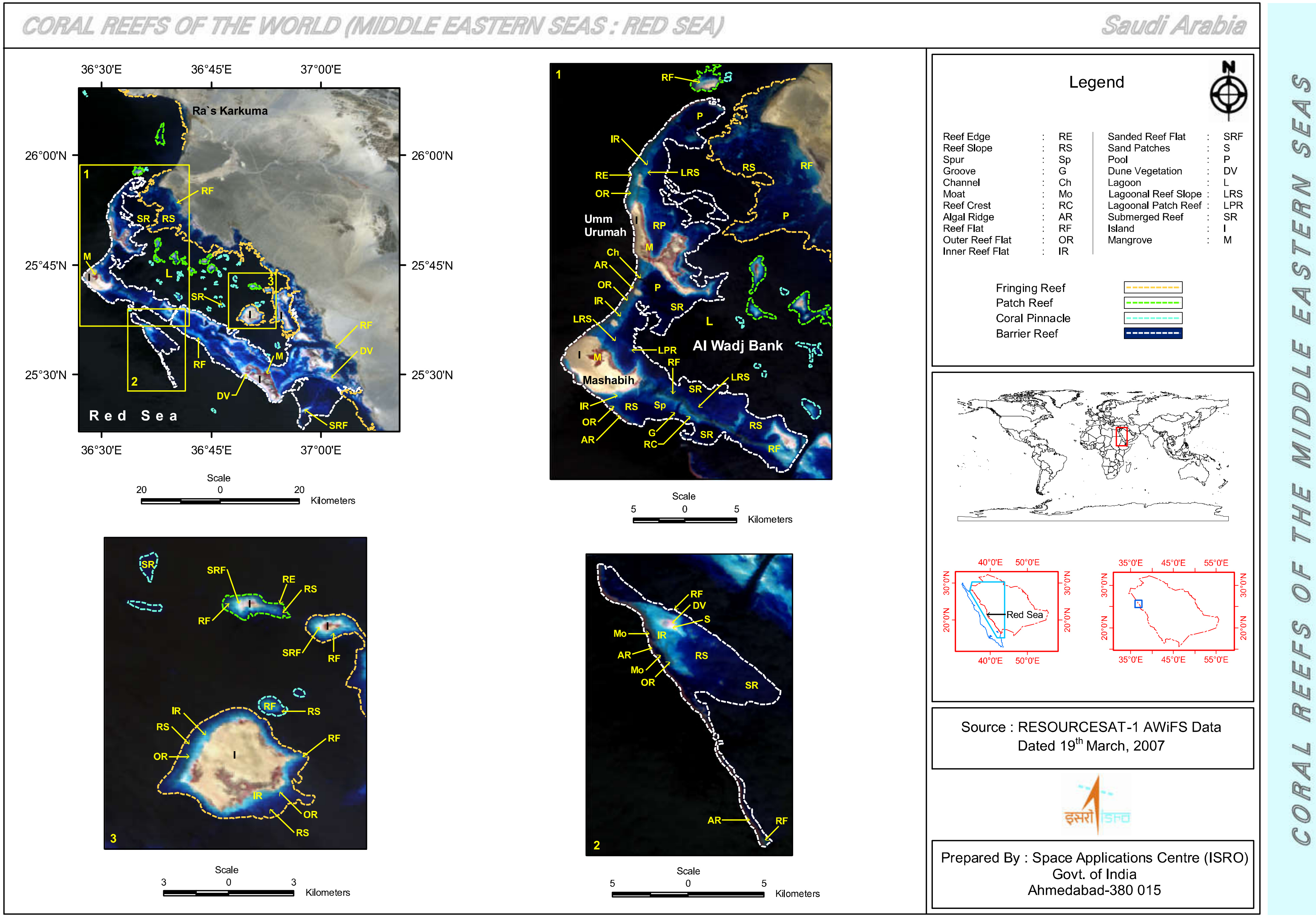
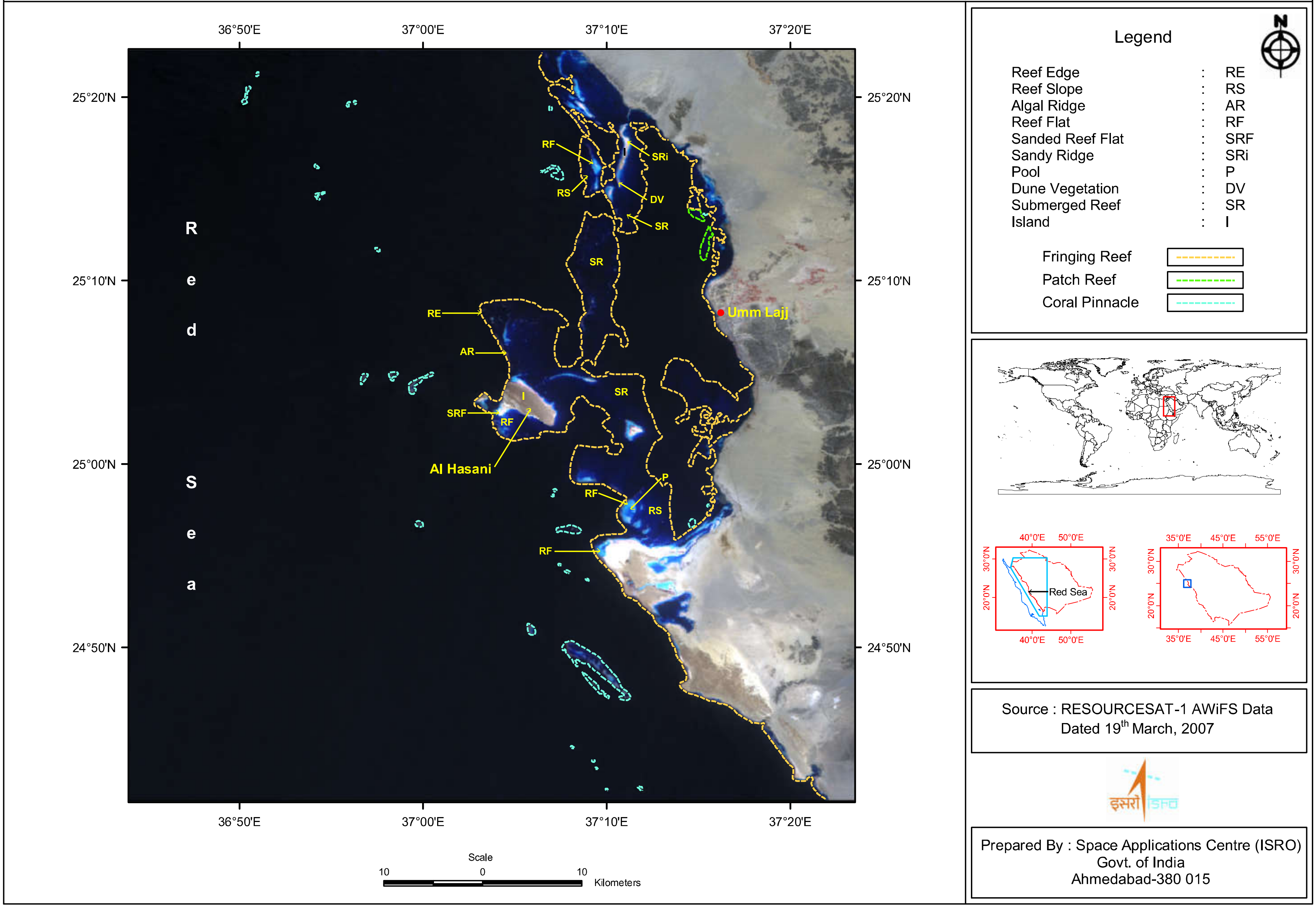
Map 6.1.5.8 : Coral reef habitats off Al Wadj and surroundings



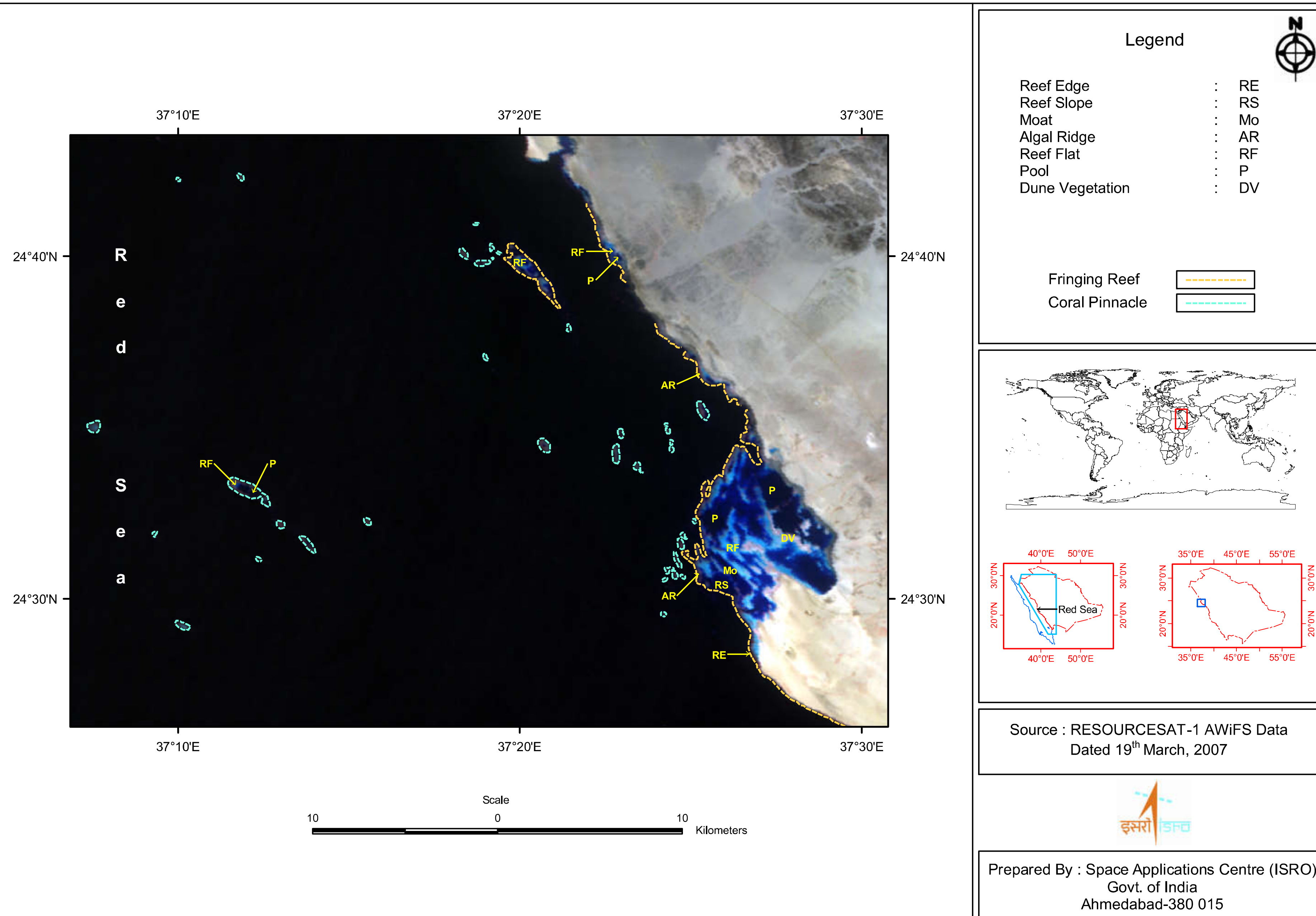
Map 6.1.5.9 : Coral reef habitats of Little Barrier Reef (Al Wadj Bank)



Map 6.1.5.9A : Selected coral reef habitats of Little Barrier Reef (Al Wadj Bank)



Map 6.1.5.10 : Coral reef habitats near Umm Lajj and surroundings



Source : RESOURCESAT-1 AWiFS Data
Dated 19th March, 2007

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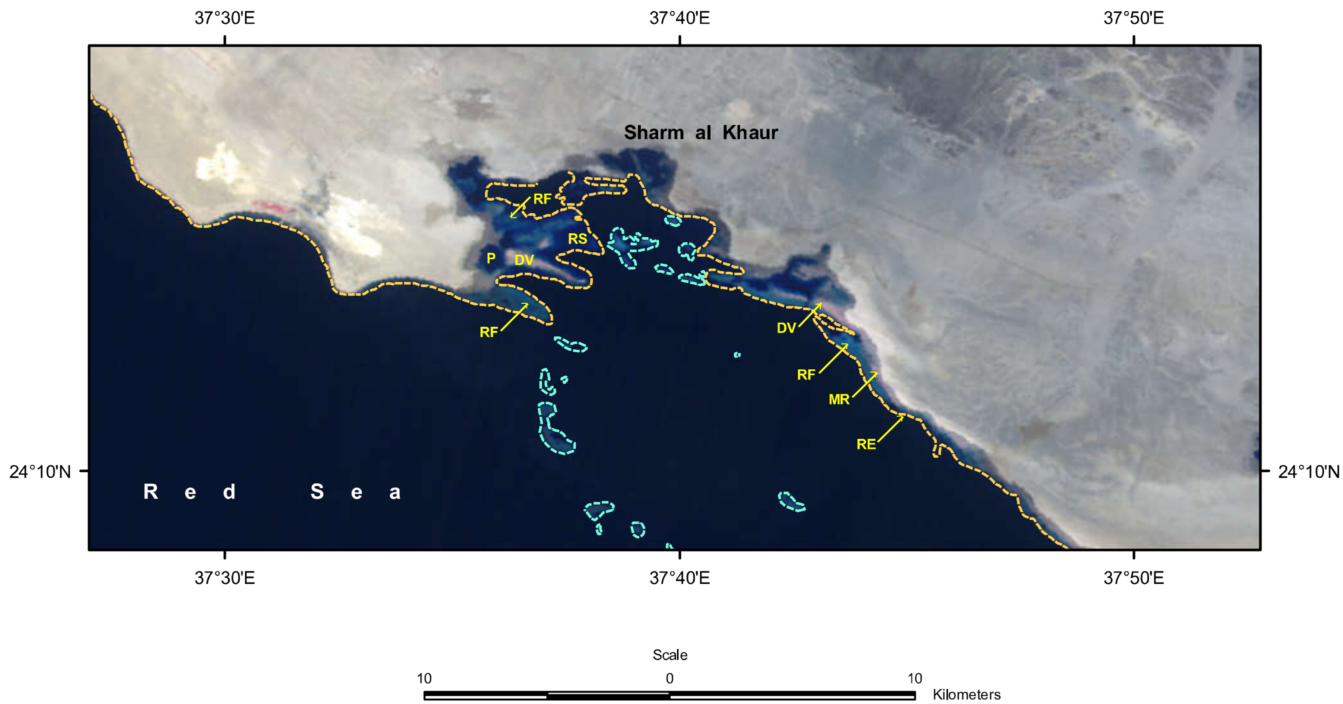
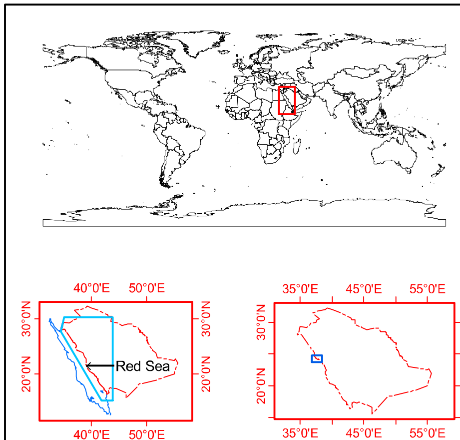
Map 6.1.5.11 : Coral reef habitats of Saudi Arabian coast to the south of Umm Lajj



Legend

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF
Muddy Reef Flat : MR
Pool : P
Dune Vegetation : DV

Fringing Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
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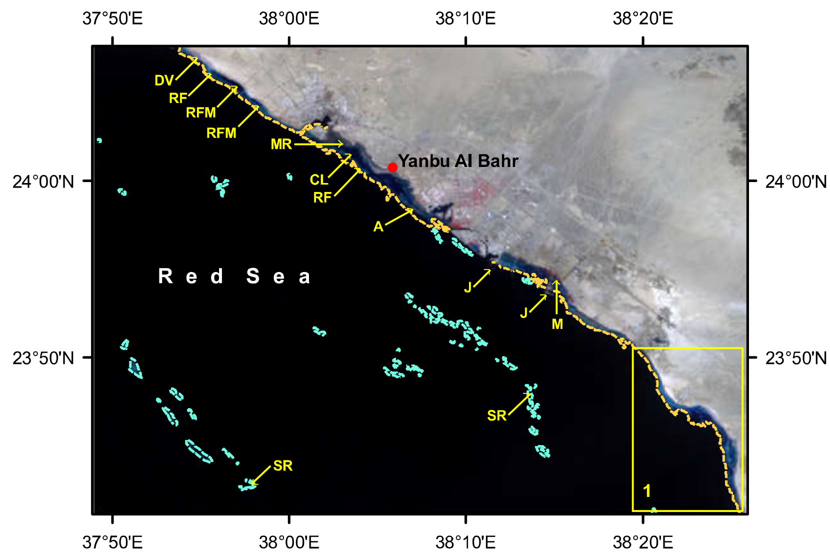
Ahmedabad-380 015

Map 6.1.5.12 : Coral reef habitats near Sharmal al Khaur and surroundings



Scale
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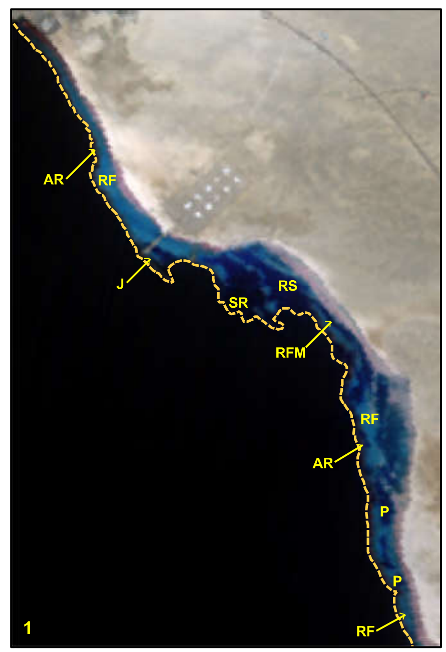
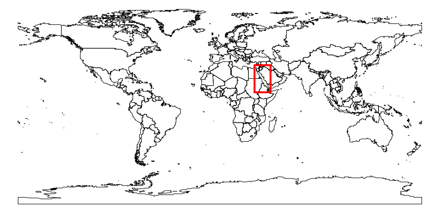


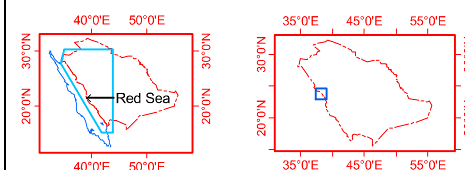
Scale
3 0 3 Kilometers

Legend

Reef Edge	:	RE
Reef Slope	:	RS
Algal Ridge	:	AR
Reef Flat	:	RF
Muddy Reef Flat	:	MR
Reef Flat Moat	:	RFM
Pool	:	P
Algae	:	A
Dune Vegetation	:	DV
Coastal Lagoon	:	CL
Submerged Reef	:	SR
Jetty	:	J

Fringing Reef
Coral Pinnacle





Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
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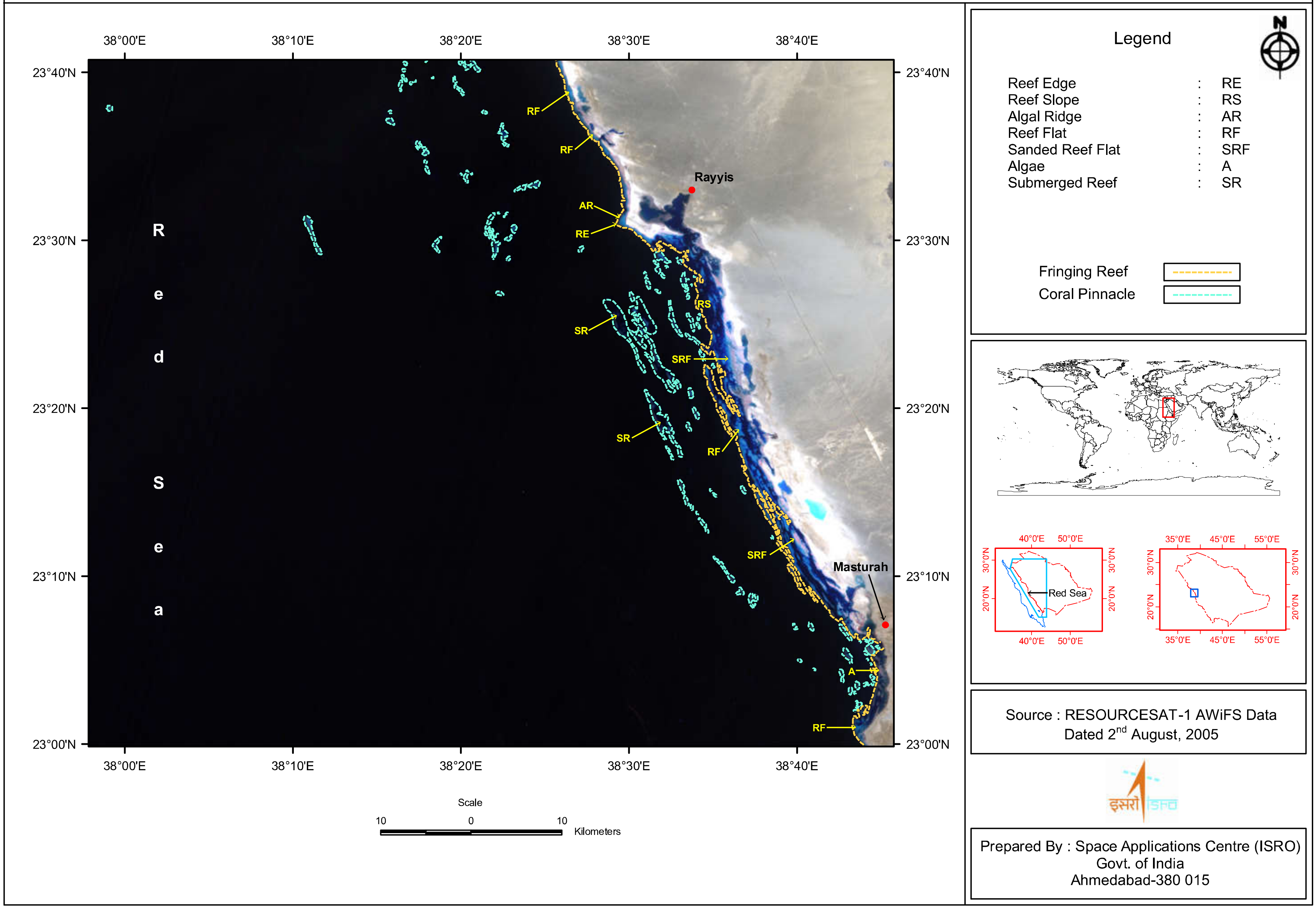
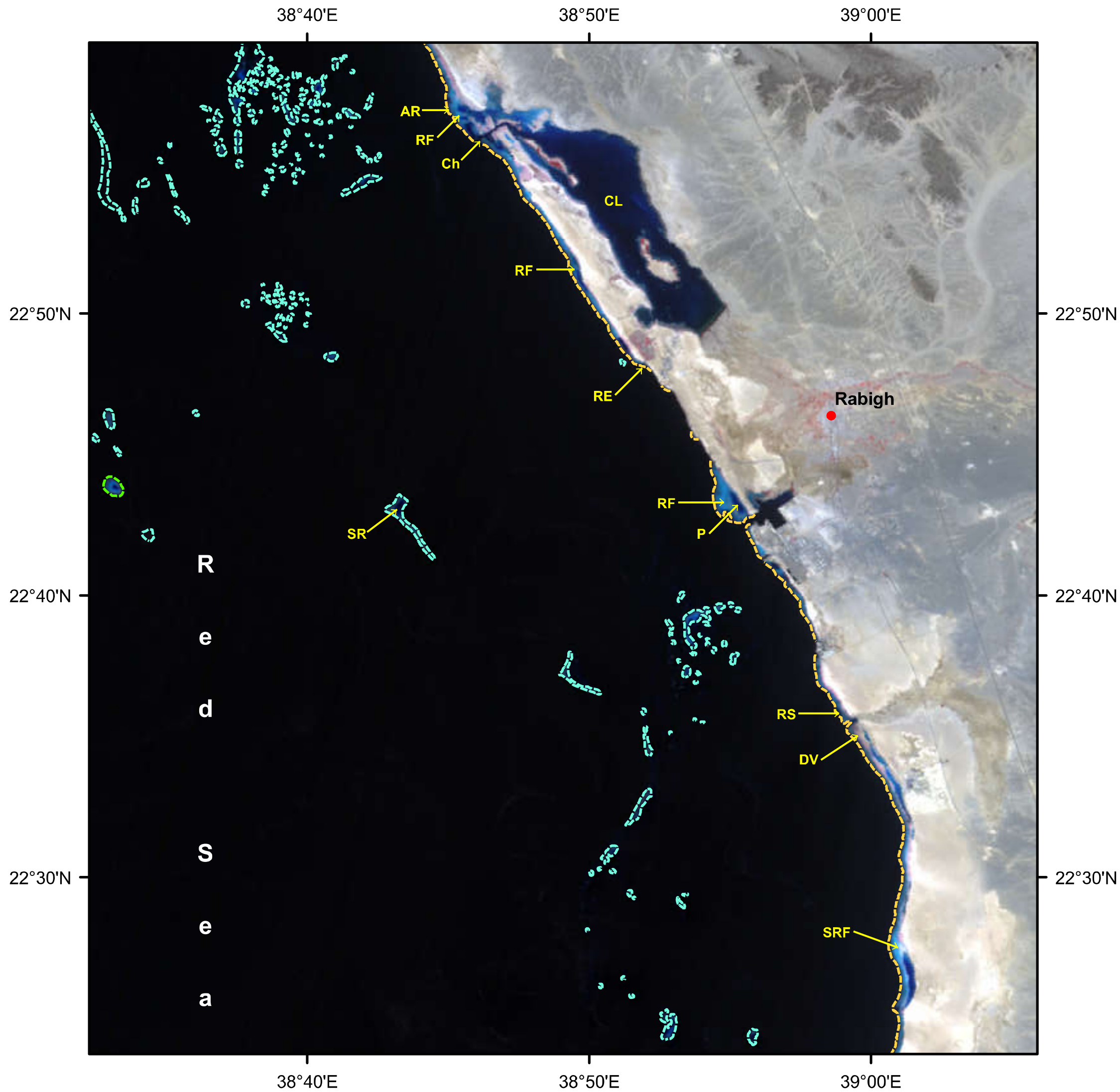
Ahmedabad-380 015

Map 6.1.5.13 : Coral reef habitats of Yanbu Al Bahr Dive Center and surroundings



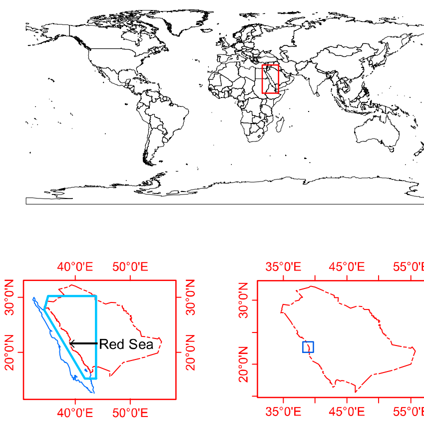
Map 6.1.5.14 : Coral reef habitats of Saudi Arabian coast near Rayyis and Masturah



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Algal Ridge	:	AR
Reef Flat	:	RF
Sanded Reef Flat	:	SRF
Pool	:	P
Dune Vegetation	:	DV
Coastal Lagoon	:	CL
Submerged Reef	:	SR

Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
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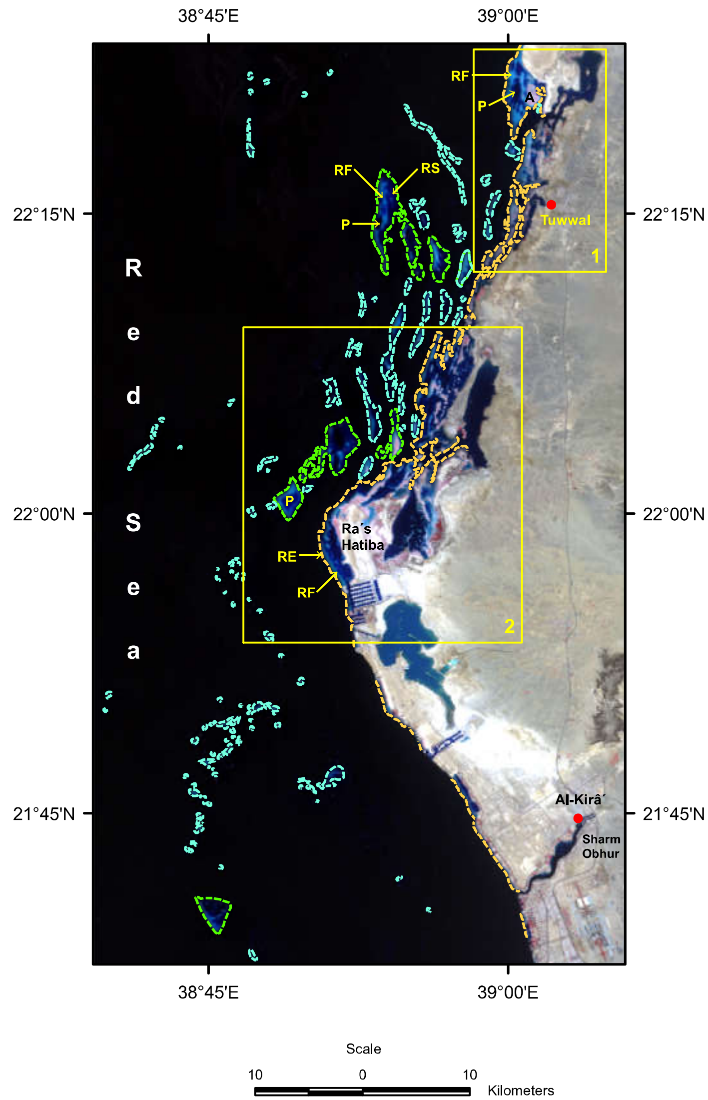
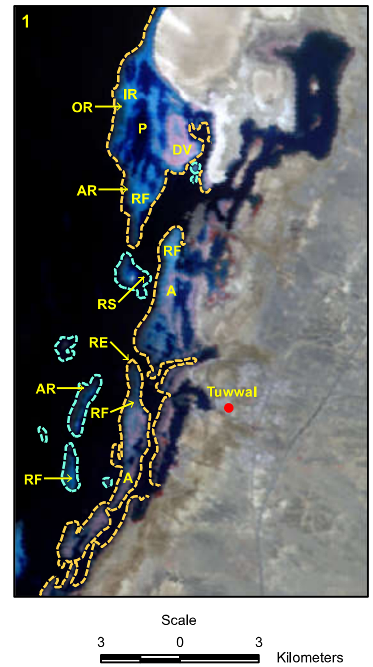
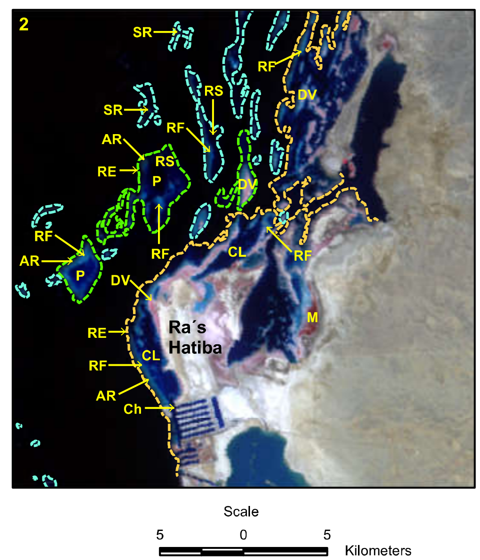
Map 6.1.5.15 : Coastal and off-shore coral reef habitats of Saudi Arabia near Rabigh



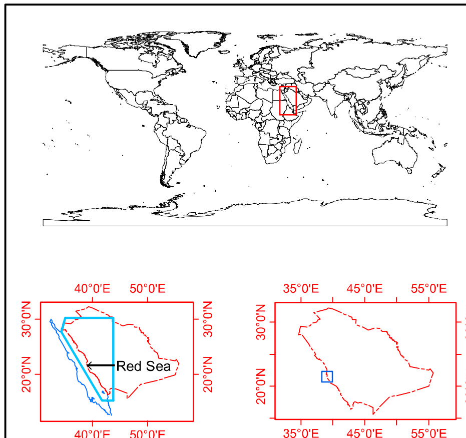




Legend

Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Algal Ridge	:	AR
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Pool	:	P
Algae	:	A
Dune Vegetation	:	DV
Coastal Lagoon	:	CL
Submerged Reef	:	SR
Island	:	I
Mangrove	:	M

Fringing Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
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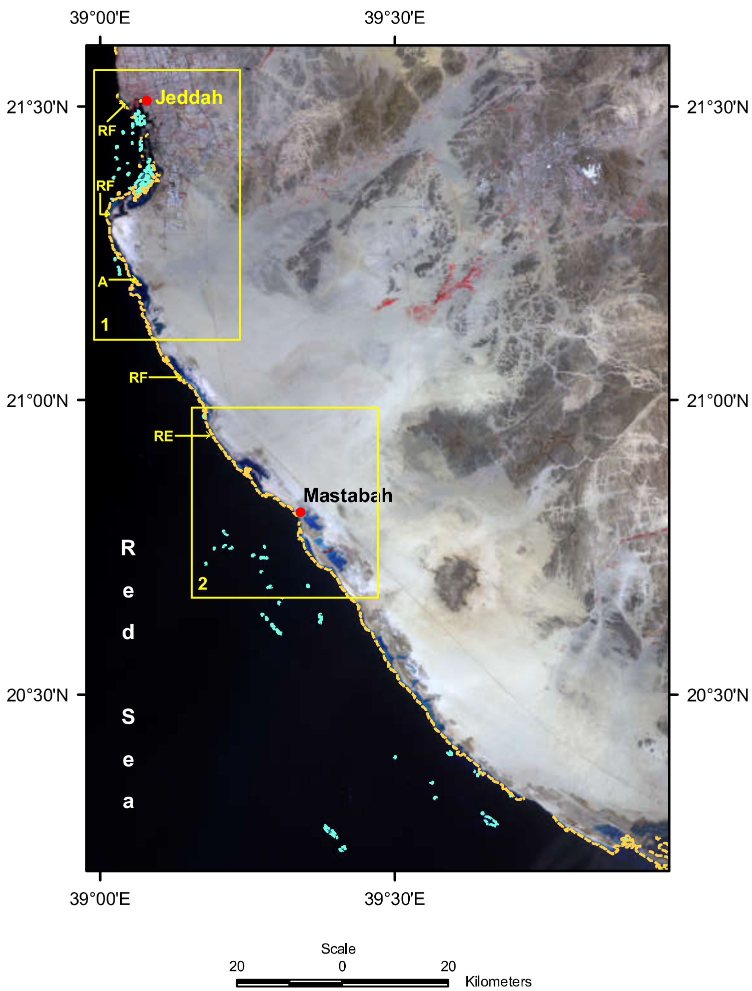
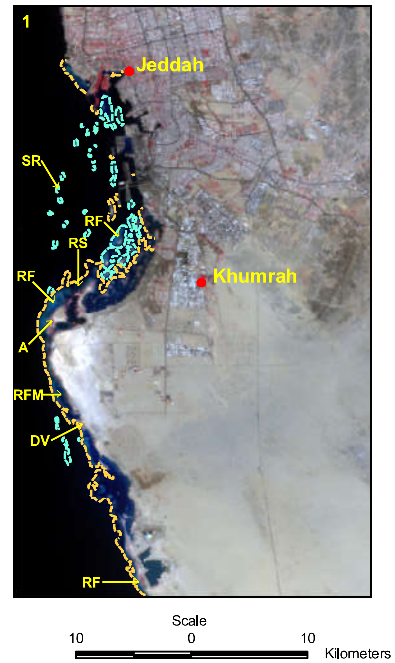
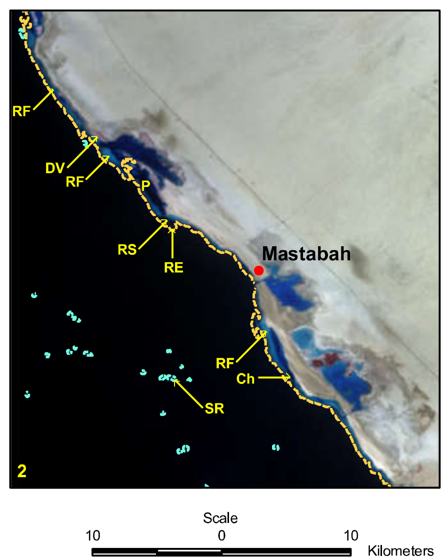
Ahmedabad-380 015

Map 6.1.5.16 : Coral reef habitats of Tuwwal, Ra´s Hatiba and surroundings



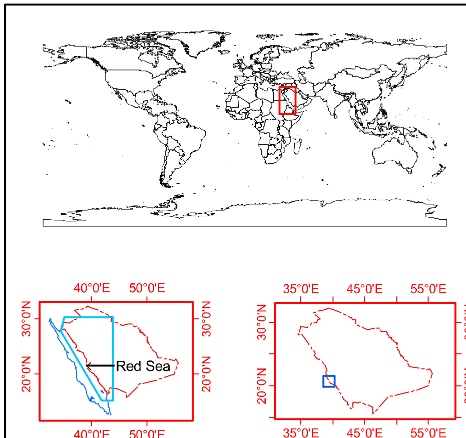




Legend

Reef Edge	:	RE
Reef Slope	:	RS
Channel	:	Ch
Reef Flat	:	RF
Reef Flat Moat	:	RFM
Pool	:	P
Algae	:	A
Dune Vegetation	:	DV
Submerged Reef	:	SR

Fringing Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
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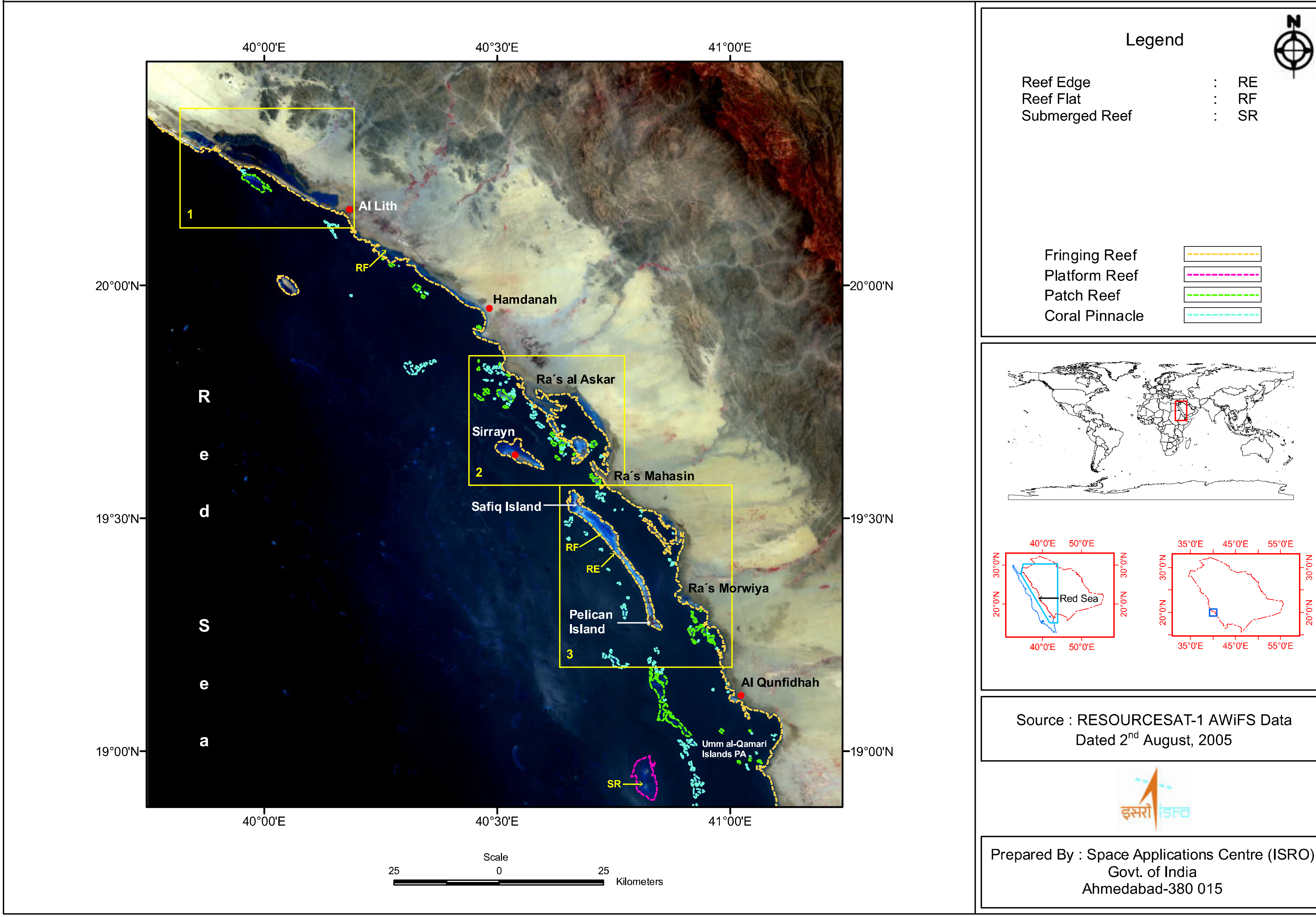
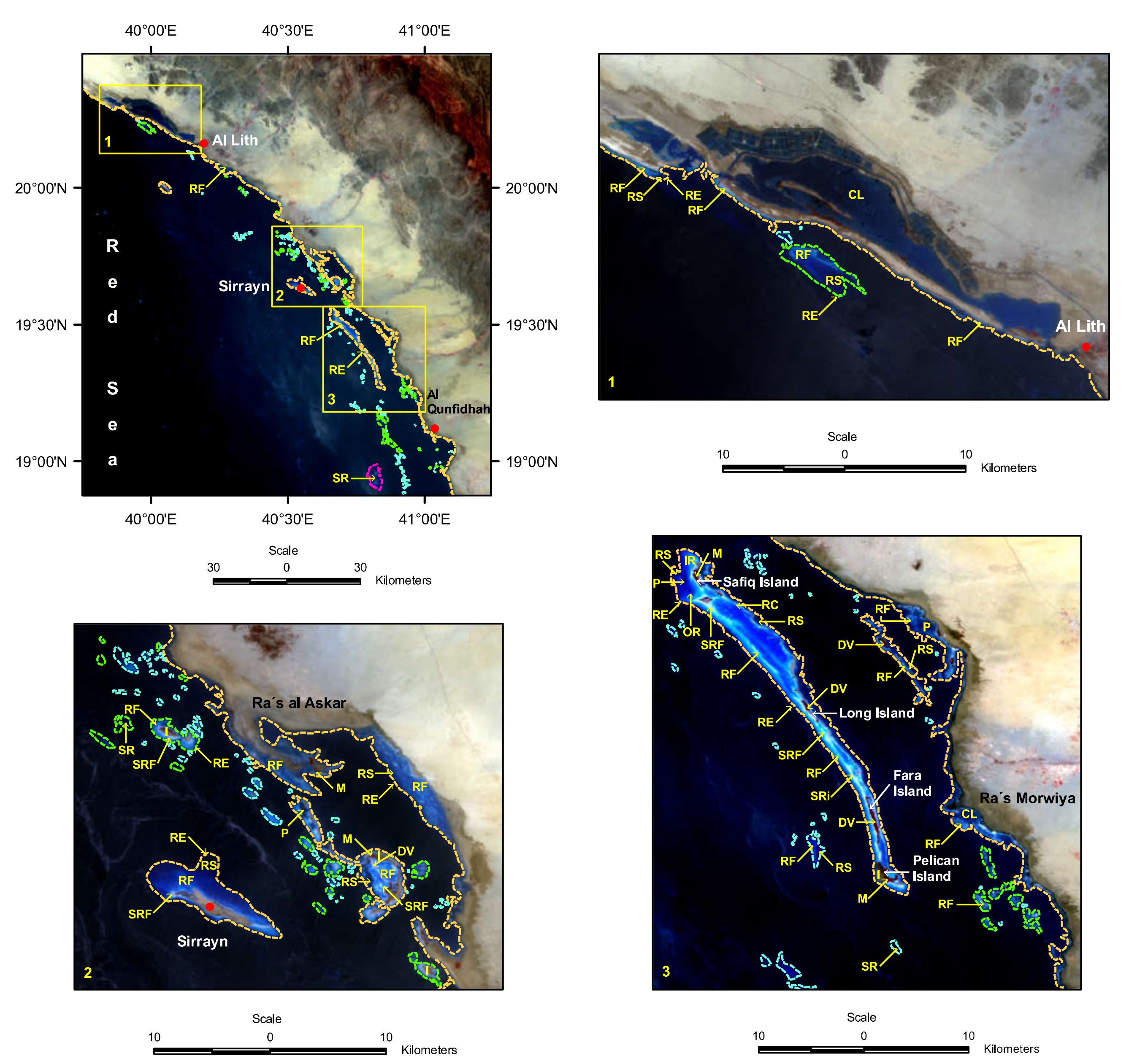
Ahmedabad-380 015

Map 6.1.5.17 : Coral reef habitats of Saudi Arabian coast near Jeddah and Mastabah



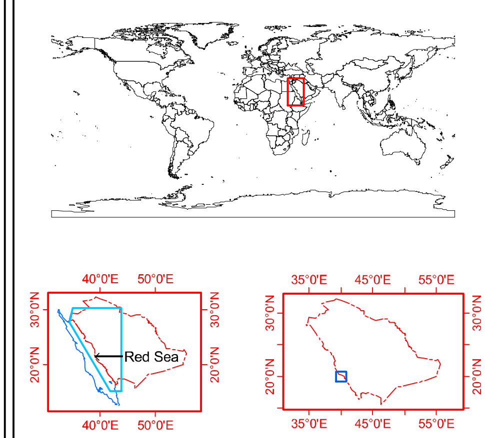
Map 6.1.5.18 : Coral reef habitats near Al Lith, Al Qunfidhah, Umm al-Qamari Islands PA and surroundings



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Crest	:	RC
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Sandy Ridge	:	SRi
Pool	:	P
Dune Vegetation	:	DV
Coastal Lagoon	:	CL
Submerged Reef	:	SR
Island	:	I
Mangrove	:	M

Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
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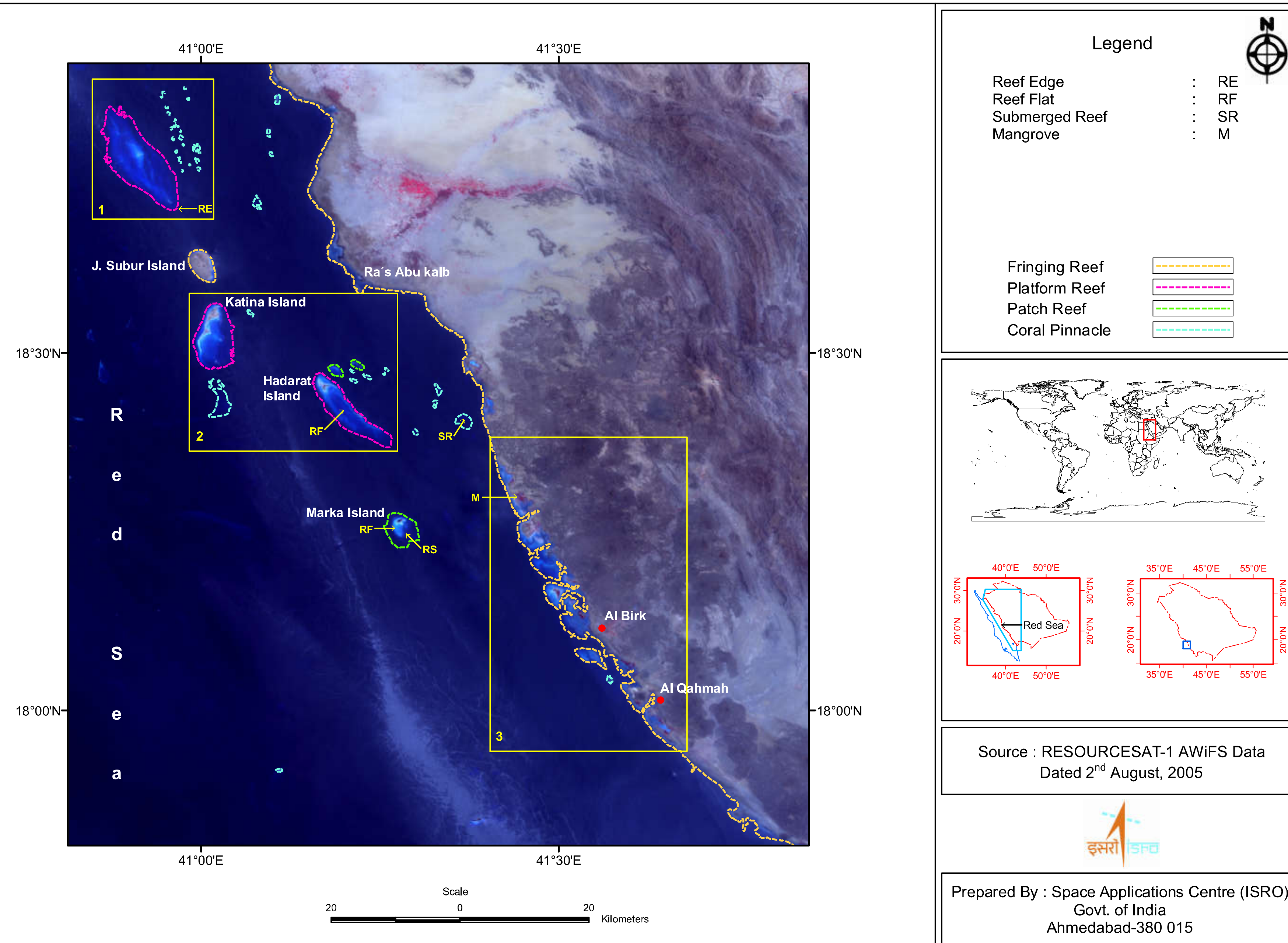
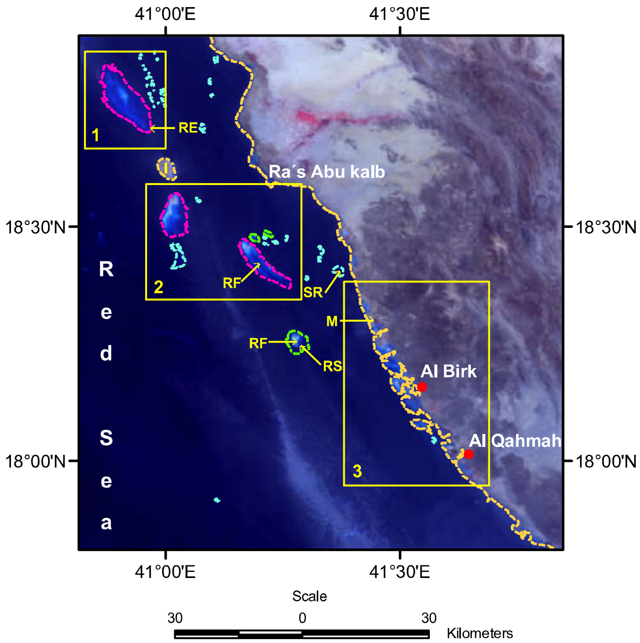
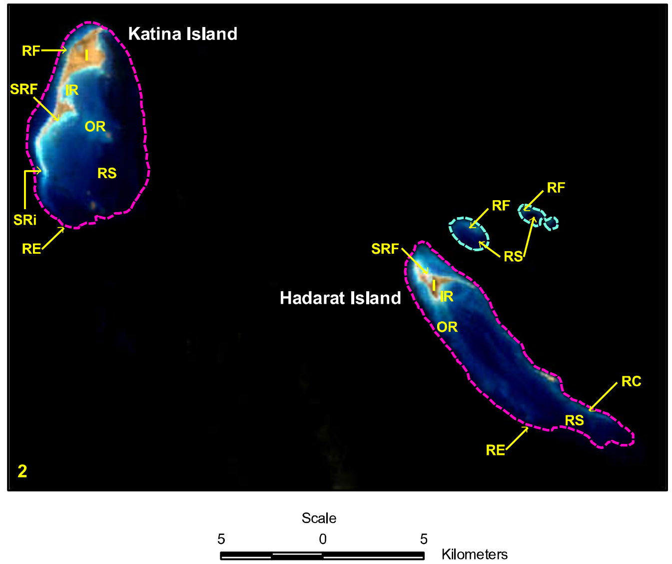
Ahmedabad-380 015

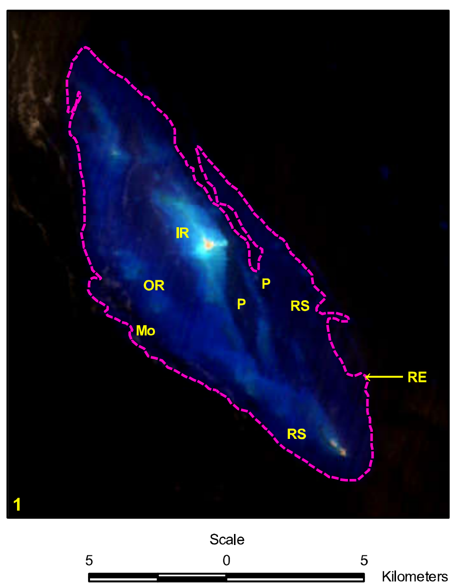
Map 6.1.5.18A : Selected coral reef habitats of Al Lith and Al Qunfidhah

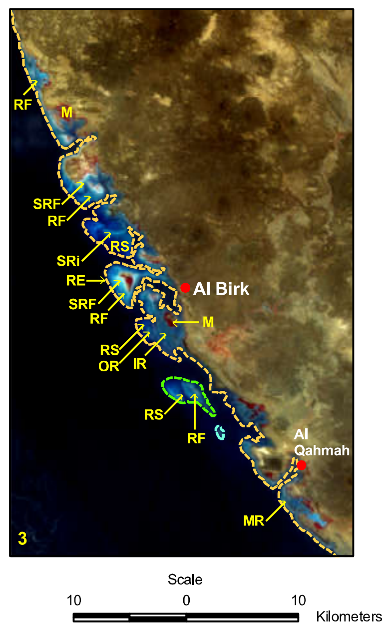


Map 6.1.5.19 : Off-shore coral reef habitats of Ra´s Abu kalb and coastal reefs of Al Birk and surroundings





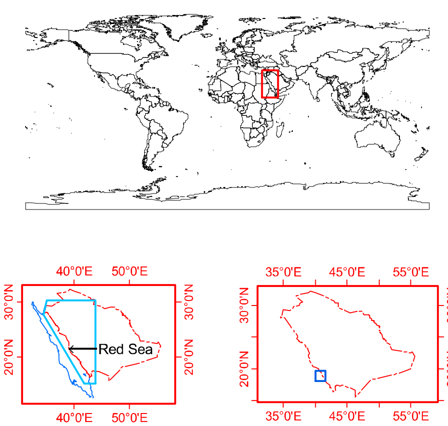




Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Crest	:	RC
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Muddy Reef Flat	:	MR
Sandy Ridge	:	SRi
Pool	:	P
Submerged Reef	:	SR
Island	:	I
Mangrove	:	M

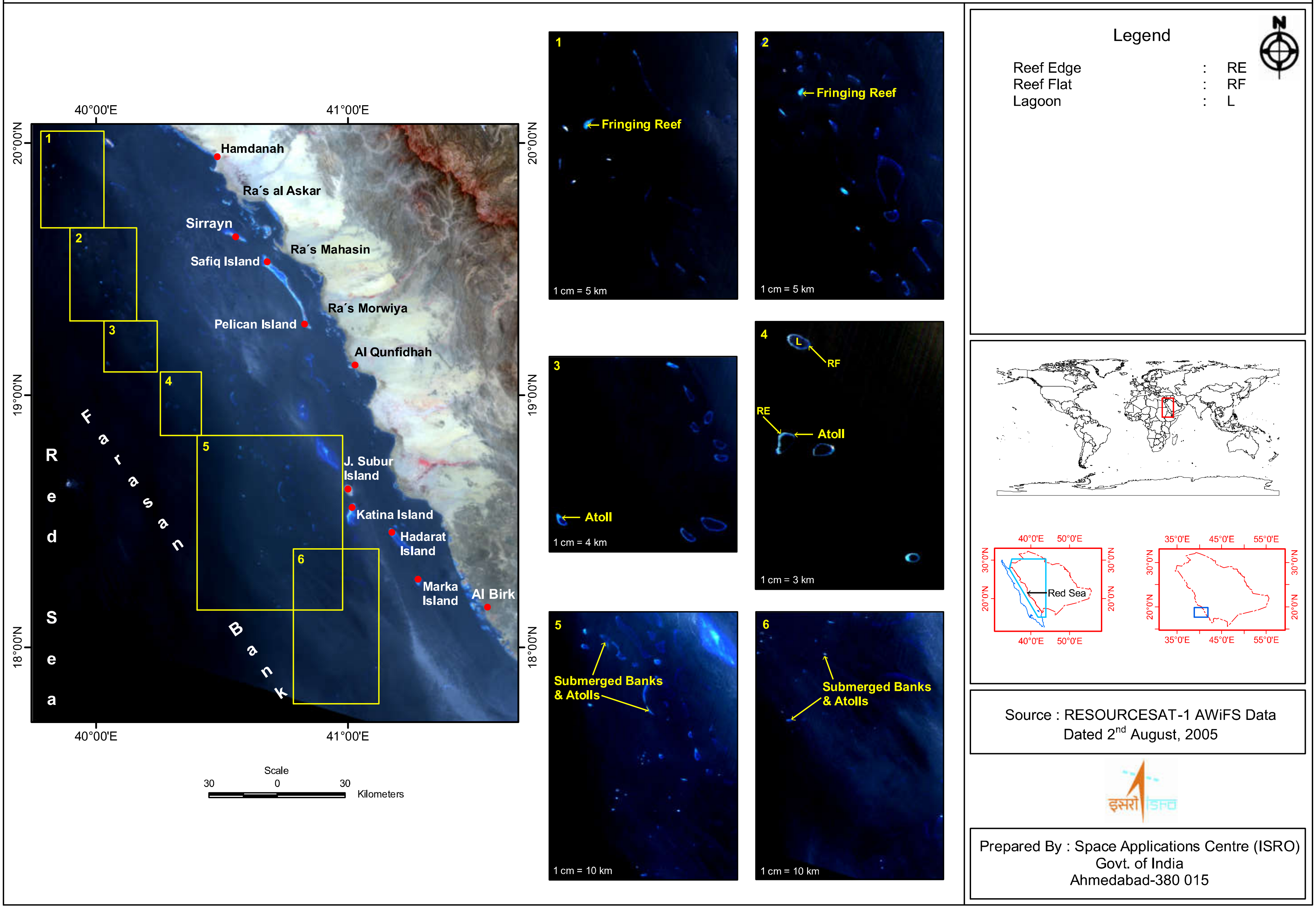
Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle



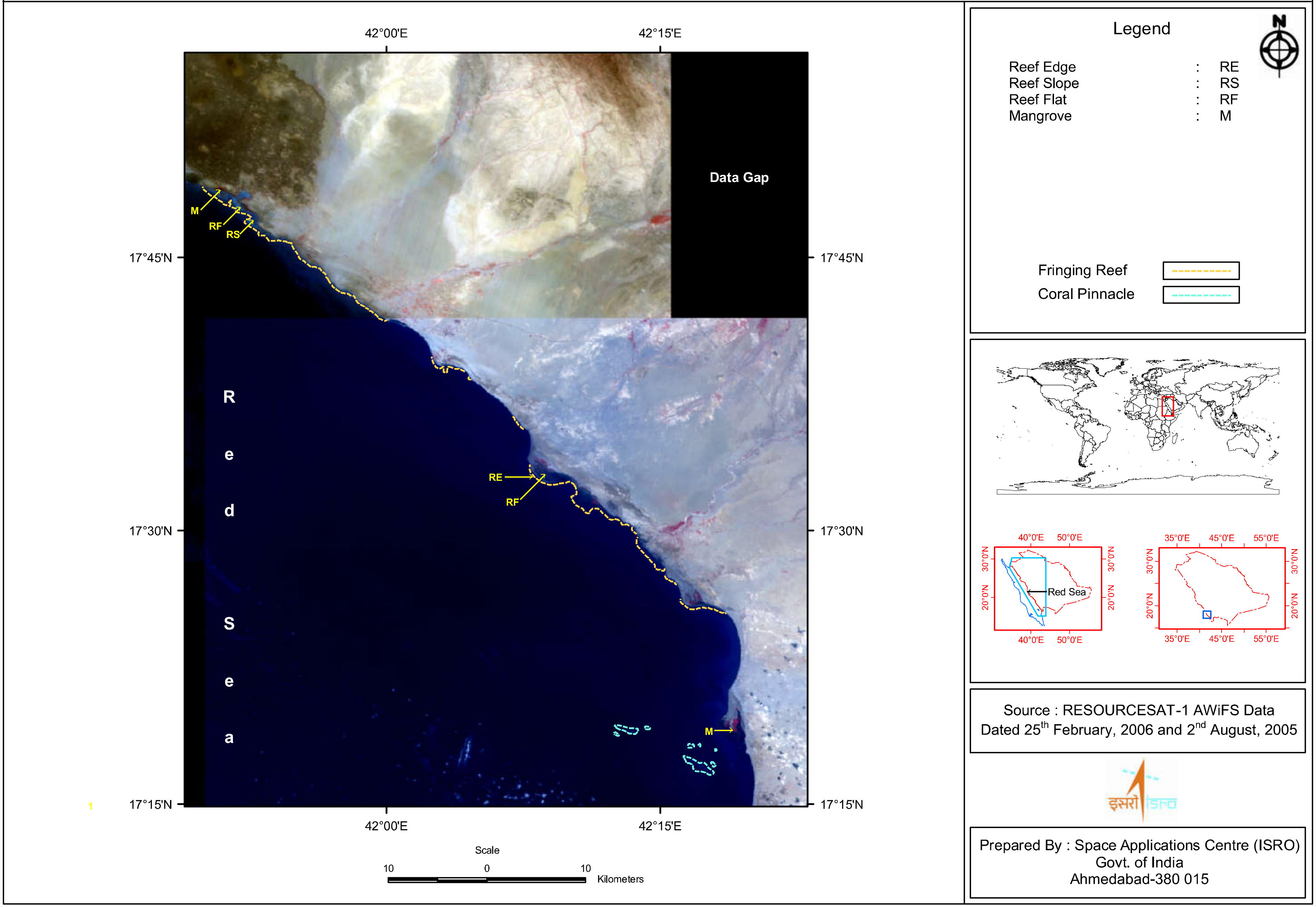
Source : RESOURCESAT-1 AWiFS Data
Dated 2nd August, 2005

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

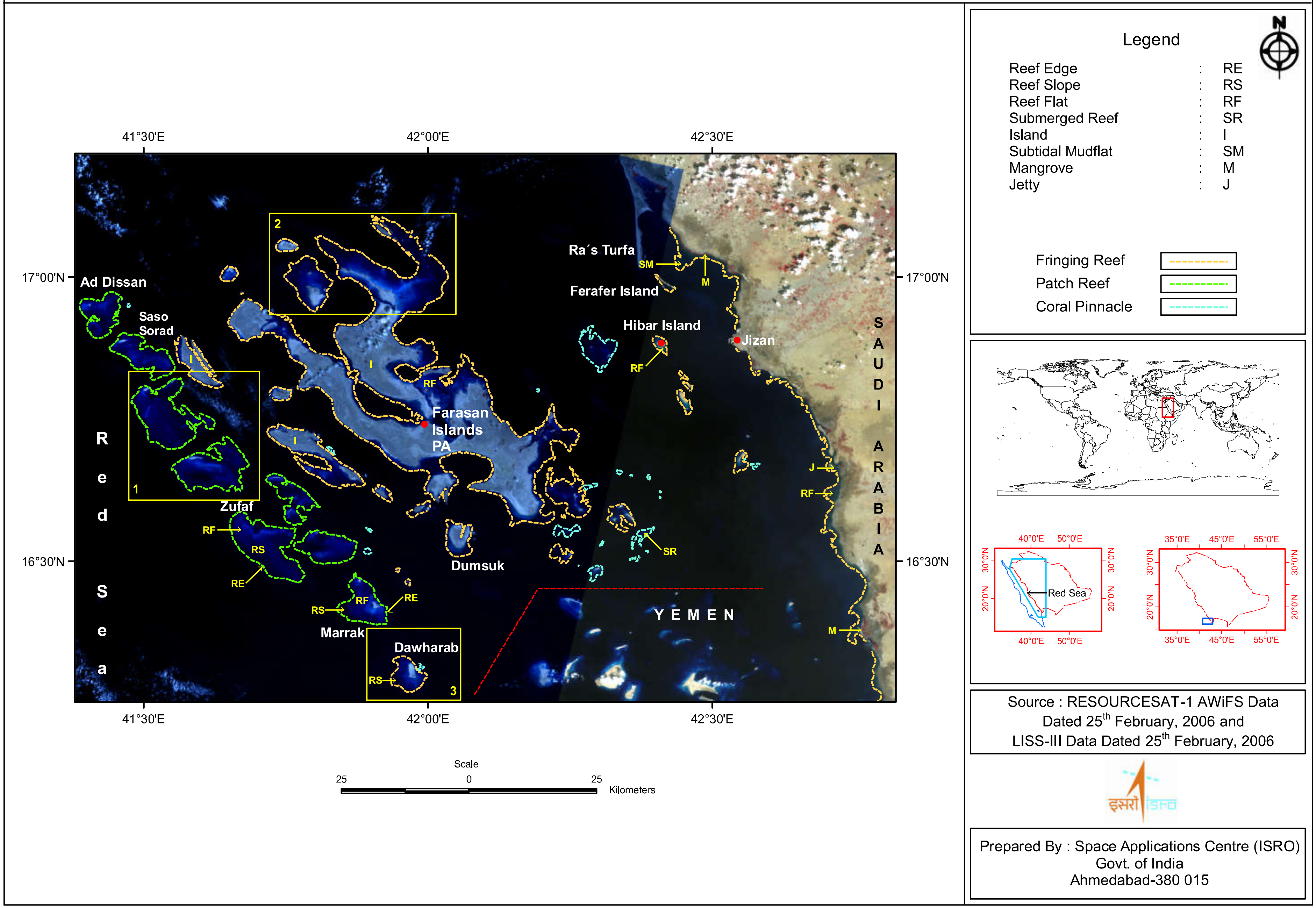
Map 6.1.5.19A : Selected off-shore coral reef habitats of Ra´s Abu kalb and coastal reefs of Al Birk



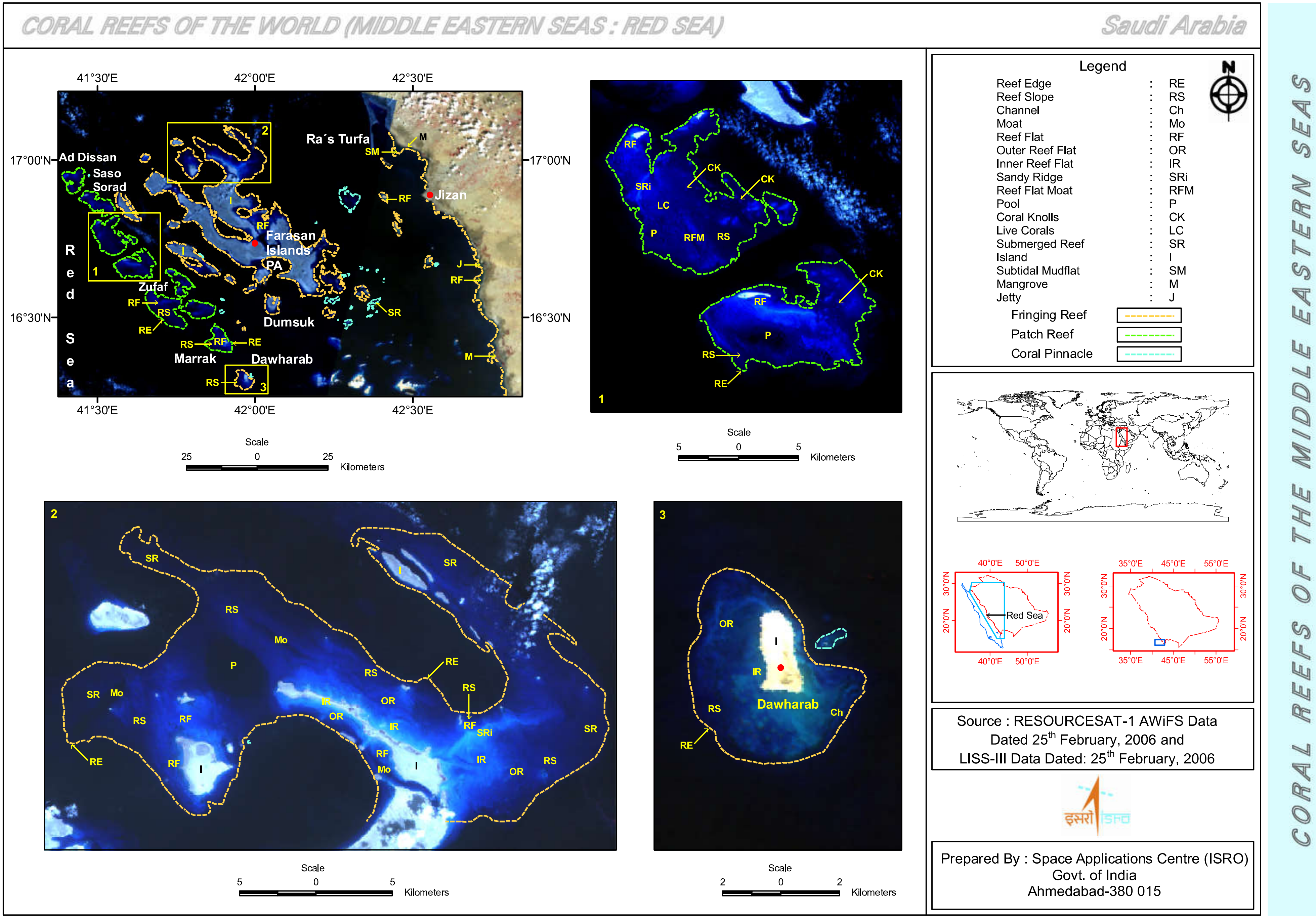
Map 6.1.5.20 : Coral reef habitats of Farasan Bank



Map 6.1.5.21 : Coral reef habitats of Saudi Arabian coast to the north of Jizan



Map 6.1.5.22 : Coral reef habitats of Saudi Arabian coast near Jizan and off-shore reefs of Farasan Islands PA



Map 6.1.5.22A : Selected coral reef habitats of Saudi Arabian coast near Jizan and off-shore reefs of Farasan Islands PA

6.1.6. Yemen

Background

One-third of Yemen's 2200 km long coastline faces the southern Red Sea while the rest two-third is shared by Gulf of Aden. Yemen's Red Sea coast extends for an approximate length of 760 km from the town of Midi, near Saudi Arabian border in the north to Bab el Mandeb in the south (Turak *et al.* 2007). This coast occurs within the geographical limits of 12°38' - 16°22' N latitudes and 41°45' - 43°30' E longitudes. Around 75% of Yemen's Red Sea coast is soft sediment coast where more than half of the shores are covered with extensive sabkhas (dried mud flats) and salt marshes (Pilcher and DeVantier 2003). Strong seasonal southerly winds stir up thick alluvial sediments and result in high turbidity (Turak *et al.* 2007). Wide and shallow coastal shelf restricts water exchange and result in comparatively high water temperatures. Lack of suitable hard substrates, high turbidity, high temperatures and salinity conditions create marginal environment for coral growth and reef-building in this coast (Spalding *et al.* 2001; Pilcher and DeVantier 2003; Kotb *et al.* 2004; Turak *et al.* 2007). Accordingly, only 25% of the mainland coast supports coral reefs (Pilcher and DeVantier 2003).

Coral growth along Yemen's Red Sea coast is found both as coral reefs and coral communities on a variety of substrates (Pilcher and DeVantier 2003). The Red Sea coral reefs of Yemen mainly comprise of coastal and island fringing reefs with some patch reefs and coral pinnacles (Kotb *et al.* 2004). The best developed coral reefs occur off-shore, mainly in the vicinity of large number of islands characterizing the Yemeni Red Sea. Reefs fringe the off-shore limestone islands of the Kamaran group or the southern Farasans and the volcanic oceanic islands of Hunaish, Zuqar and Zubairy groups (Kotb *et al.* 2004). Near-shore reefs are more extensive and diverse to the south of Al Khawkhah than further north (Pilcher and DeVantier 2003). Reef structures often lack the classical zonation pattern and have developed more as reef flats without true reef crests and slopes (Kotb *et al.* 2004; Turak *et al.* 2007).

The condition of Yemen's Red Sea reefs varies widely. Monitoring of ten reef sites on this coast in 2004 showed a range of healthy live coral cover from 28% to 63% (Kotb *et al.* 2004). It is reported that in other areas coral cover ranged from 5% to 85%, at sites with mixed macroalgae and coral communities. At certain sites, there were evidences of extensive damage (coral cover loss upto 90%) due to 1997-98 bleaching event, COTS outbreaks and trawling leading the reefs to large piles of rubbles. There has been good recovery since 1998, however, COTS and *Drupella* outbreaks still remain major ecological threats to Yemen's Red Sea coral reefs.

Coral Reefs: Distribution and Habitat Characteristics

Red Sea coast coral reefs of Yemen have been mapped with Resourcesat-1 AWiFS data (2 scenes; dated: 25th February, 2006 and 12th October, 2008). Habitat characteristics of these reefs have been depicted in seven habitat maps (Maps: 6.1.6.1 to 6.1.6.7). In Yemen, the major coral reefs occur in two settings: fringing the off-shore, carbonate and volcanic oceanic islands and fringing the mainland coast in discontinuous patches. The coastal fringing reef is more prominent in the southern part of the coast as compared to the north. Patch reefs and coral pinnacles occur along with the off-shore fringing reefs.

Off-shore coral reef habitats off Midi near the Saudi Arabian border comprise of the southern Farasan Islands (Maps: 6.1.6.1 and 6.1.6.1A). The southern Farasan Islands are carbonate platforms which have been uplifted and have undergone further modifications (Spalding *et al.* 2001). This island group consists of fringing reefs along with patch reefs and coral pinnacles. AWiFS data (dated 25th February, 2006 and 12th October, 2008) could detect distinct geomorphic zonation of outer and inner reef flat along with reef edge and reef slope in the reef habitats of major islands of Zamhar, Fasht and Buklan. Three areas have been zoomed (Map 6.1.6.1A) to show the geomorphic zones detected for these selected islands. These islands show clear distinction between the outer and inner reef flats. In case of Fasht Island, coralline shelf could be detected in the extreme south of the reef. Eighteen fringing reefs have been detected for this Island group. A constellation of six patch reefs and five coral pinnacles are found in between the mainland coast and the off-shore islands. These patch reefs appear as submerged reefs with very few exposure of reef slope and reef flat categories. Several large reef patches were so far not marked on the available hydrographic charts as they are known to develop below 6m depth in turbid waters (Turak *et al.* 2007). In terms of surface and volume of contemporary reef formations in Yemeni Red Sea these patch reefs are quite important and support a moderately diverse coral fauna dominated by *Porites* and other small massive corals (Turak *et al.* 2007).

The mainland coast near Midi and to the south of Midi (Map: 6.1.6.2) is found to support some submerged reef patches along with sub-tidal and inter-tidal mudflats dominated by mangrove vegetation.

The southern Farasan island group further continues in south near Al Luyhayyah and extends upto Kamaran Island near Ras Isa (Maps: 6.1.6.3, 6.1.6.3A and 6.1.6.3AB). These island fringing reefs are based on fossil reef plateaus situated on the continental shelf. Further away, reefs occur fringing the volcanic oceanic islands of Zubayr and Hanish in comparatively clearer waters. These reefs are considered as true coral reefs with substantial biogenic carbonate accretion by corals (Turak *et al.* 2007). These reefs could only be detected with AWiFS data, their intra-reef feature details could not be delineated because of coarse resolution.
To the north of Kamaran Island, the southern Farasan group consists of fringing reefs along with patch reefs and coral pinnacles. Sixteen patch reefs and twelve coral pinnacles could be detected from AWiFS data dated 12th October, 2008. Selected islands of Antufash and Tigfash and Al Badhi (Map: 6.1.6.3A, subset: 1 and 2) have been zoomed to show the intra-reef geomorphological zonation. These reefs have a characteristic elongated shape with reef flats clearly divisible into outer and inner reef flats. Exposures of coralline shelf in these reefs indicate their foundation on fossil reef plateus. Coral heads have also been detected here. In this part of the mainland coast, fringing reefs occur in submerged condition in association with subtidal mudflats and mangroves. The Kamaran Island is a large, low-lying, near-shore island off the Ras Isa peninsula (Map: 6.1.6.3B). Here too fringing reefs have developed on uplifted paleo carbonate platform. The reef flat can be separated into outer and inner reef flats. A moat separating the reef slope and reef flat zones and a reef flat moat are detected in the northern part of the reef fringing the island. A structural pool is also located here. Kamaran Island is frequently cited

as the origin for many coral specimens (Turak *et al.* 2007). Coastal fringing reefs occur near Ras Isa along with mudflats and mangrove vegetation.

Coastal fringing reefs occur in discontinuous patches in the mainland coast to the north of Hudaydah and near Ad Dayr Bahmi (Maps: 6.1.6.4 and 6.1.6.5). Reef edge, reef slope and reef flat categories could be detected for these reefs.

Further down south on the mainland coast, coastal fringing reefs occur to the south of Al Khawkhah and off-shore reefs occur fringing the volcanic islands of Jazir Zugar, Al Hanish and Al Kabir (Maps: 6.1.6.6 and 6.1.6.6A). These island fringing reefs represent biogenically accreting reefs with extensive reef flats, gradual reef slopes of broken-up reef patches and intermittent sand areas (Turak *et al.* 2007). Jazir Zugar Island has been zoomed (Map: 6.1.6.6A, subset: 3) for showing the intra-reef features in detail. The narrow fringing reef can be separated into reef slope and reef flat zones. Sanded reef flat occurs extensively in the western and southern parts of the Island. Benthic category of algae is detected in the northern part. However, a high resolution image can be of much use to depict the intra-reef details of these island fringing reefs. A spit formation is noticed in the north of the coastal fringing reef (Map: 6.1.6.6A, subset: 2).

An extensive, long, continuous, coastal fringing reef occurs on the mainland coast of Yemen in the Red Sea from the south of Al Khawkhah to the entrance of Bab el Mandeb (Maps: 6.1.6.7 and 6.1.6.7A). This reef is one of the most important coastal features of the southern Red Sea. The reef's width varies from less than 100 m to 1 km. To the south of Mukha, a prominent sanded reef flat zone is noticed. Near Dhubab the reef flat can be distinguished into outer and inner reef flat while an algae dominated sanded reef flat is found to the south of Dhubab. Reef edge and reef slopes are other geomorphological sub-zones that could be detected in this reef.

The frequencies of the classes/categories detected for the coral reef habitats of Yemen's Red Sea coast are represented in Figure 6.1.6.1. Geomorphological zones like reef flat and geomorphological sub-zones like reef edge and reef slope appear as commonly detected classes. Exposure of coral heads as a geomorphological zone occurs along with submerged reef and coralline shelf as level 2 classes. Channel, moat and reef flat moat classes have also been detected in case of these reefs. Among the benthic classes algae could be detected. Islands and exposures of sub-tidal mudflat along with mangrove vegetation dominate among the associated classes.

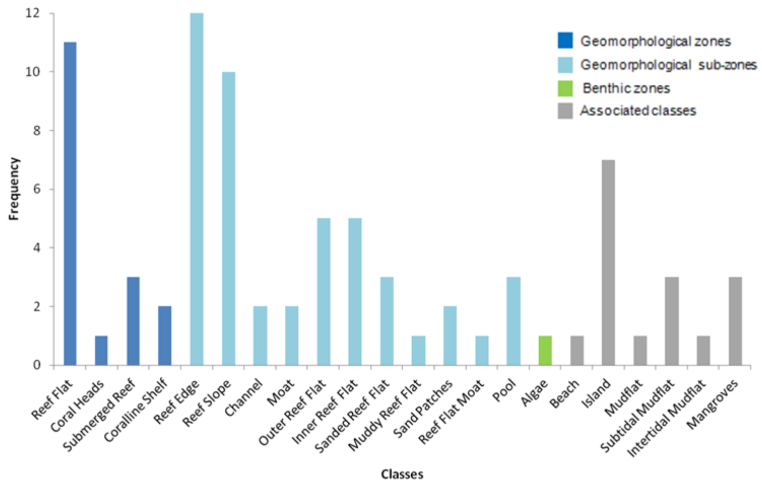


Figure 6.1.6.1 Frequency of classes detected for coral reef habitats of Yemen's Red Sea coast

Areal Extent of Coral Reefs of Yemen

The coral reef habitats of Yemen's Red Sea coast as mapped from AWiFS data cover a total area of 793.07 sq km. Reef area corresponding to each habitat map is summarized in Table No. 6.1.6.1. The off-shore coral reef group off Midi (the southern Farasan Islands) occupies the highest reef area of 389.81 sq km while coastal fringing reefs near Ad Dayr Bahmi and surroundings occupy the minimum area of 2.44 sq km.

Table 6.1.6.1 Areal Extent of coral reefs of Saudi Arabia

Map No.	Location	Reef Area (sq km)
6.1.6.1	Off-shore coral reef habitats off Midi	389.81
6.1.6.2	Midi and surroundings	-
6.1.6.3	Off-shore and coastal coral reef habitats near Al Luyhayyah and Ras Isa	237.54
6.1.6.4	North of Hudaydah and surroundings	14.93
6.1.6.5	Ad Dayr Bahmi and surroundings	2.44
6.1.6.6	Al Khawkhah and off-shore islands of Jazir Zugar, Al Hanish Al Kabir	58.90
6.1.6.7	Mukha, Dhubab and surroundings	89.45
	Total Area	**793.07**

Summary

In the Red Sea coast of Yemen, the major coral reef habitats appear as clusters of off-shore reefs fringing the carbonate and volcanic oceanic islands along with coastal reefs fringing the mainland in discontinuous segments. Semi-submerged patch reefs and coral pinnacles are also found along with the off-shore fringing reefs. The coastal fringing reef occurs continuously in the southern coast of Yemen. Significant intra-reef geomorphic details could be delineated for Yemen's Red Sea reefs from the AWiFS data. However, the patch reefs, coral pinnacles and in certain places the coastal fringing reefs require high (spatial) resolution data for detailed habitat mapping. The interesting aspect of Yemen's Red Sea coast coral reefs is their lack of reef crest zone and presence of extremely shallow reef slopes. Yemen's Red Sea coast is a densely populated coastline as compared to other areas. Artisanal fishing is the main source of income of the Yemeni coastal population and high fishing efforts have reached beyond sustainable levels for many target species (Kotb *et al.* 2004). Destructive methods are used to collect aquarium fish around the Kamaran Island group. There are major oil terminals in Hudaydah and Mukha. Oil pollution, sewage discharge and industrial development have been reported to cause localized impacts on the reefs in vicinity (Spalding *et al.* 2001). These coral reefs as mapped from the AWiFS data cover a total area of 793.07 sq km and appear in *near-pristine* condition.

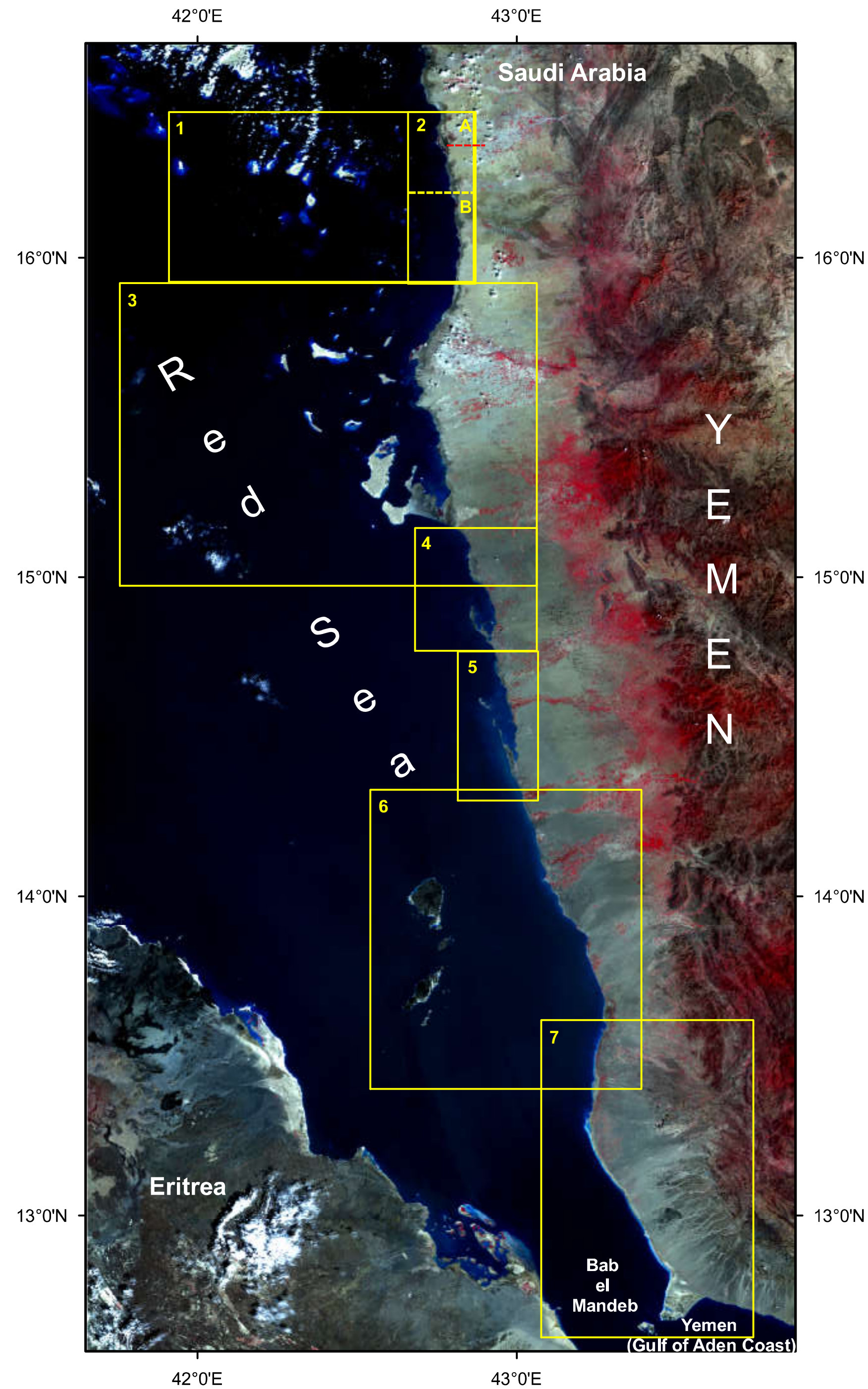
Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.1 represents Results > under **Basin 1. Red Sea**
6.1.6 represents Results > under Basin 1. Red Sea > for **Country 2. Yemen**
6.1.6.1 represents **Coral Reef Habitat Map** of **Yemen coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

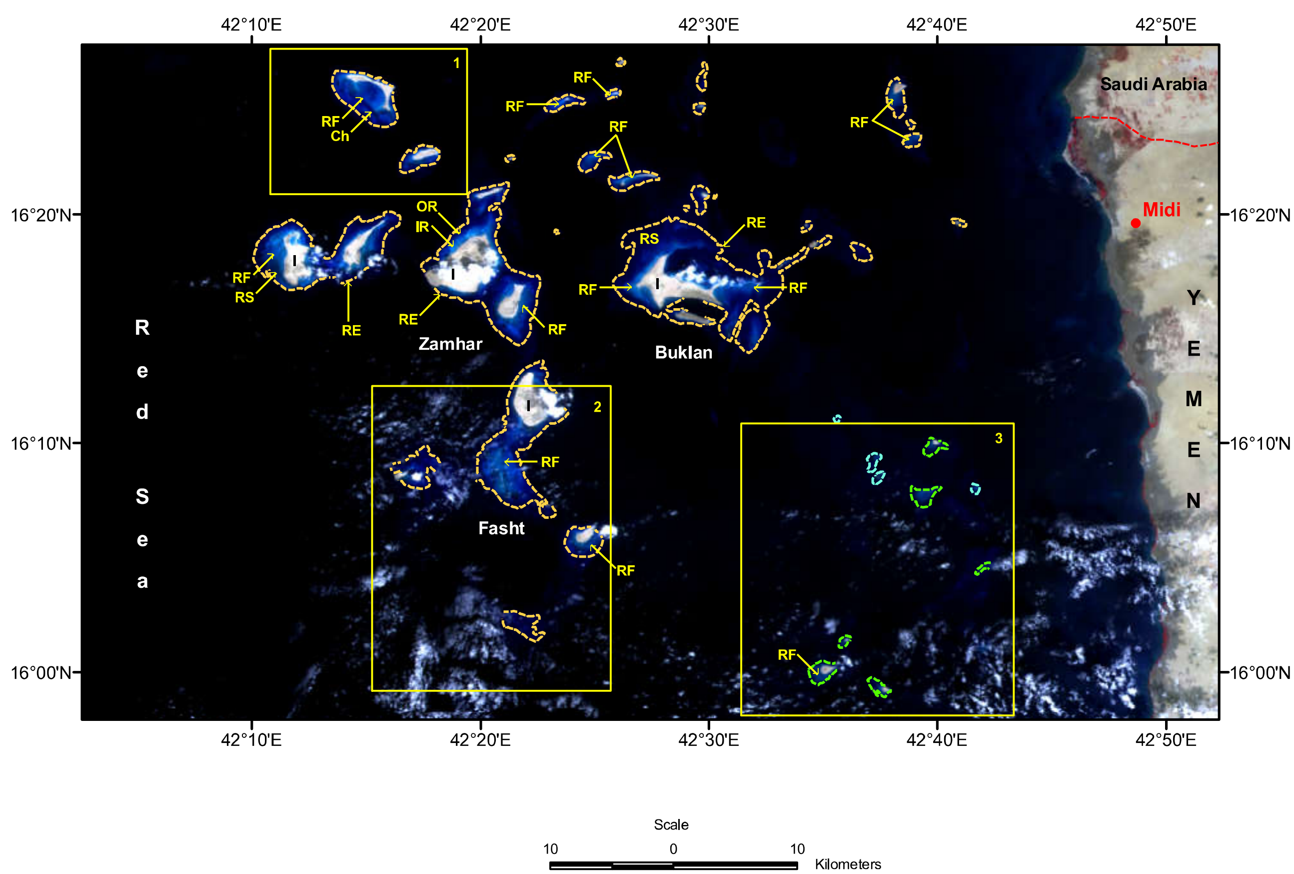
1. Off-shore coral reef habitats off Midi
2. Midi and surroundings
3. Off-shore and coastal coral reef habitats near Al Luhayyah and Ra´s Isa
4. North of Hudaydah and surroundings
5. Ad Dayr Bahmi and surroundings
6. Al Khawkhah and offshore islands of Jazir Zugar, Al Hanish Al Kabir
7. Mukha, Dhubab and surroundings



--- International boundary

Source: Resourcesat-1 AWiFS mosaic from data dated: 12th October, 2008

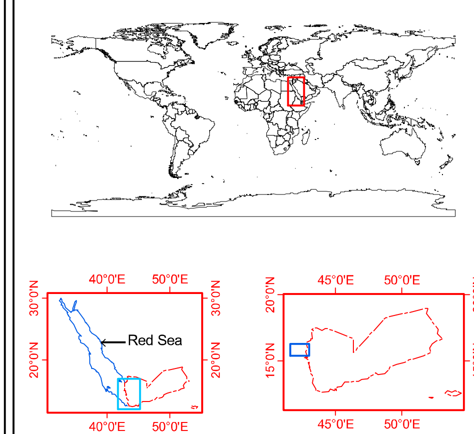
Figure 6.1.6 Index to coral reef habitat maps of Yemen



Legend

Reef Edge : RE
Reef Slope : RS
Channel : Ch
Reef Flat : RF
Outer Reef Flat : OR
Inner Reef Flat : IR
Island : I

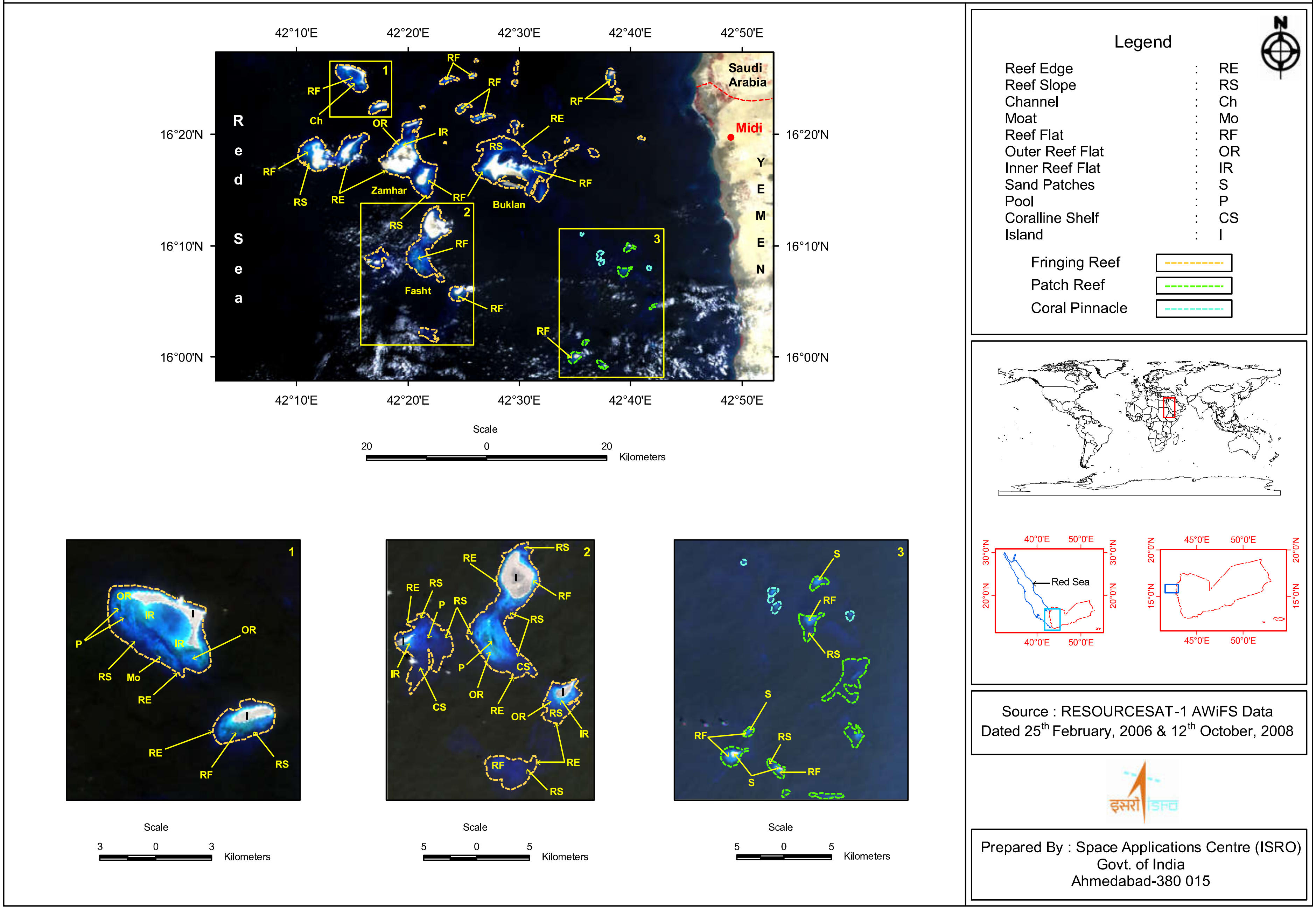
Fringing Reef
Patch Reef
Coral Pinnacle



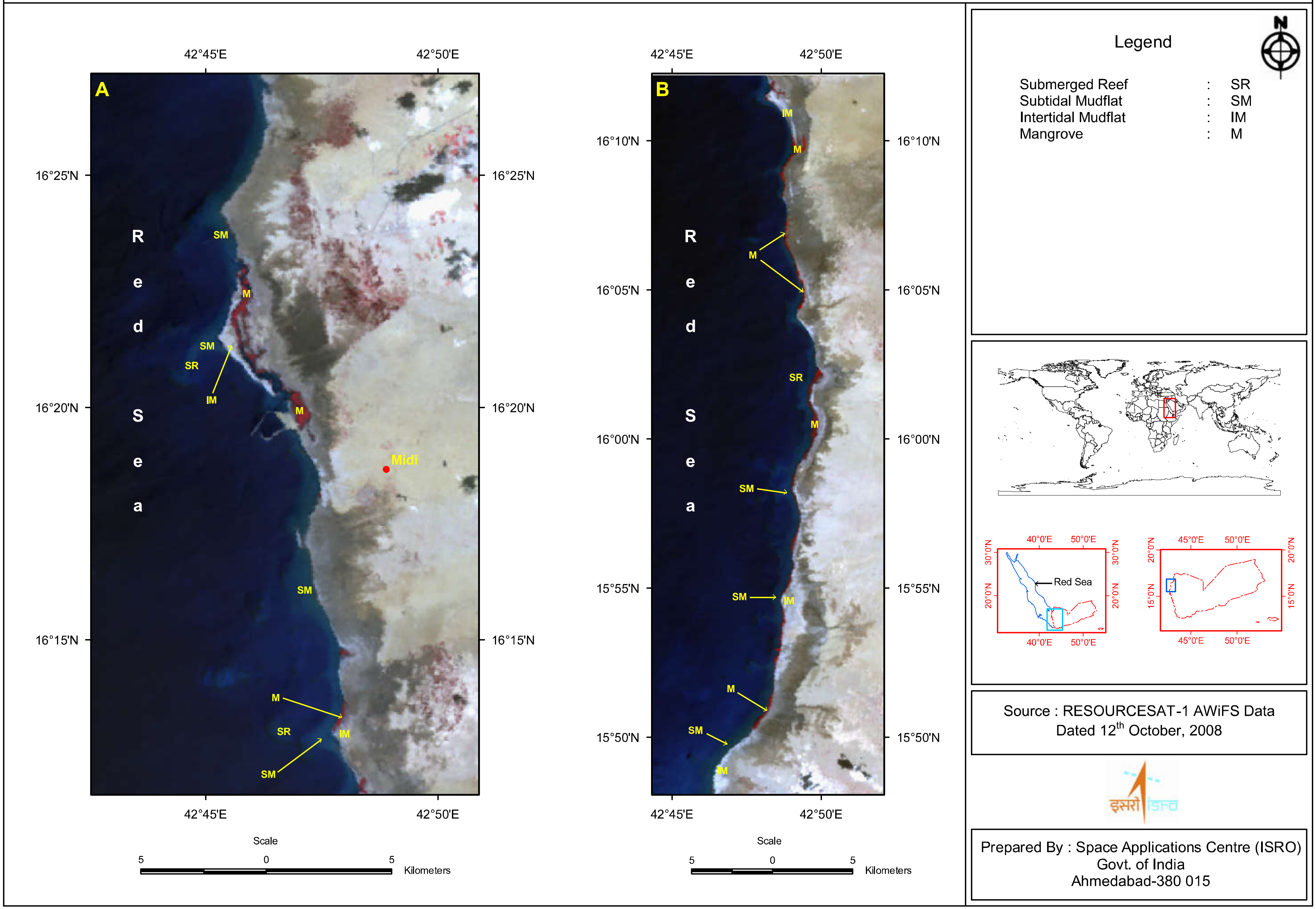
Source : RESOURCESAT-1 AWiFS Data
Dated 25th February, 2006

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

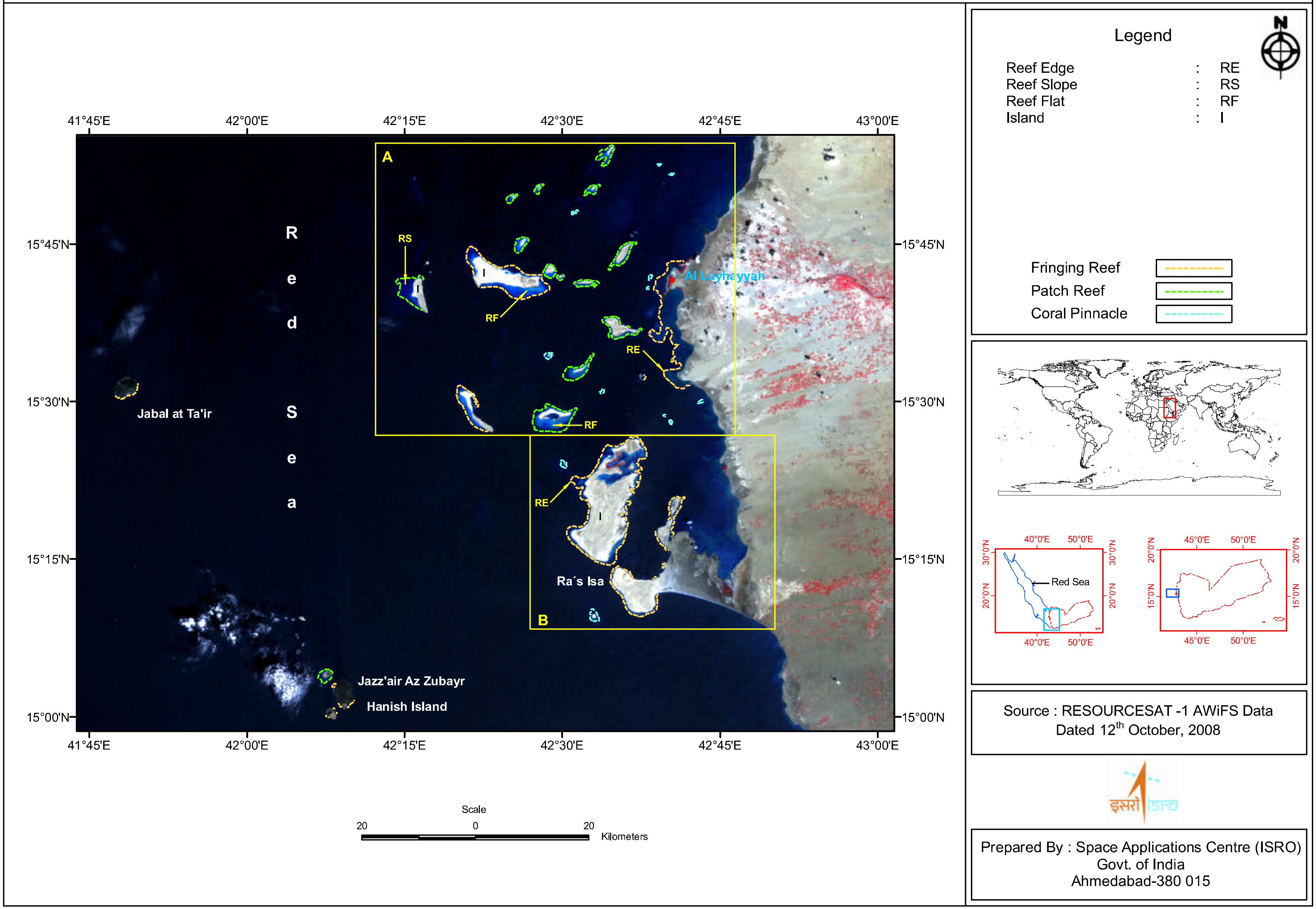
Map 6.1.6.1 : Off-shore coral reef habitats off Midi



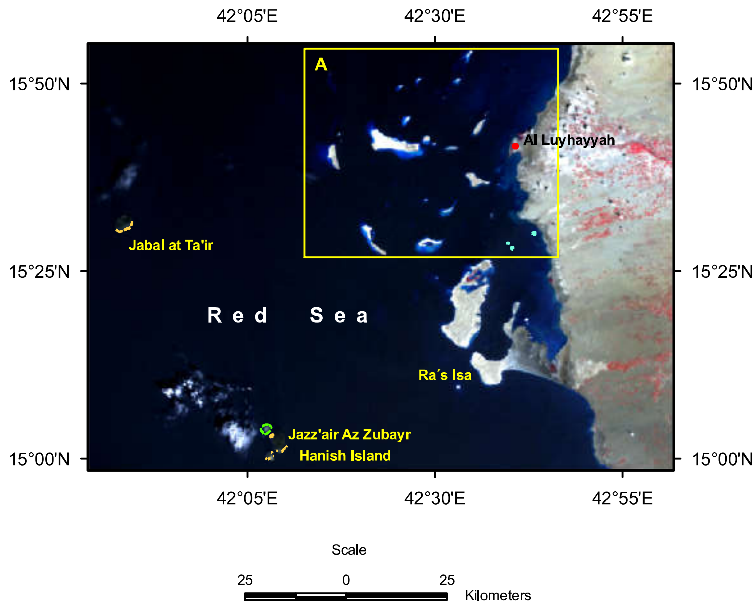
Map 6.1.6.1A : Selected off-shore coral reef habitats off Midi

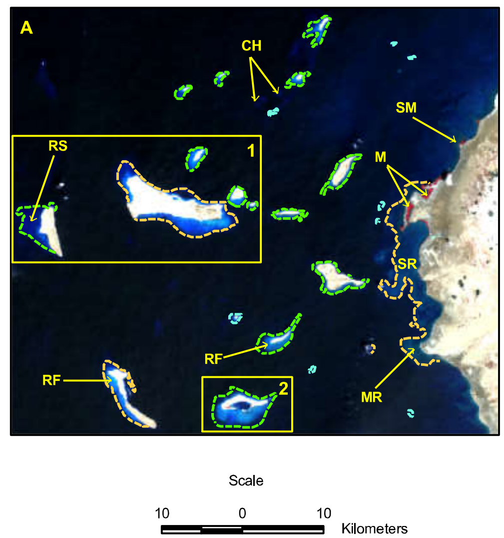


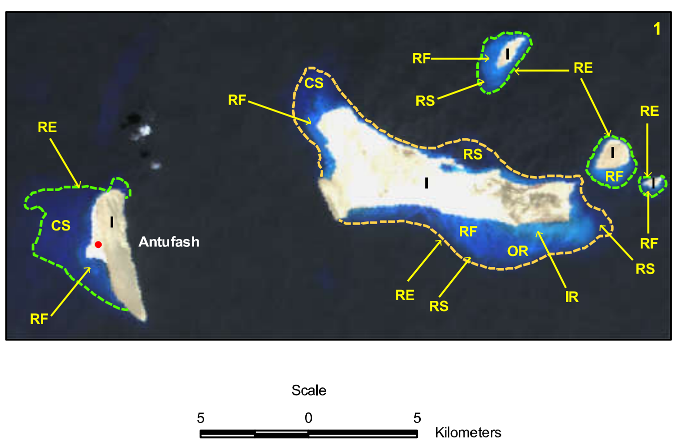
Map 6.1.6.2 : Coral reef habitats of Midi and surroundings

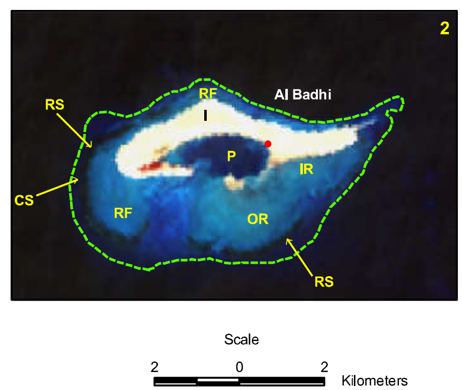


Map 6.1.6.3 : Off-shore and coastal coral reef habitats near Al Luyhayyah and Ra´s Isa





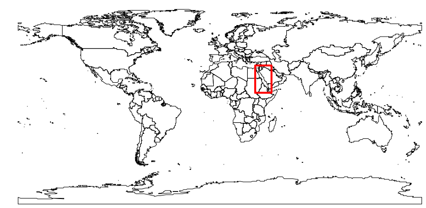


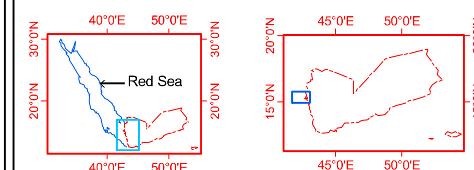


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Muddy Reef Flat	:	MR
Pool	:	P
Coral Heads	:	CH
Submerged Reef	:	SR
Coralline Shelf	:	CS
Island	:	I
Subtidal Mudflat	:	SM
Mangrove	:	M

Fringing Reef
Patch Reef
Coral Pinnacle

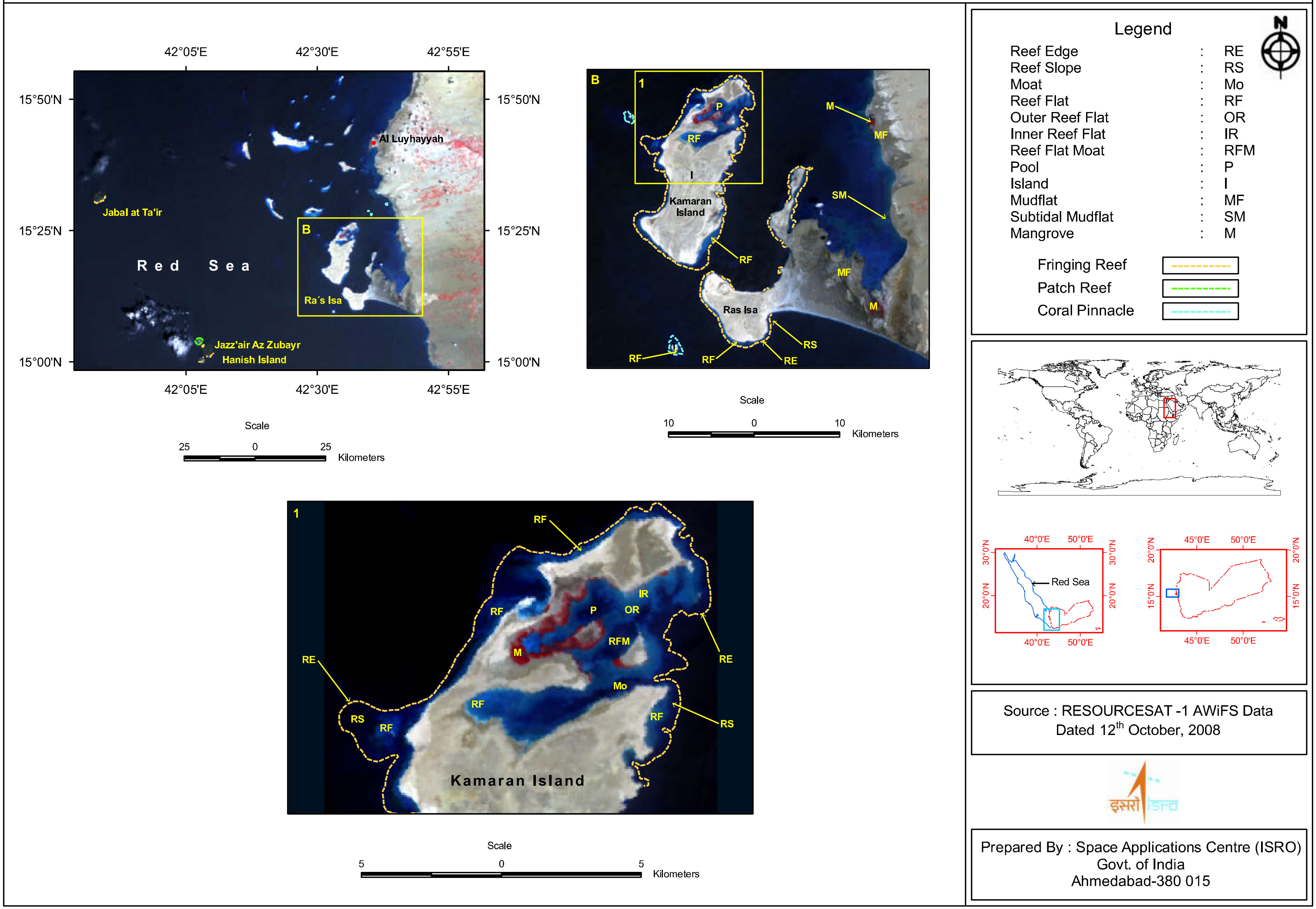




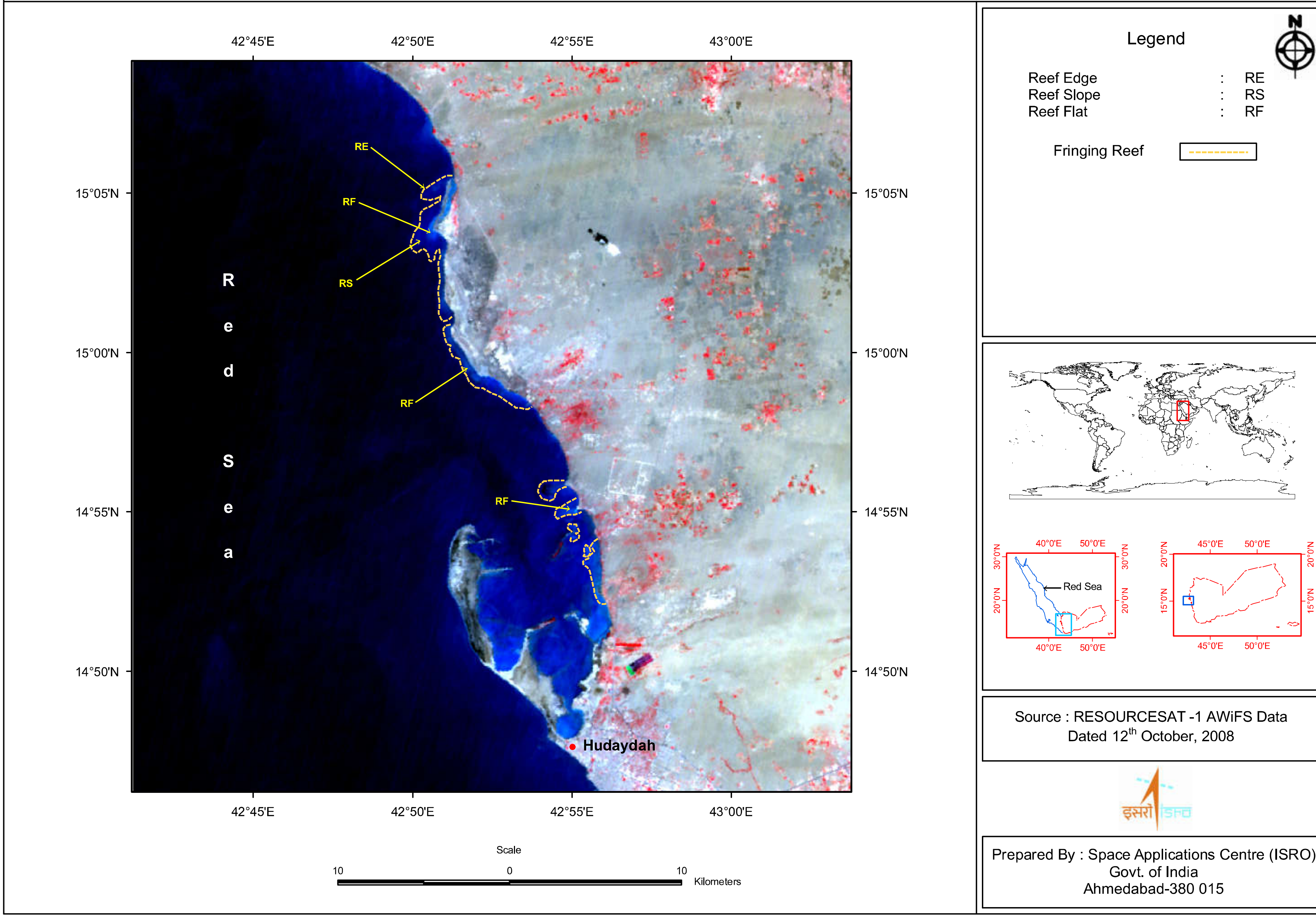
Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

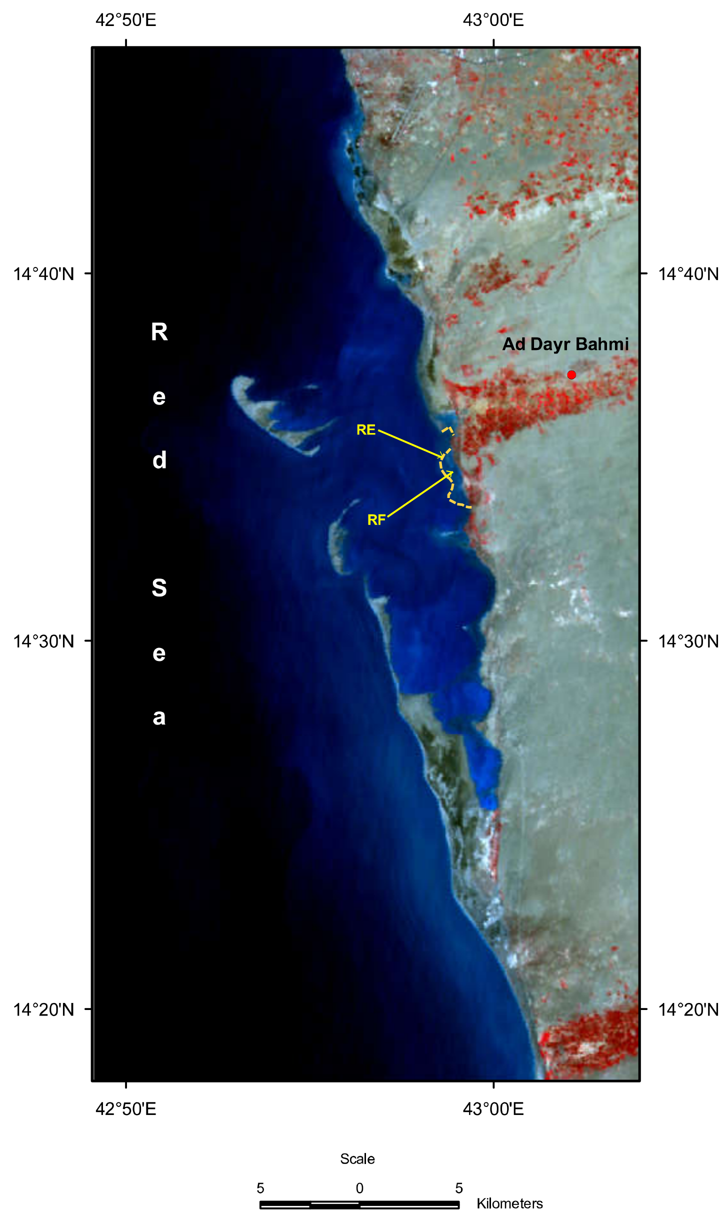
Map 6.1.6.3A : Selected off-shore and coastal coral reef habitats near Al Luyhayyah and Ra´s Isa



Map 6.1.6.3B : Coral reef habitats of Kamaran Island and Ras Isa



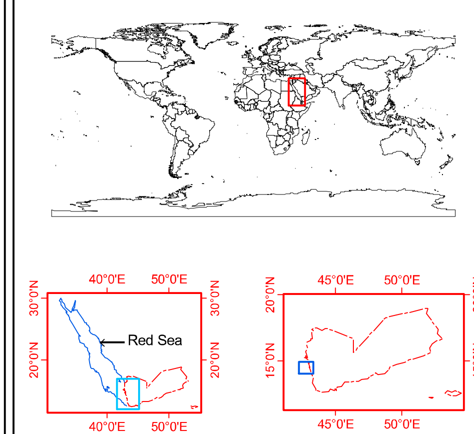
Map 6.1.6.4 : Coral reef habitats to the north of Hudaydah and surroundings



Legend

Reef Edge : RE
Reef Flat : RF

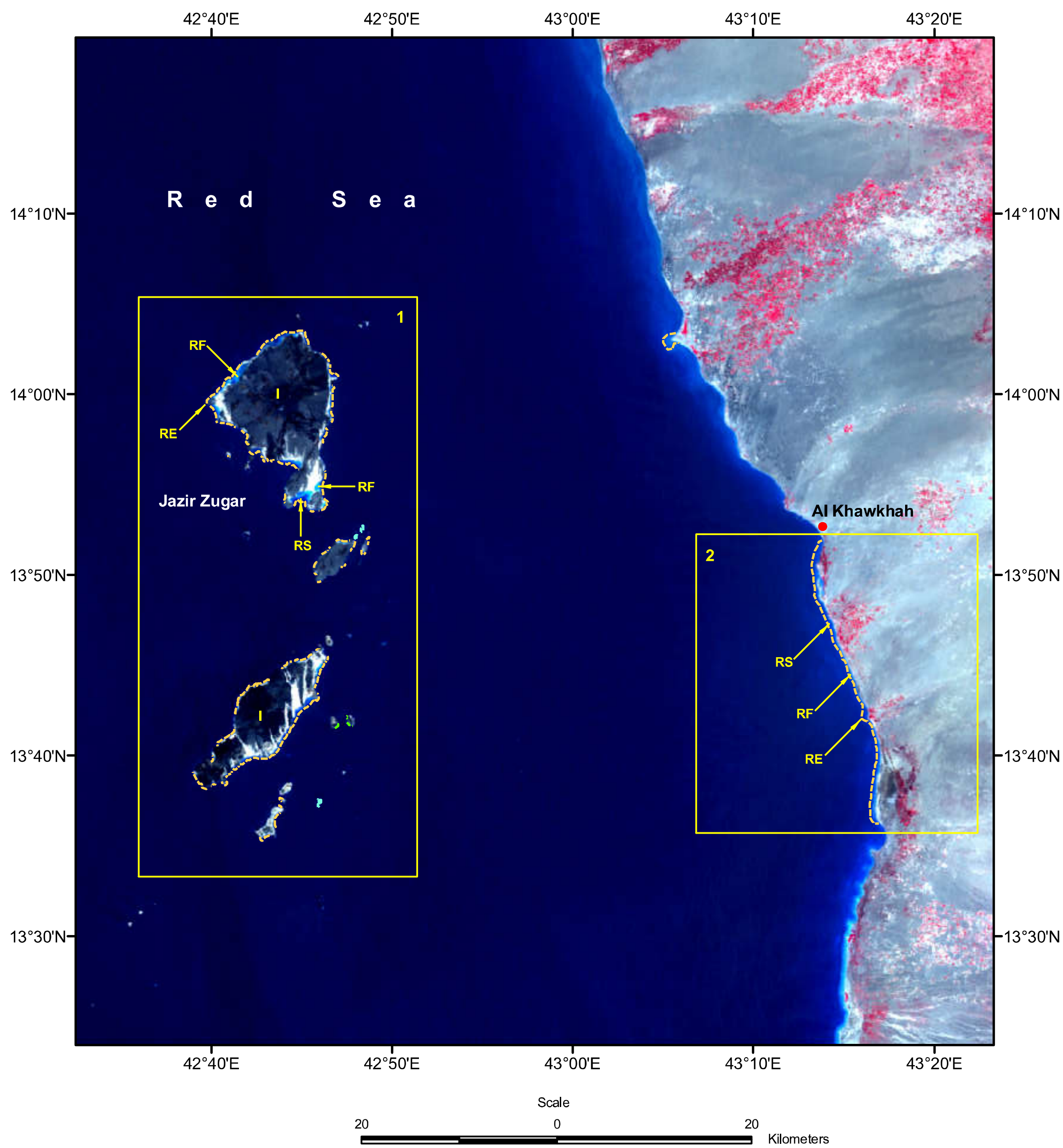
Fringing Reef



Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

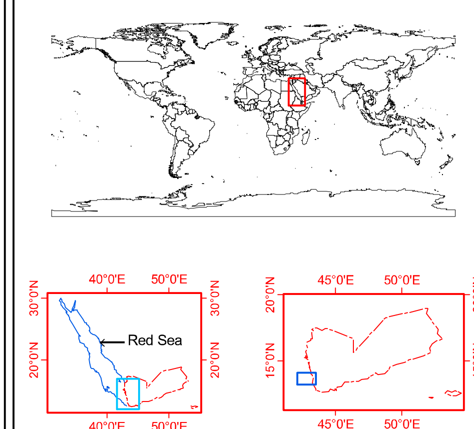
Map 6.1.6.5 : Coral reef habitats near Ad Dayr Bahmi and surroundings



Legend

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF
Island : I

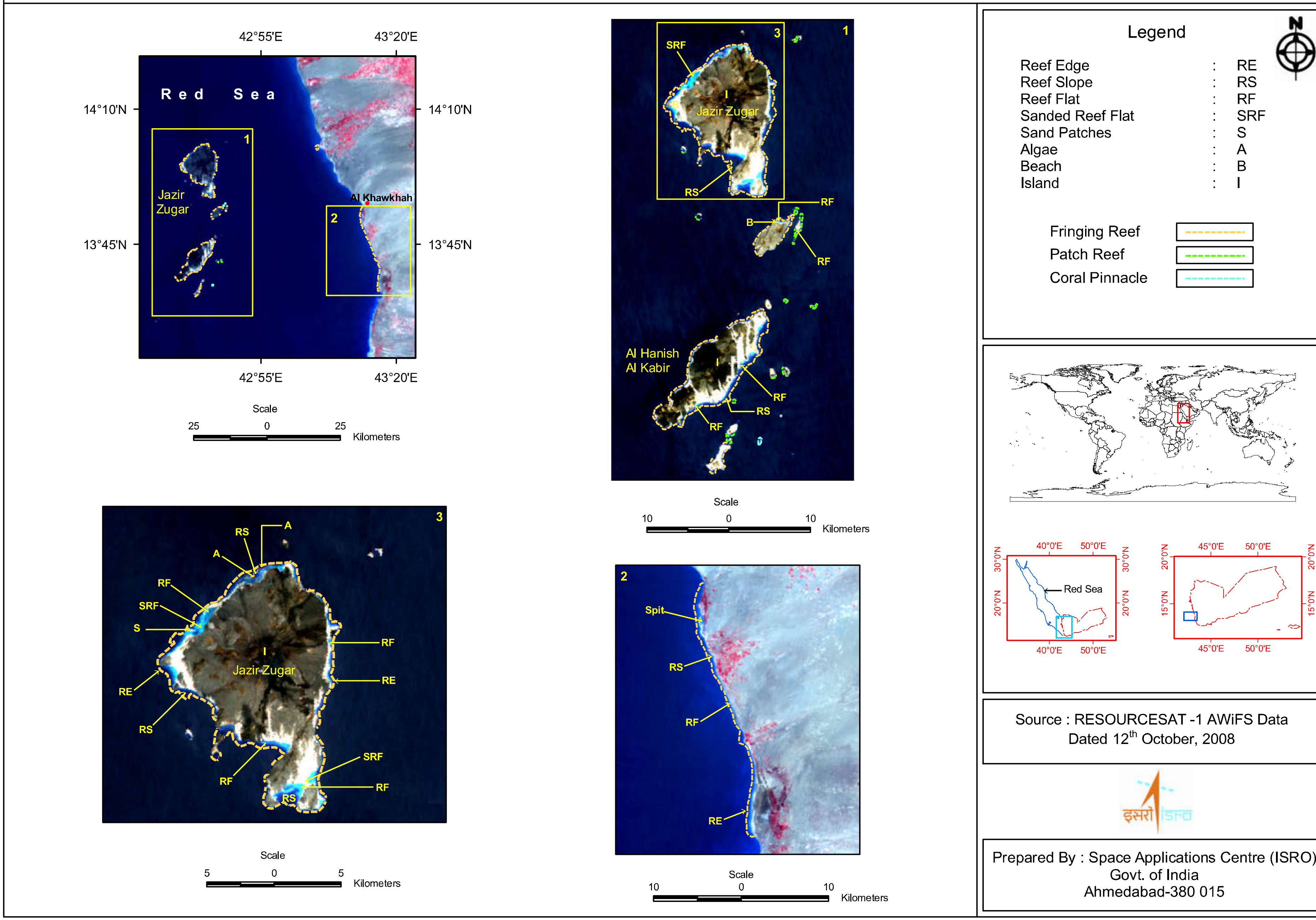
Fringing Reef
Patch Reef
Coral Pinnacle



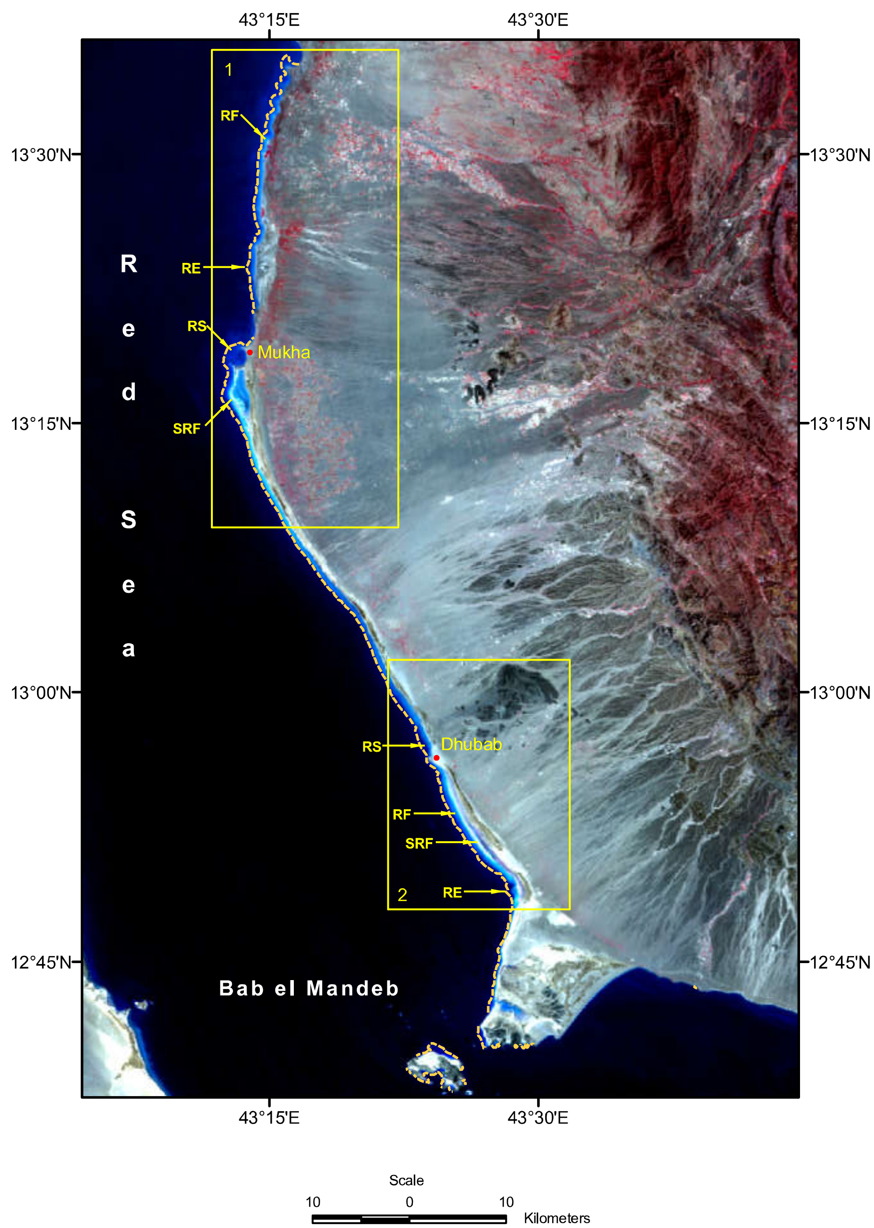
Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.6.6 : Coral reef habitats around Al Khawkhah and offshore islands of Jazir Zugar, Al Hanish Al Kabir



Map 6.1.6.6A : Selected coral reef habitats around Al Khawkhah and offshore islands of Jazir Zugar, Al Hanish Al Kabir

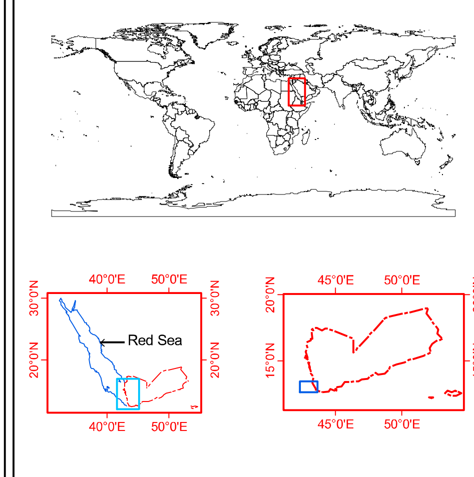


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Sanded Reef Flat	:	SRF

Fringing Reef

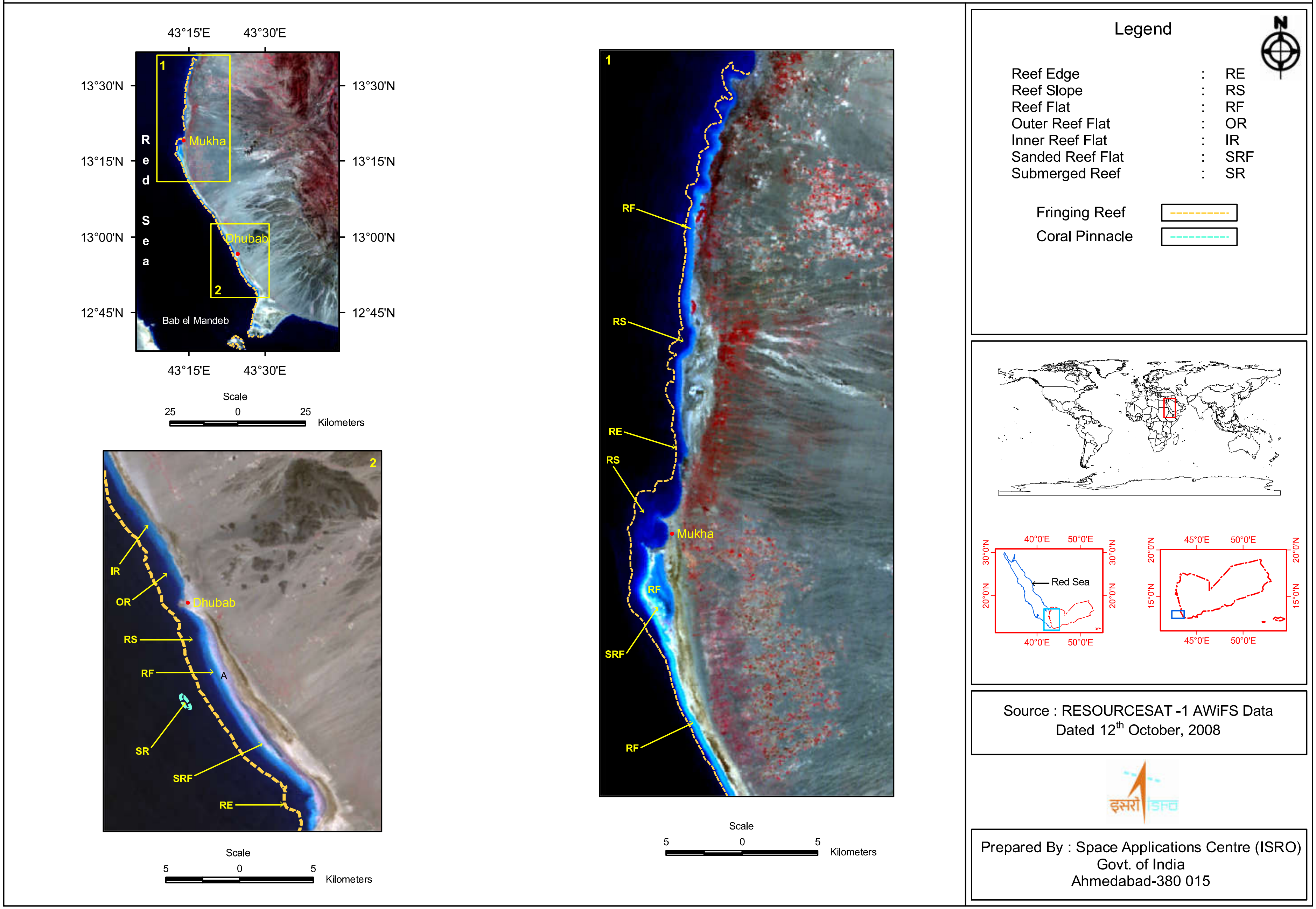
Coral Pinnacle



Source : RESOURCESAT -1 AWiFS Data
Dated 12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.1.6.7 : Coral reef habitats of Mukha, Dhubab and surroundings



Map 6.1.6.7A : Selected coral reef habitats of Mukha and Dhubab

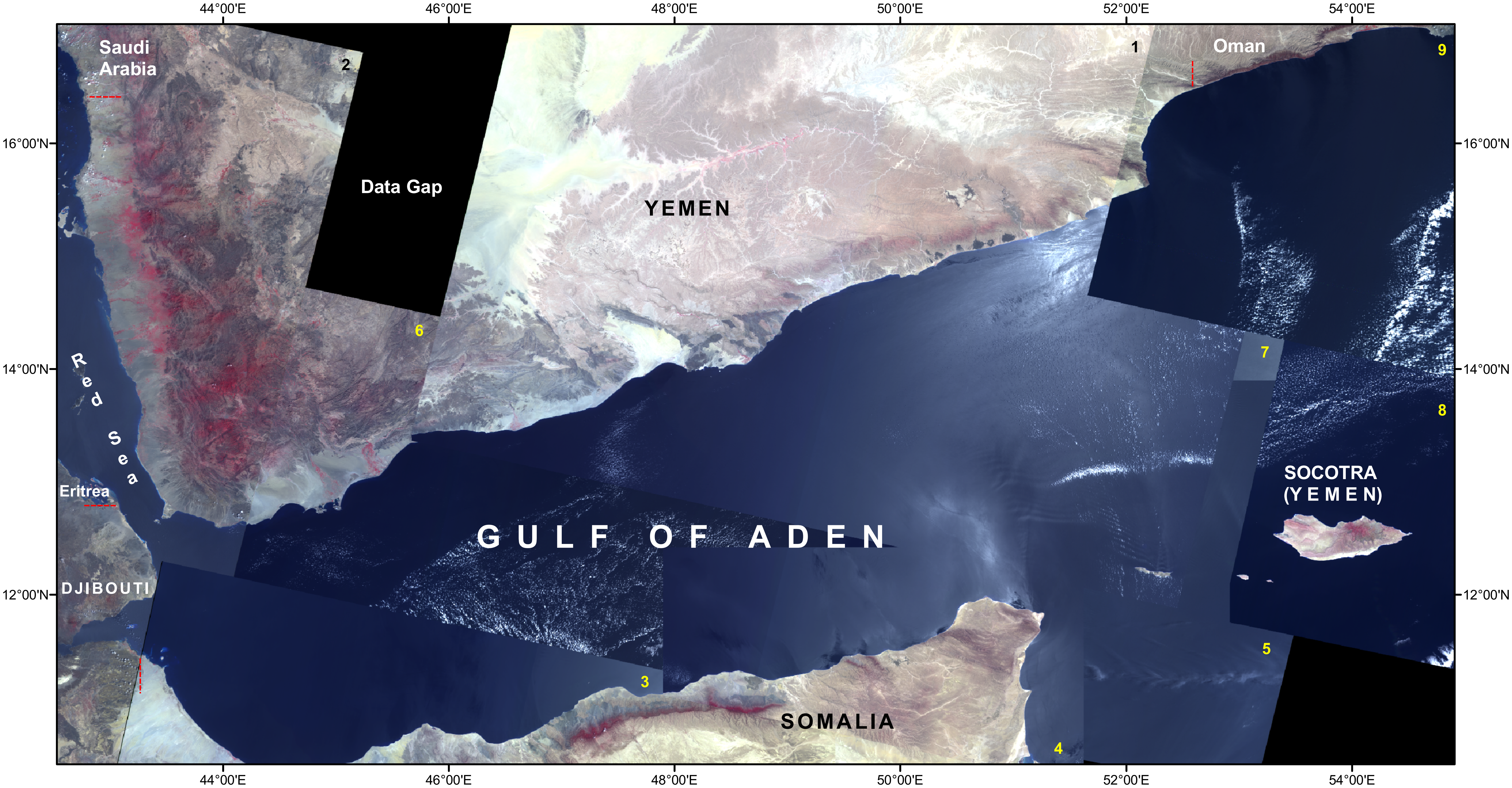


Figure 6.2 Resourcesat-1 AWiFS mosaic showing Gulf of Aden and surrounding countries.

--- International boundary delimiting coastlines of the countries surrounding Gulf of Aden.

Source: RESOURCESAT-1 AWiFS mosaic from data dated
8th May, 2009 (1); 12th Oct, 2008(2); 31st Aug, 2008(3); 22nd Aug, 2008(4,5); 12th Nov, 2007(6); 16th April, 2006(7); 24th March,2006(8); 21st Jan, 2004(9)

6.2.1. Djibouti

Background

Djibouti's 370 km long coastline marks the western boundary of Gulf of Aden (Figure 6.2). The coastline of Djibouti occurs within the geographical limits of 11°28' – 12°42'N latitudes and 43°07' - 43°15'E longitudes. The northern coast of Djibouti faces the Strait of Bab el Mandeb while rest of the coastline borders the 800m deep trench of Gulf of Tadjoura which opens out to Gulf of Aden (Kotb *et al.* 2004). A small part of this coastline borders Ghoubet al- Kharab, a shallow, semi-enclosed basin separated from the Gulf of Tadjoura by a narrow opening. The shallow, sandy northern coast has some of the best developed coral reefs outside the Red Sea while the southern coast towards Somalia is characterized with several estuaries and poorly developed coral reefs. Ghoubet al- Kharab contains low diversity coral reefs. Cold water upwelling from the Indian Ocean is a limiting factor to coral growth and reef development in this part of Djibouti's coastline. At the entrance of Gulf of Tadjoura, to the north of Djibouti city, are the islands of Musha and Maskali, surrounded by extensive reefs.

The best developed coral reefs of Djibouti are the fringing reefs of the mainland coast in the north, off-shore islands of Sept Frères to the south of Bab el Mandeb and the fringing and platform structures around the vast fossil reef plateau of Musha and Maskali islands in Gulf of Tadjoura (Spalding *et al.* 2001; Kotb *et al.* 2008). At the confluence of three biogeographic zones, Djibouti is home to a unique assemblage of coral reef species. Ecologically, the unusual combination of warm-water tropical biota (from the Red Sea and Indian Ocean) with cold-water upwelling habitats (from Somalia and Arabian regions) is noted in the islands of Sept Frères which is rarely found in few other parts of the world (Pilcher and Abdi 2003). Surveys in 1998 and 1999 have reported 167 coral species while coral cover was highly varied, ranging from 20% to 90% in Sept Frères (Spalding *et al.* 2001). A survey in 2007-2008 have estimated average coral cover of Djibouti at 56% (33% hard corals and 23% soft corals; Kotb *et al.* 2008). Some of the Djibouti reefs have been significantly impacted by the 1997-98 bleaching event with an estimated 30% mortality (Spalding *et al.* 2001).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Djibouti coast have been mapped with Resourcsat-1 AWiFS data (2 scenes; dated 12th November, 2007 and 12th October, 2008). The detailed habitat characteristics of Djibouti reefs have been depicted in seven habitat maps (Maps: 6.2.1.1 to 6.2.1.7). Fringing reefs along with its sub-types (Platform, Patch and Pinnacle types) are detected in Djibouti. The major reef structures on Djibouti coast occur within the geographical co-ordinates of 12°42'N, 43°07' E in the north and 11°28'N, 43°15'E in the south. The Djibouti coast is characterized with continuous coastal fringing reefs in the northern part (facing the Red Sea), discontinuous coastal fringing reefs in the central section (outlining Ghoubet al- Kharab and partially Gulf of Tadjoura) and again continuous, coastal fringing and off-shore platform reefs in the southern part (in Gulf of Tadjoura).

The coastal, fringing reefs of northern Djibouti coast (Maps: 6.2.1.1, 6.2.1.2) run parallel to the coastline from Eritrea border in the north to a little south of Ras el Bir and show distinct geomorphological zonation. In the seaward side, geomorphological sub-zones of reef edge and reef slope could be detected in these reefs. An algae inhabited moat, separating the reef slope and reef flat is found in the central part of this reef (Map: 6.2.1.1). The reef flat can be distinguished between outer and inner reef flats throughout its length. Reef flat moat, partially occupied by dense algae separates the outer and the inner reef flat in the northern part. The southern part of this reef is dominated by sandy substrate and both outer and inner reef flat together culminates into a sanded reef flat. Presence of associated habitats of beach and mangroves (near Fagal) is noticed in the southern part of this reef. In the coastal segment between Khor Anghar and Ras el Bir (Map: 6.2.1.2), the coastal fringing reef shows similar geomorphological zonation. Here too, the reef flat can be distinguished between outer and inner reef flats throughout its length. Reef flat moats are detected in northern and southern part of this reef. The narrow, linear feature of moat in the south is more prominent compared to the northern one on the satellite image. Mangroves occur in discontinuous patches near Khor Anghar and to the north of Ras el Bir. The off-shore fringing reefs of Sept Frères could only be detected with AWiFS data dated 12th October, 2008, however, their mapping demands very high resolution data.

Coastal fringing reefs occur in patches near Obock on the Djibouti coast and off-shore platform reefs are found surrounding the islands of Maskali and Musha just at the entrance of Gulf of Aden (Maps: 6.2.1.3, 6.2.1.3A). In case of the coastal fringing reef near Obock, reef edge, reef slope and reef flat classes could get detected from AWiFS data. The off-shore platform reef surrounding Maskali, Musha and Island Du Large appear in a rectangular shape with crenulated reef boundary. In this case, the coral reef features have been interpreted using two AWiFS images, dated 12th November, 2007 and 12th October, 2008 for considering the reef features under different levels of exposure and cloud cover. In the northern side of this reef, geomorphological sub-zones of reef edge, reef slope and reef crest could get detected while in the southern part these sub-zones appear in a submerged condition. The reef flat could be distinguished into outer and inner reef flat. In between, Musha Island and Island Du Large, part of the reef flat has turned into sanded reef flat. A moat exists to the north of Musha Island while oceanic pools are found in the eastern side of the reef. Four distinct coral pinnacles are found to the south of this platform structure; however their levels of exposure vary when compared between the images. This platform reef structure has actually developed on a vast fossil reef plateau where corals grow from 1 to 45 m depth (Kotb *et al.* 2008). However, relatively high turbidity limits coral growth to 15 to 25m depth. Musha and Maskali Islands have been reported to have coral cover ranging between 5% and 35.6% (Kotb *et al.* 2008) with several sites off Maskali Islands found in deteriorating condition during the surveys carried out since 2000 (Kotb *et al.* 2004).

Discontinuous, narrow fringing reefs occur on the Djibouti coast near Ras Duan and Ras Ali (Map: 6.2.1.4) in the northern coast of Gulf of Tadjoura and near the narrow constriction between Gulf of Tadjoura and Ghoubet al- Kharab (Map: 6.2.1.5). Geomorphological zone of reef flat and geomorphological sub-zones of reef edge and reef slope could only get detected with AWiFS data for these reefs. Pocket beaches are found bordering the cliffy coastline in the southern coast of Ghoubet al- Kharab. High resolution data is required for detailed habitat mapping of these reefs of Djibouti coast.

Continuous, coastal fringing reefs again appear in the southern coast of Djibouti near Doba Libah and continue upto the border of Somalia (Maps: 6.2.1.6, 6.2.1.7). The reef widens to the west of Djibouti city, where the reef flat can be distinctly divided into outer and inner reef flats. The inner reef flat shows an influx of terrestrial sediments from the associated zone of mangrove habitats. Reef edge and reef slope categories have been detected. Two small, off-shore patch reefs and four coral pinnacles are located to the west and north-west of Djibouti city. In the north, near Rf du Héron, portion of the reef remains submerged. To the east of the Djibouti city (Map 6.2.1.7), the fringing reef runs parallel to the coastline upto Somalia border, near Loyado and shows the influence of associated habitat of sub-tidal mudflat. The reef flat, especially the inner reef flat appears muddy. Off-shore patch reefs and coral pinnacles have been detected and delineated.

The frequency of the classes/categories detected for the coral reefs of northern coast of Somalia are represented in Figure 6.2.1.1.

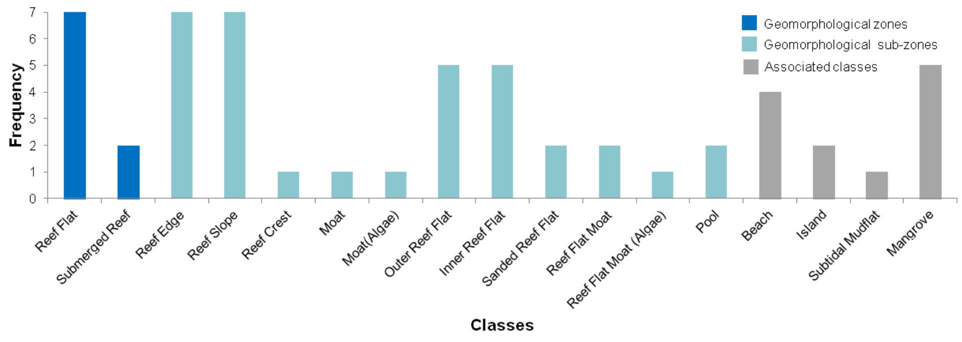


Figure 6.2.1.1 Frequency of classes detected for coral reef habitats of northern coast of Djibouti

Areal Extent of Coral Reefs of Djibouti

The coral reef habitats of Djibouti coast as mapped from AWiFS data cover a total area of 198.93 sq km. Reef area corresponding to each habitat map is summarized in Table No. 6.2.1.1. The coastal fringing reef habitat to the north of Fagal occupies the highest reef area of 56.10 sq km while the fringing reefs near Ras Ali and Ras Duan occupy the minimum area of 5.79 sq km.

Table 6.2.1.1 Areal Extent of coral reefs of Djibouti

Map No.	Location	Reef Area (sq km)
6.2.1.1	Coral reef habitats to the north of Fagal	56.10
6.2.1.2	Coastal coral reef habitats from Khor-Anghar to Ras el Bir and off-shore islands of Sept Frères	47.46
6.2.1.3	Coral reef habitats near Obock and off-shore islands of Maskali and Musha	51.02
6.2.1.4	Coral reef habitats of Ras Ali and Ras Duan	5.79
6.2.1.5	Coral reef habitats of Ghoubet al Kharab and surroundings	8.59
6.2.1.6	Coral reef habitats of Djibouti City and surroundings	20.02
6.2.1.7	Coral reef habitats of Loyado and surroundings	9.95
	Total Area	**198.93**

Summary

Coral reef habitats of Djibouti mainly comprise of coastal fringing and off-shore platform reefs. Fringing, patch and coral pinnacles also occur in off-shore settings at Sept Frères, off Djibouti city and near Maskali and Musha islands respectively. Significant intra-reef geomorphic details can be delineated for the coastal fringing reefs of north and the southern parts of Djibouti coastline and the off-shore platform reefs. However, detailed mapping of the coastal fringing reefs near Obock, near Ras Ali and Ras Duan, in Ghoubet al- Kharab and near Doba Libah and off-shore fringing reefs of Sept Frères need high (spatial) resolution data. Presence of moat, reef flat moat and pools is a characteristic feature of Djibouti reefs. Coral reef habitats of the northern Djibouti coast appear in good health condition as compared to the coral reefs of the southern coast which bears signs of influx of terrestrial sediments from the adjacent mudflats and mangrove areas. The coral reefs vary in status, from very poor to good, with coral cover, often well over 50% and upto 90% in the best areas (Kotb *et al.* 2004). At certain places the reef flats are covered with rubbles from the eroding table corals and are completely covered with algae. This kind of habitat loss is primarily due to the combination of coral bleaching and COTS predation events (Kotb *et al.* 2004). Djibouti's coral reefs face anthropogenic threats from domestic tourism, sewage discharges, shipping and associated spills and pollution, with maximum pressure near the capital city of Djibouti (Kotb *et al.* 2008). Shipping is an important commercial sector as Djibouti is the major harbour for Ethiopia. Coral reef areas around Djibouti port is understood to be heavily degraded (Spalding *et al.* 2001). Coral reef habitats of Maskali and Musha enjoy MPA status under Integral Park/Reserve and Territorial Park designations respectively (Spalding *et al.* 2001; Kotb *et al.* 2004). They were included in the list of first MPAs declared in the Red Sea and Gulf of Aden in the early 1970s. PERSGA has recommended protection and management plans for Sept Frères/Ras Siyyan and Godoria in 2004 (Kotb *et al.* 2004). The coral reef habitats of Djibouti coast as mapped with 2007-08 AWiFS data cover a total area of 198.93 sq km. Coral reef habitats Djibouti's northern coast appear in *near-pristine* condition while the reefs of the southern coast and off-shore reefs of Maskali and Musha islands appear in a *degrading* condition.

Guide to Index Map

(Map numbering scheme :
6 represents section : **Results**
6.2 represents Results > under **Basin 2. Gulf of Aden**
6.2.1 represents Results > under Basin 2. Gulf of Aden > for **Country 1. Djibouti**
6.2.1.1 represents **Coral Reef Habitat Map** of **Djibouti coast.)**

Numbers of the location boxes correspond to the map numbers with names of the reefs in ascending order.

The Coral Reef Habitat Maps are given subsequently as below :

1. North of Fagal
2. Khor-Anghar to Ras el Bir and offshore Islands of Sept Frères
3. Obock and offshore Islands of Maskali and Musha
4. Ras Ali and Ras Duan
5. Ghoubet Kharab and surroundings
6. Djibouti city and surroundings (southern Golfe de Tadjoura)
7. Loyado and surroundings

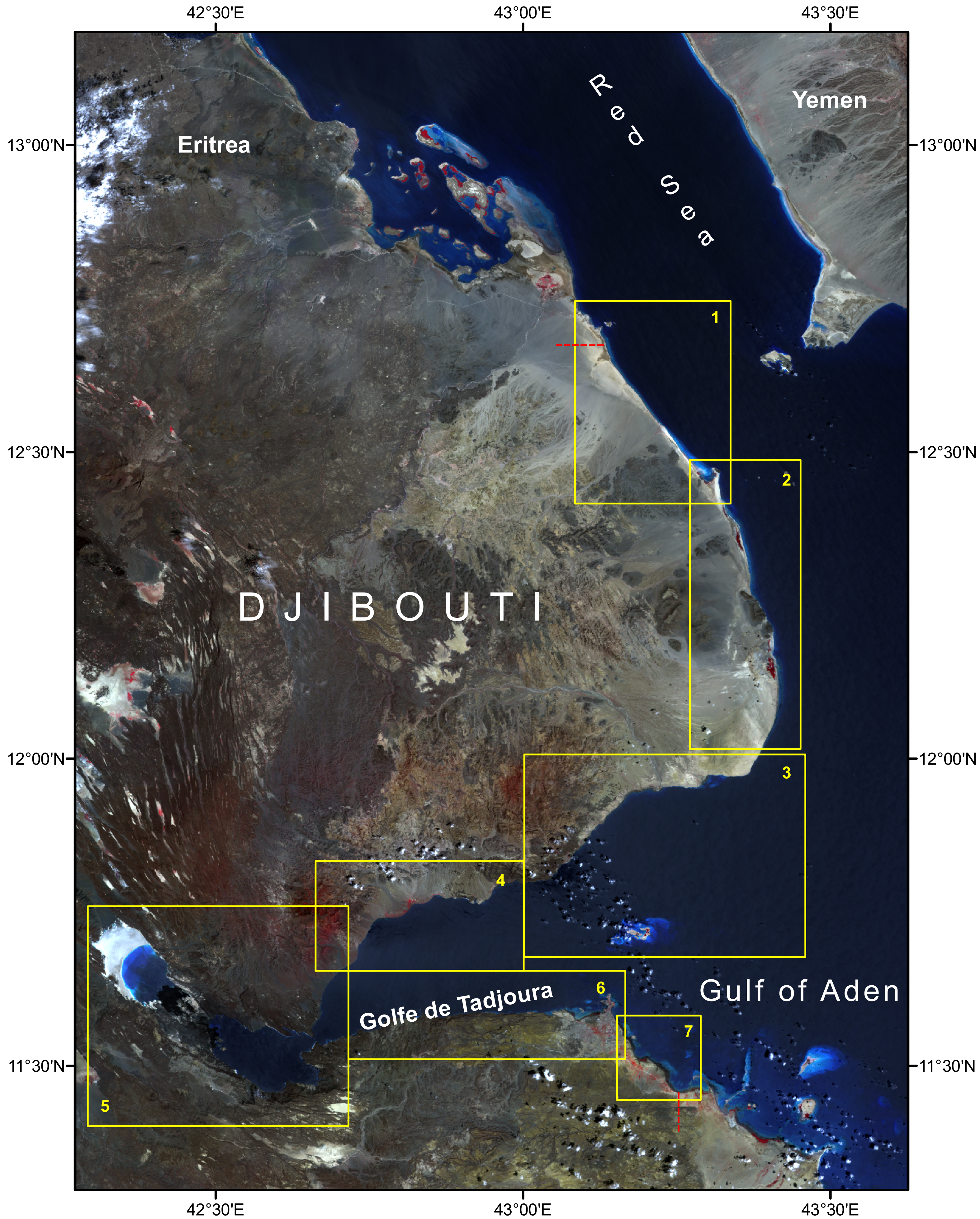
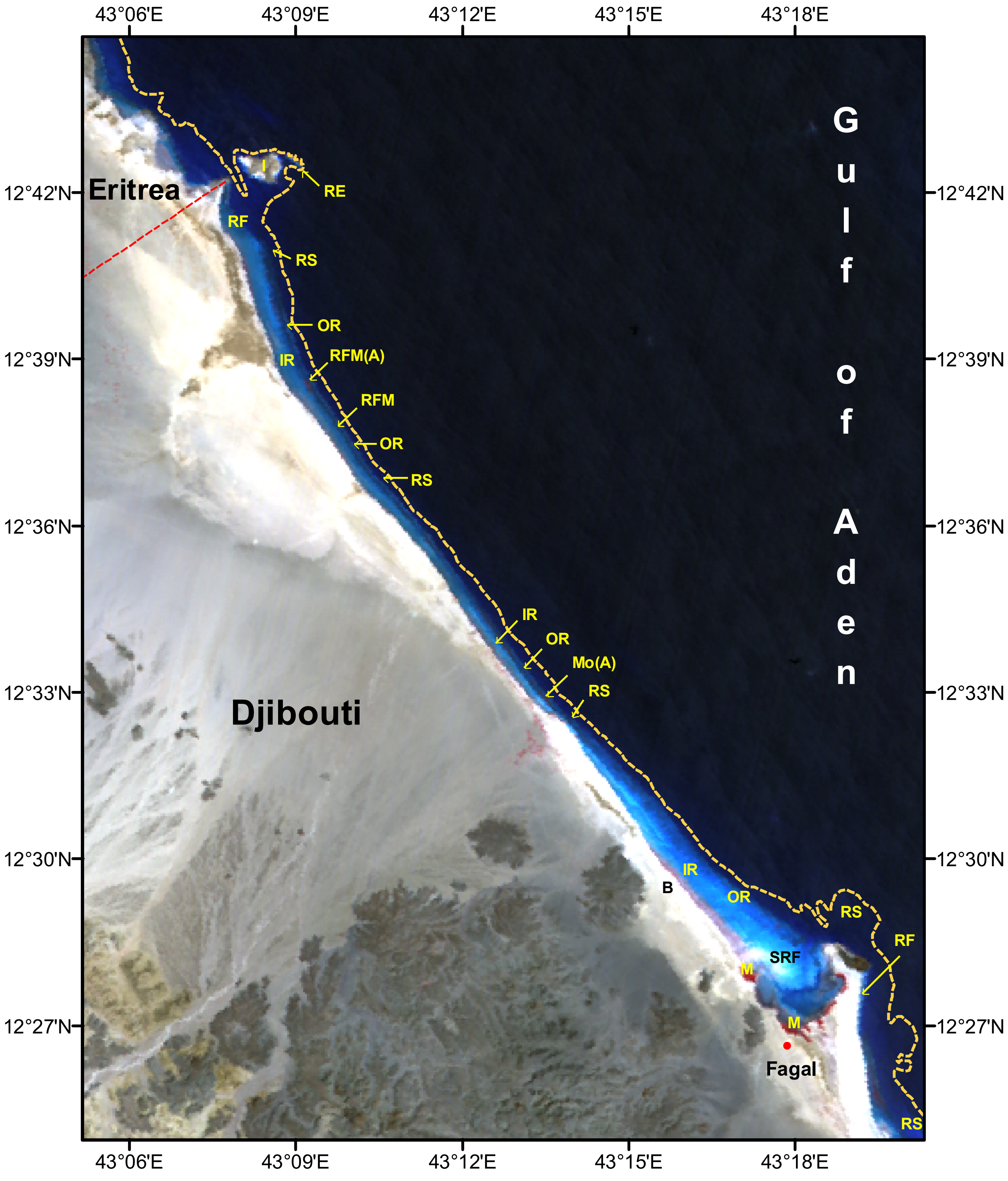


Figure 6.2.1 Index to coral reef habitat maps of Djibouti

--- International boundary

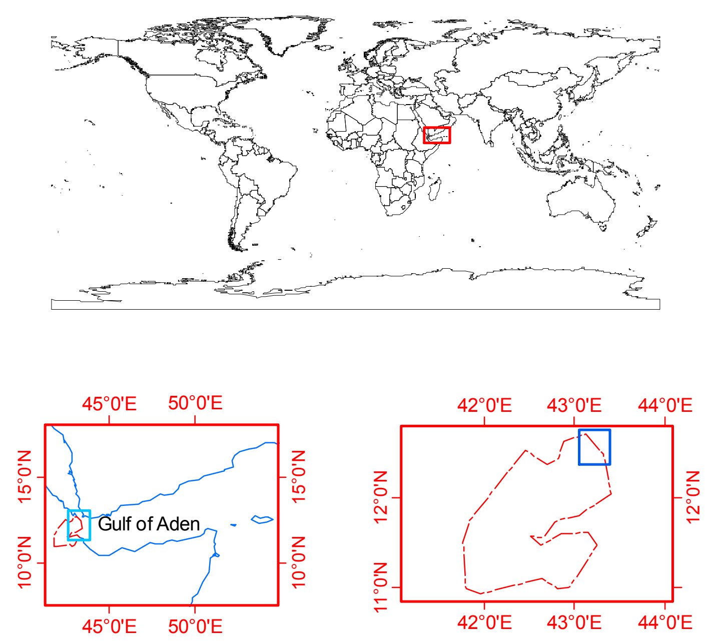
Source: Resourcesat-1 AWiFS mosaic from data dated: 12th October, 2008



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat (Algae)	:	Mo(A)
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Muddy Reef Flat	:	MR
Reef Flat Moat	:	RFM
Reef Flat Moat (Algae)	:	RFM(A)
Beach	:	B
Island	:	I
Mangrove	:	M

Fringing Reef



Source : RESOURCESAT-1 AWiFS Data
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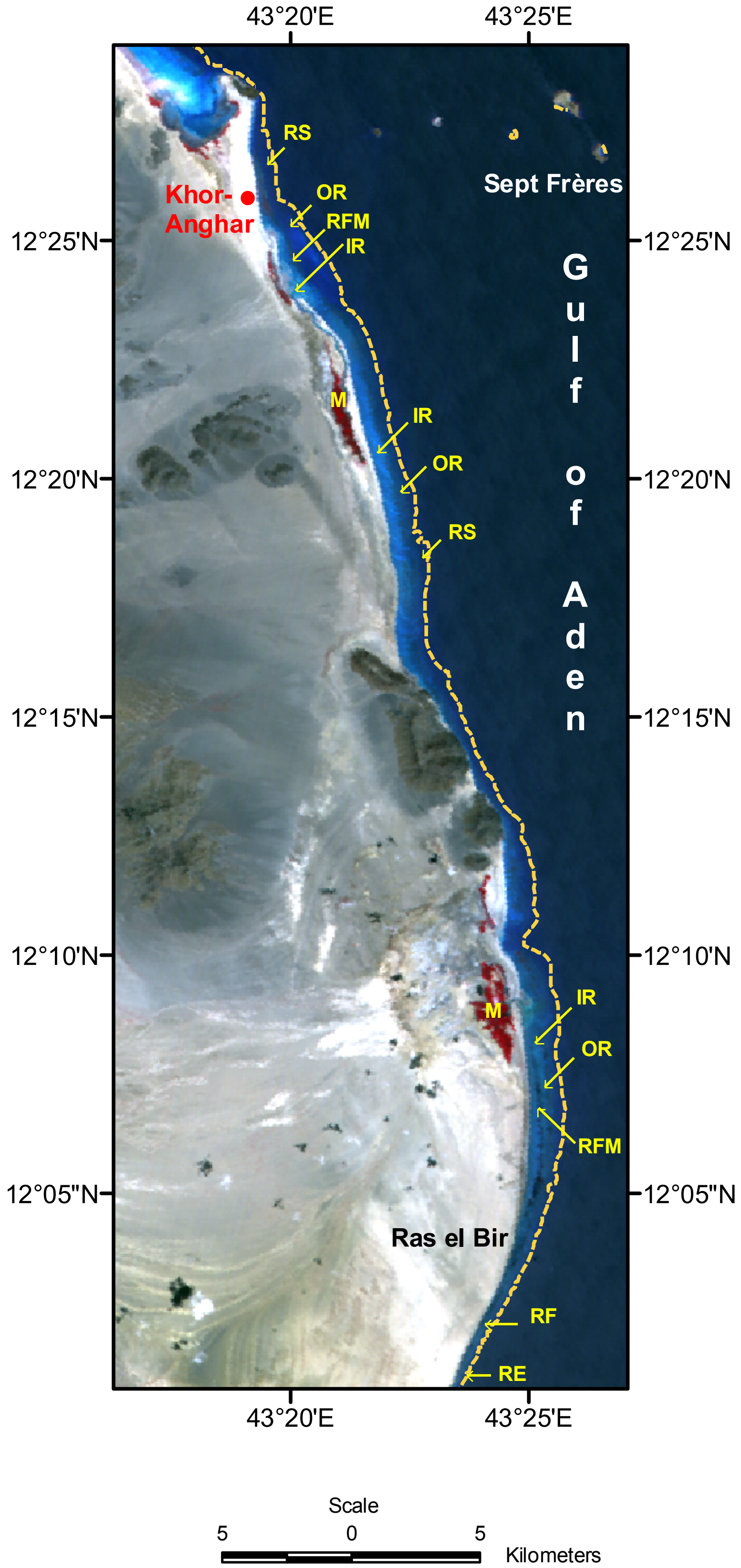
CORAL REEFS OF THE MIDDLE EASTERN SEAS

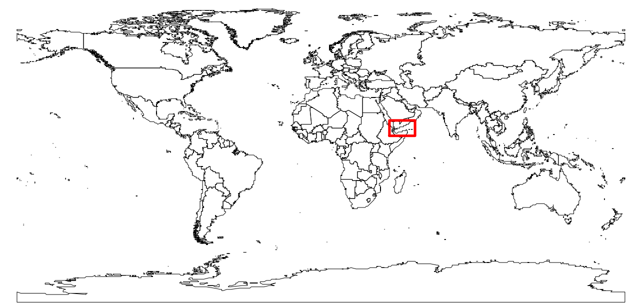
Map 6.2.1.1 : Coral reef habitats to the north of Fagal

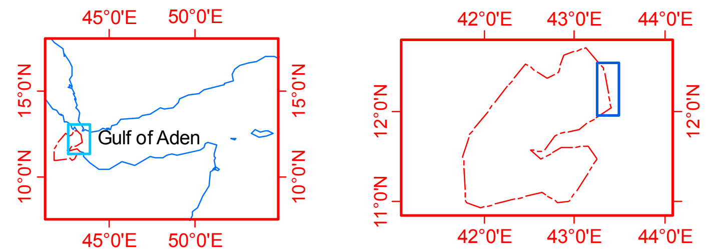


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Reef Flat Moat	:	RFM
Mangrove	:	M

Fringing Reef





Source : RESOURCESAT-1 AWiFS Data
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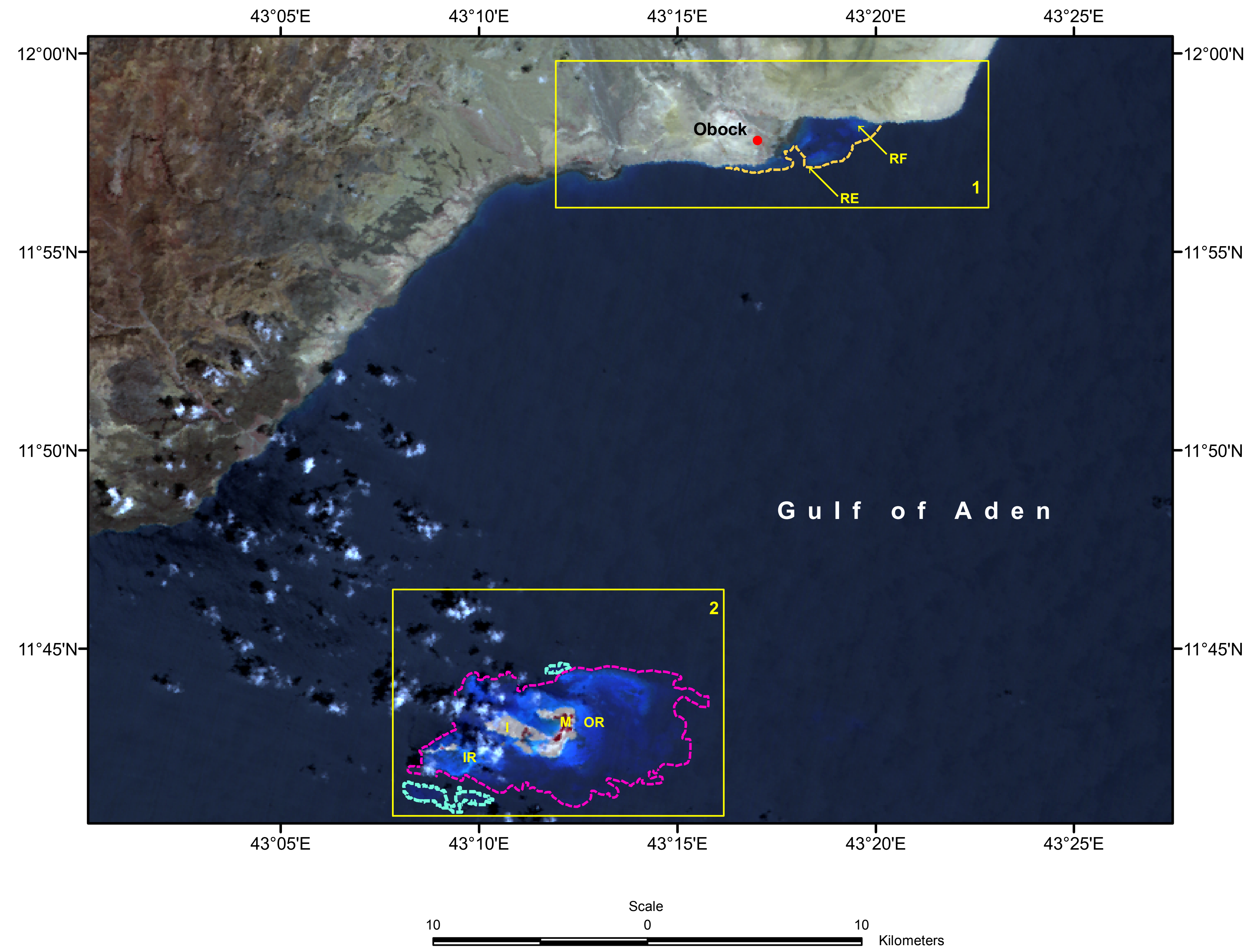
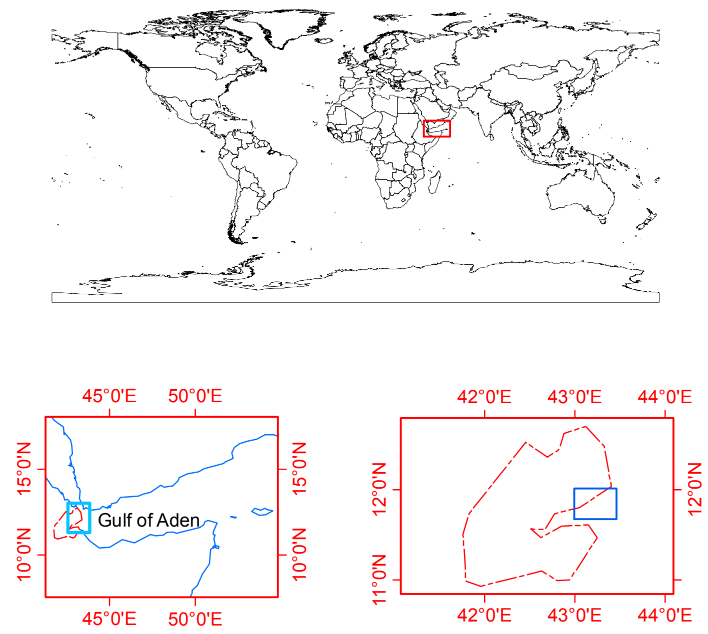
Map 6.2.1.2 : Coastal coral reef habitats from Khor-Anghar to Ras el Bir and offshore Islands of Sept Frères



Legend

Reef Edge	:	RE
Reef Slope	:	RS
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Island	:	I
Mangrove	:	M

Fringing Reef
Platform Reef
Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data Dated 12th October, 2008 & 12th November, 2007

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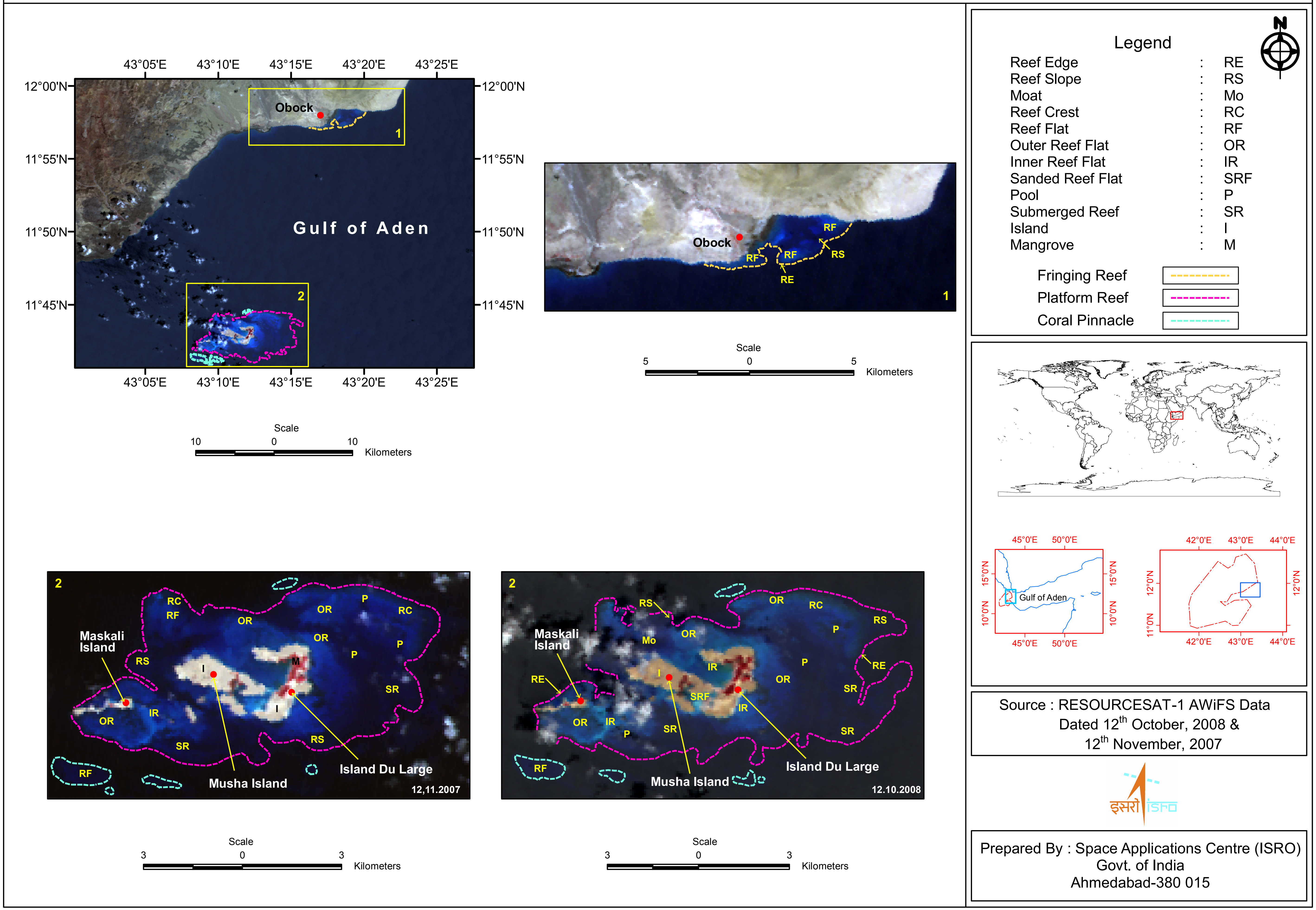
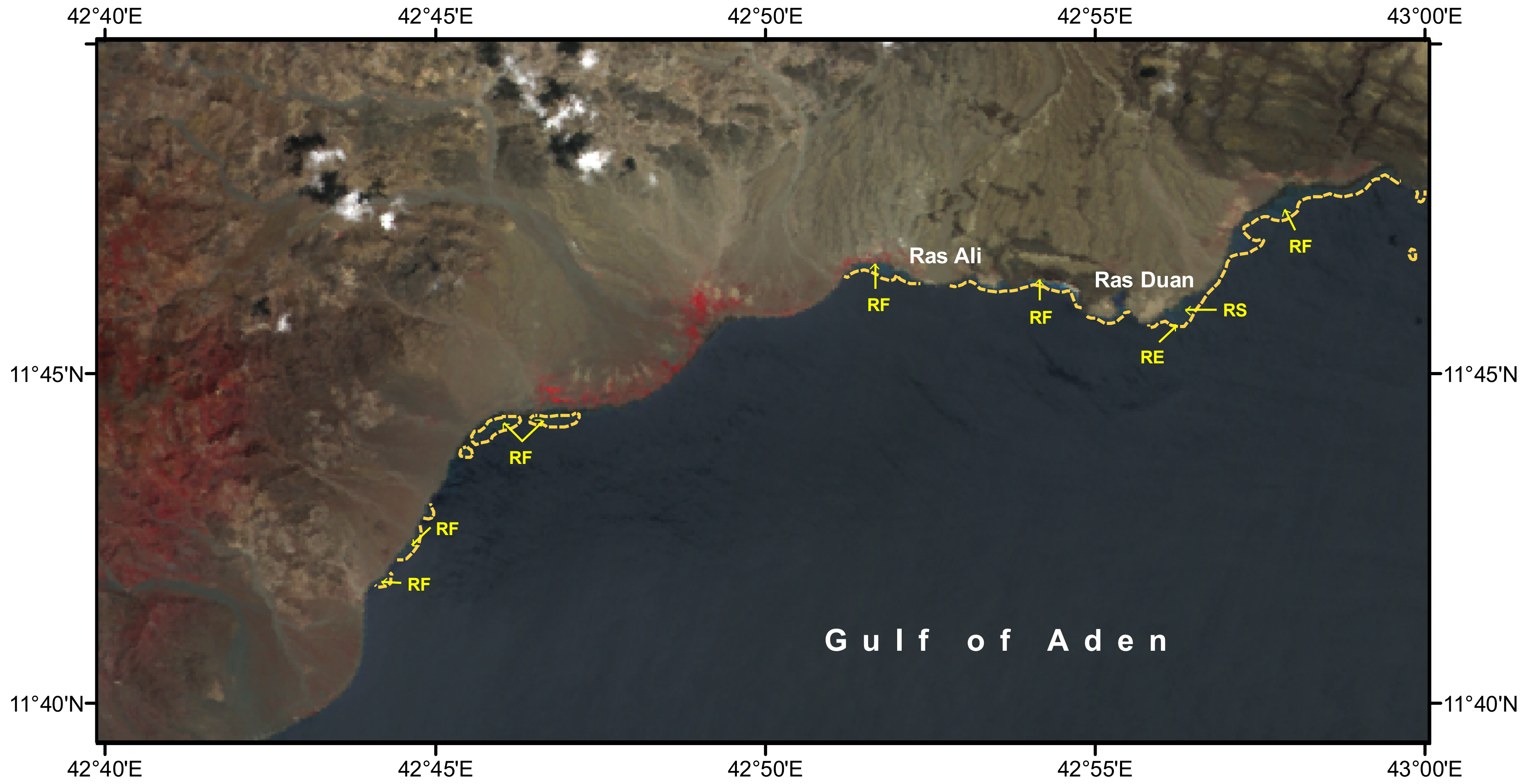
Map 6.2.1.3 : Coral reef habitats near Obock and offshore Islands of Maskali and Musha



Map 6.2.1.3A : Coral reef habitats near Obock and offshore Islands of Maskali and Musha

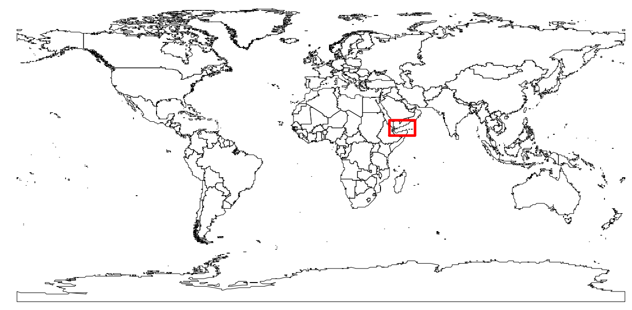


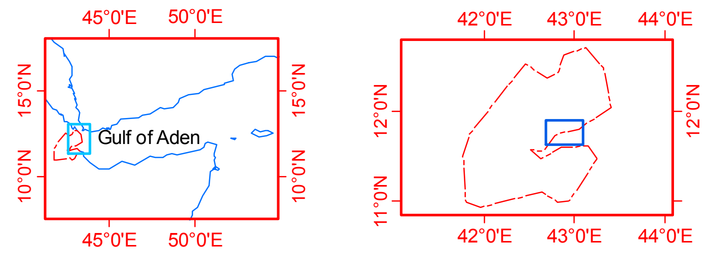
Legend

N

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF

Fringing Reef





Source : RESOURCESAT-1 AWiFS Data
Dated 12th October, 2008

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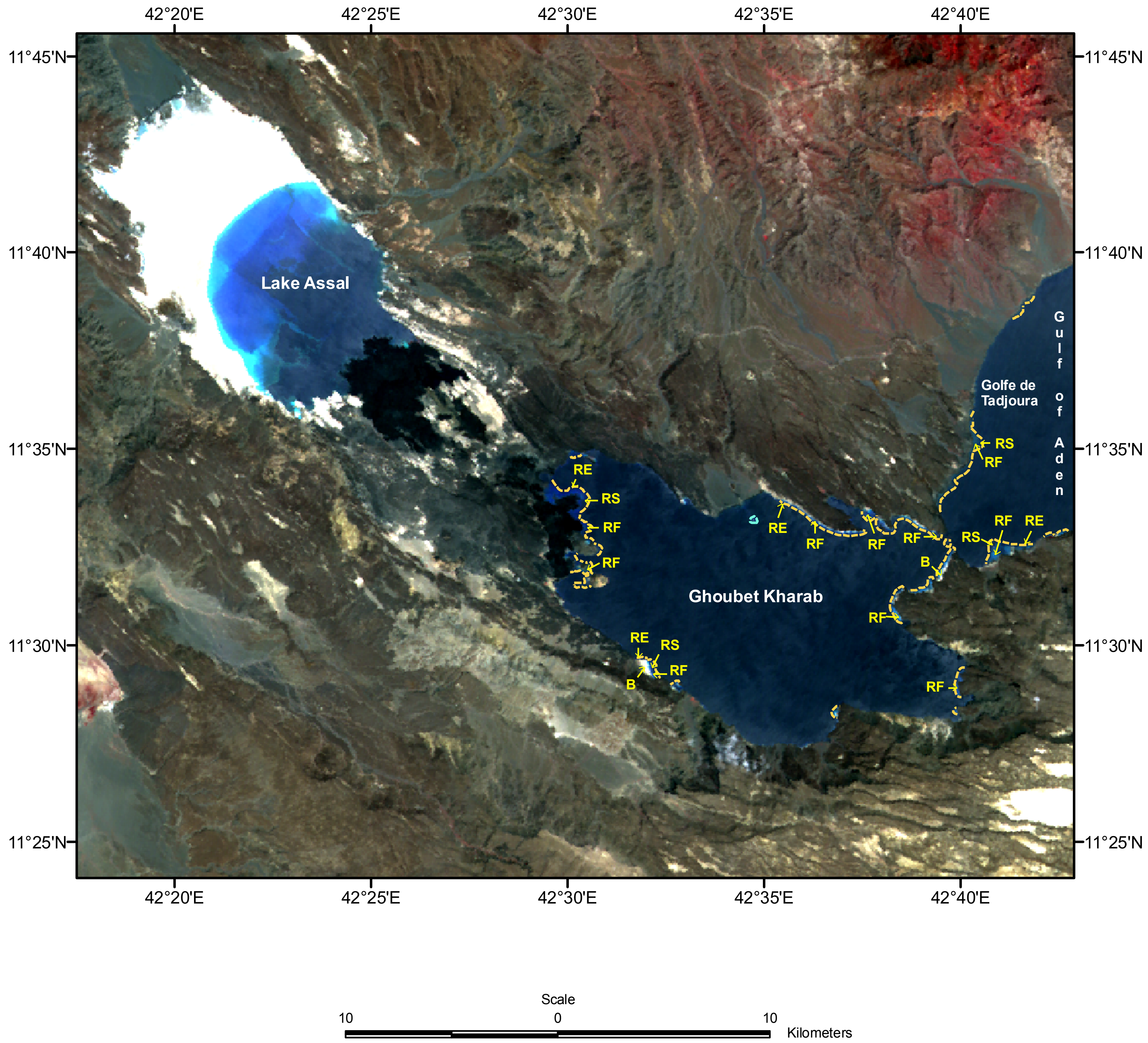
Map 6.2.1.4 : Coral reef habitats near Ras Ali and Ras Duan

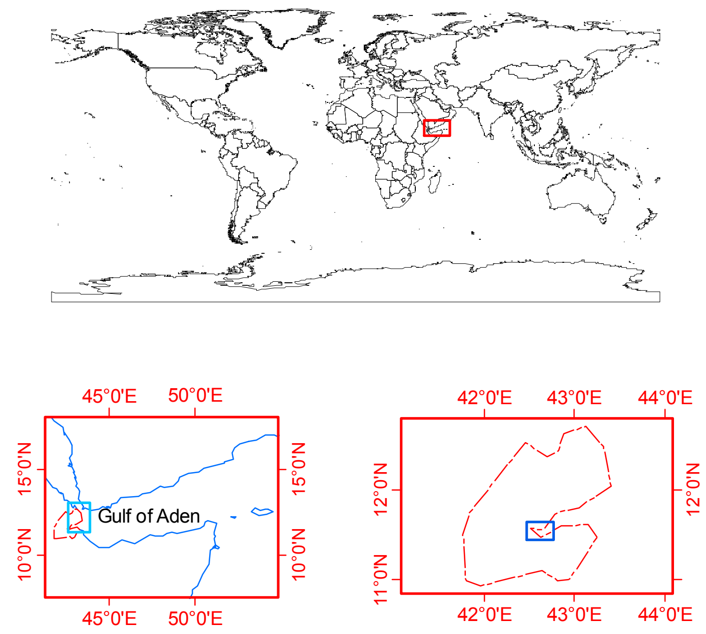


Legend

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF
Beach : B

Fringing Reef

Coral Pinnacle



Source : RESOURCESAT-1 AWiFS Data
Dated 12th October, 2008

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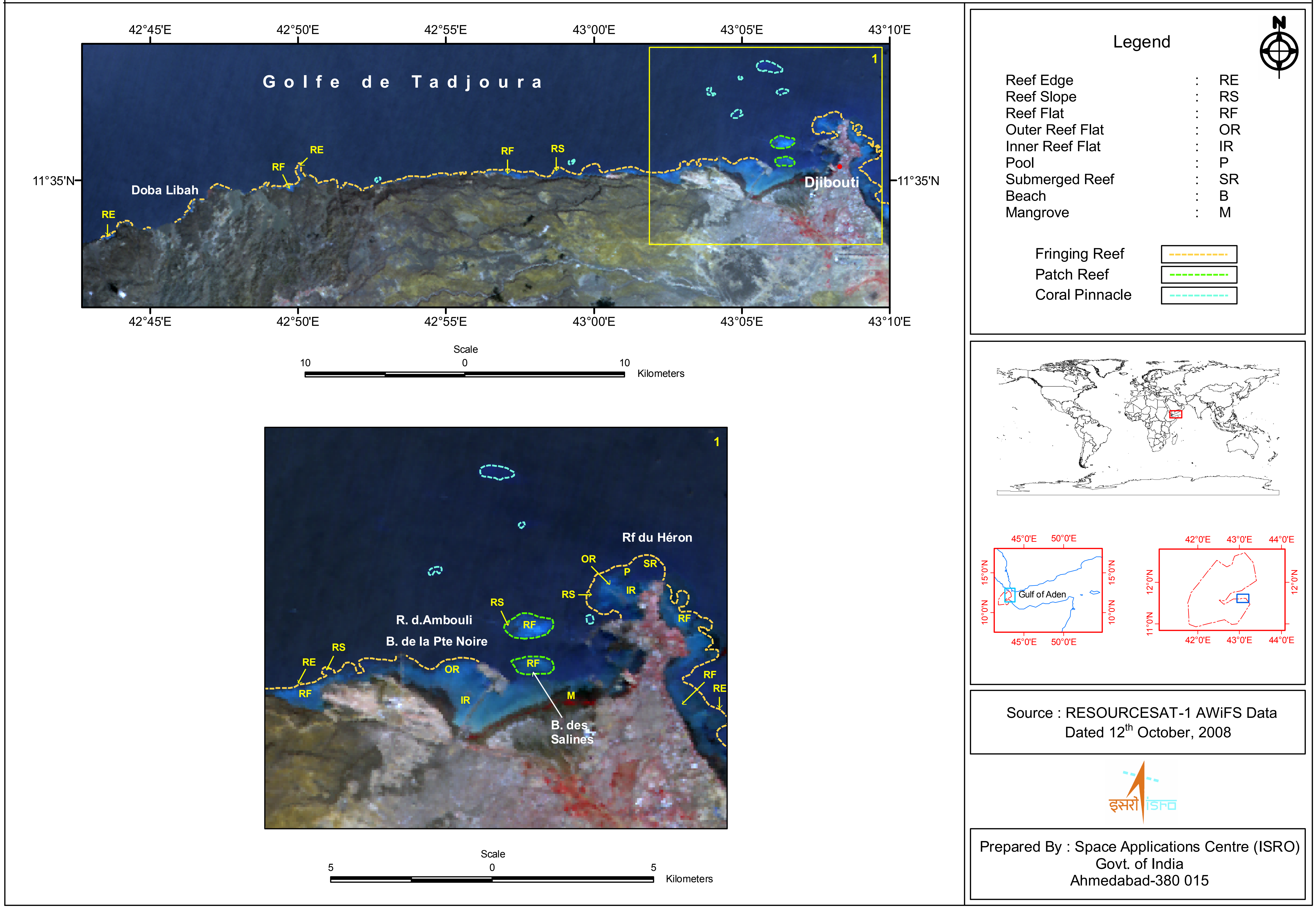
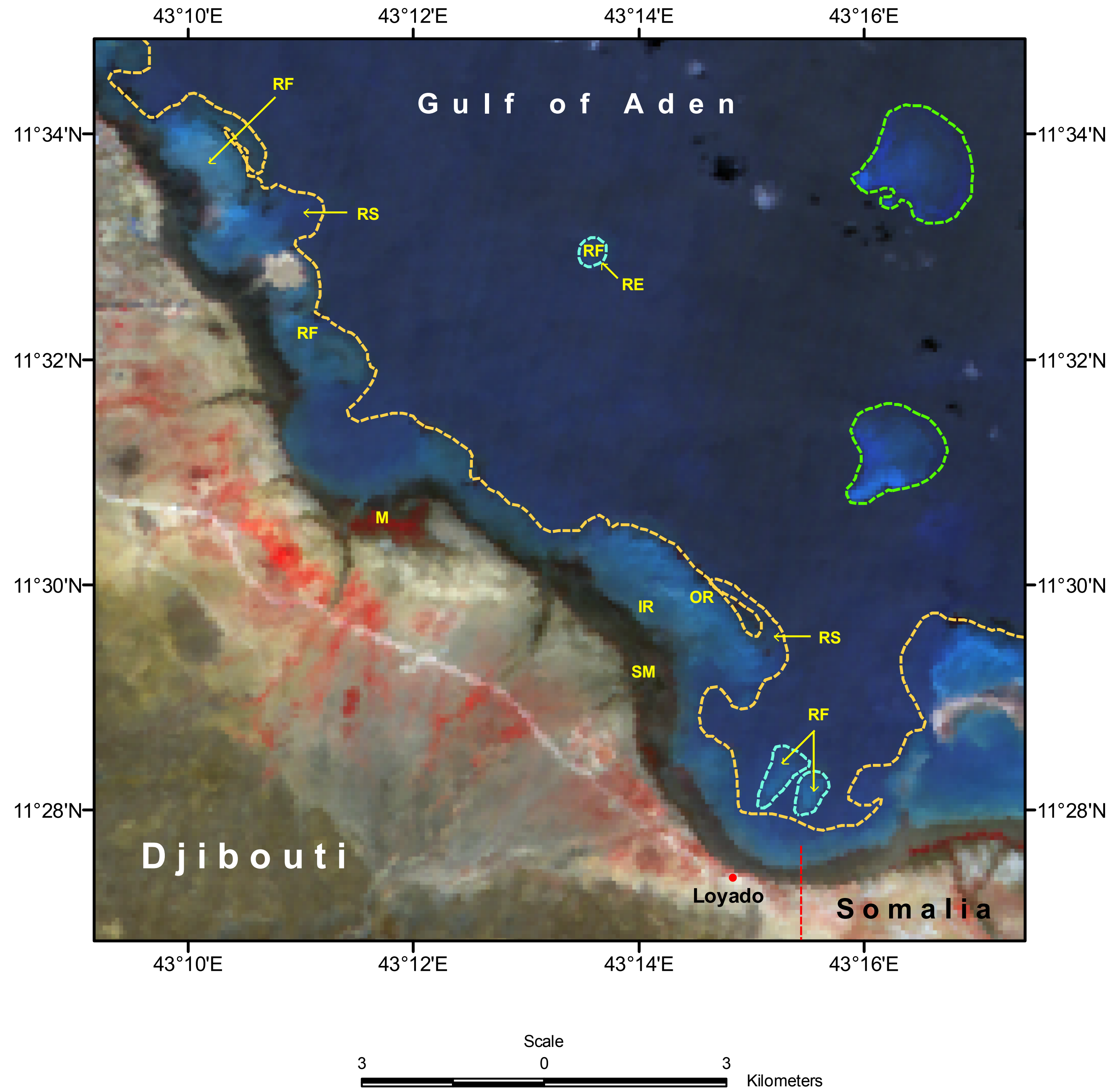
Map 6.2.1.5 : Coral reef habitats of Ghoubet Kharab and surroundings



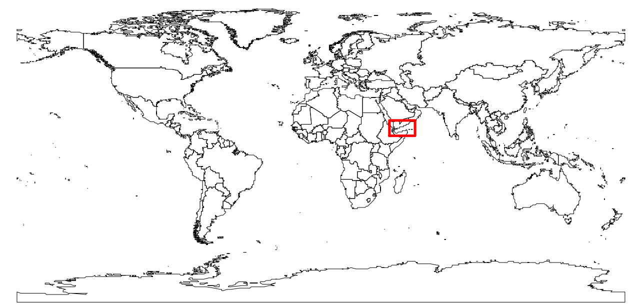
Map 6.2.1.6 : Coral reef habitats of Djibouti city and surroundings (southern Golfe de Tadjoura)

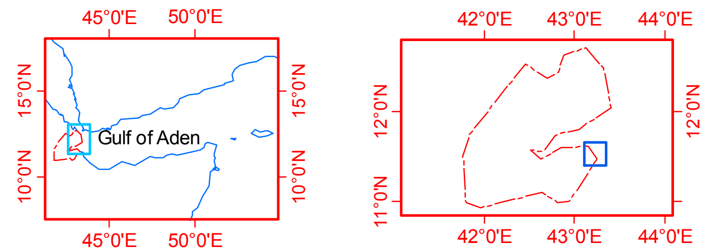


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Beach	:	B
Subtidal Mudflat	:	SM
Mangrove	:	M

Fringing Reef
Patch Reef
Coral Pinnacle





Source : RESOURCESAT-1 AWiFS Data
Dated 12th October, 2008

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Map 6.2.1.7 : Coral reef habitats of Loyado and surroundings

6.2.2. Somalia

Background

Somalia's 3300 km long coastline is naturally divided into north and south sectors. The northern coast of Somalia occurs within the geographical limits of 11°28' - 11°49'N latitudes and 43°15'- 51°16'E longitudes and forms the southern boundary of Gulf of Aden with a length of 1300 km. This coastline shares the border of Djibouti to its west and extends upto Ras Caseyr in the east. Northern coast of Somalia is generally characterized with shallow, sandy areas with exposures of high-energy, sandy beaches and few seagrass beds (Kotb *et al.* 2004, 2008). The central portion of this coastline consists of shallow sandy shores with occasional rocky outcrops and cliffs extending into the sea as rocky promontories. Reef development is sporadic in this coast as coral growth is limited due to non-availability of suitable bottom substrate and hydrographic conditions. A seasonal upwelling in the Gulf of Aden is known to encourage macro-algal growth on most of the hard substrates of northern Somalia coast (Kotb *et al.* 2004). However, there are few true reefs and some extensive areas of coral-dominated communities in this coast.

The best developed reefs of northern Somalia coast are the fringing, platform and patch reef structures near Saad ed Din and other islands close to Djibouti border in the west (Figure 6.2.2). Coral species diversity is comparatively low and few areas are known to be covered with monospecific stands of Acropora, sometimes with live coral cover of 80% (Spalding *et al.* 2001; Kotb *et al.* 2008). Seventy-four scleractinian coral species have so far been reported from this coast (Schleyer and Baldwin 1999; Spalding *et al.* 2001). Towards little east, there are limited coral reefs near Ras Khansir, Ras Cuuda and Siyara, off El Girdi and to the west of Berbera. These reefs have mostly grown on shallow, fossilized beach rocks at a depth of 1 to 10 m. The coral communities in these reefs considerably vary with respect to their health conditions as all have been affected by periodic coral bleaching events (Kotb *et al.* 2008). The shallow reefs to the east of Berbera suffered extensive mortality due to the 1997-98 bleaching event (Kotb *et al.* 2008; Spalding *et al.* 2001) and were reported to be encrusted and accreted by coralline algae (Schleyer and Baldwin 1999). The deeper reefs at 2 to 5 m depth are known to be in better condition (Kotb *et al.* 2008).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of northern coast of Somalia have been mapped with Resourcesat-1 AWiFS data (3 scenes; dated: 12th November, 2007, 31st August, 2008 and 12th October, 2008). Detailed habitat characteristics of these reefs are depicted in five habitat maps (Maps: 6.2.2.1 to 6.2.2.5). Fringing reef structures along with its all sub-variants (Platform, Patch and Pinnacle types) are detected in northern Somalia. The major reef structures of this coast occur within the geographical limits of 11°00' to 11°33'N latitudes and 43°15' to 43°40'E longitudes. This part of the northern Somalia coast is characterized with coastal fringing reefs occurring in the west (near Djibouti border), off-shore platform and patch reefs in the central portion and off-shore patch reef structures in the east.

The coastal fringing reefs in the west (to the east of Loyado near Djibouti border) occurs along with two off-shore patch and three offshore pinnacle reefs as detected in the AWiFS data dated 12th November, 2007 and 12th October, 2008 (Maps: 6.2.2.1, 6.2.2.2). In the seaward side, geomorphological sub-zones of reef edge and reef slope could be detected in these reefs. The broad reef flat area could be differentiated into outer and inner reef flats. The inner reef flat gradually culminates into the sub-tidal mudflat lined with mangrove vegetation on the coast in the western side. In the central portion, where the coastline is free of mangrove vegetation, the reef extends into the sea in a shore-perpendicular fashion (Map 6.2.2.2). A well-defined reef crest with a top substrate of sand can be demarcated onto the western side of this shore-perpendicular, linear reef. Towards the east, the reef exposure is irregular and hence crenulated. Partial exposures of reef edge and reef slopes could be found in the northern side. The width of the reef-flat varies from north to south. Towards the south, the reef flat widens and hence could be differentiated into outer and inner reef flats. These coastal fringing reefs show a hooked-spit formation on its western side and four, small sandy islands in its eastern part. The off-shore patch reefs and coral pinnacles along with some parts of these coastal fringing reefs appear in submerged condition during the imaging time.

In the central portion, there are large off-shore platform and patch reef structures while the coast is free of any coral reef habitats (Maps: 6.2.2.3, 6.2.2.4). Coastal fringing reefs again reappear in the coast near Saylac (Map: 6.2.2.3). The off-shore platform reef (Map: 6.2.2.3; subset: 1) appearing in a near-circular shape fringes the central island with an area of 15.68 sq km. The reef flat is wider in the western side as compared to the east and narrows down in the north. Well-defined geomorphic zones could be identified. Reef edge and reef slope could be detected. The reef flat could be differentiated into outer and inner reef flat. In the western and southern part, presence of sanded reef flats is noticed. These sanded reef flats appear to resemble the shape of hooked-spits in plan-view. In the eastern side, a moat separates the reef flat from the reef slope region. The inner reef flat region is indicative of sediment loading in the western and the southern side. The coastal fringing reef near Saylac extends into the sea in a shore-perpendicular fashion with a broad reef flat towards the sea (Map: 6.2.2.3; subset: 2). The reef flat becomes narrow close to the coast. Reef edge and reef slope could be detected for this reef. The reef flat could be differentiated into outer and inner reef flats. Formation of a hooked-spit in the inner reef flat is noticed here also.

The reef around Saad ed Din Island is the largest off-shore platform reef structure in northern Somalia coast with an area of 32.47 sq km (Map: 6.2.2.4). This platform reef appears in the shape of a Japanese fan in plan-view from space. The small, narrow island is situated in the south-eastern corner of the reef. The coral reef habitat of Saad ed Din Island has been mapped with two individual subsets extracted from AWiFS data dated 12th November, 2007 and 12th October, 2008. The latter appears to have captured the reef with a better natural exposure of the reef enabling a better delineation of the reef, more precisely the outer rim feature in the north. The satellite data captures the linear reef crest feature in partial continuity in the north and the eastern side. One moat located to the east differentiate the outer rim area from the reef crest while another sizable moat located in the north separates the reef crest from the extended reef flat area. There is a distinct gradation between the outer and inner reef flat; the outer reef flat appears at a higher depth as compared to inner reef flat. The boundary of inner reef flat runs parallel to that of the island boundary. Close to the eastern side of the island, sanded reef flat is detected in both the subsets. However, prominent signature of dune vegetation on the sanded reef flat appears only in 12th October, 2008 image. A coral pinnacle is detected to the west of this reef. This reef is known to support diverse coral and reef associate communities. Sixty nine species of scleractinian corals, 11 species of alcyonacean corals and 2 fire corals were recorded along with many large fishes in reef surveys carried out in 2002 (Kotb *et al.* 2008). This area is reported to be productive and relatively pristine barring the effects of periodic coral bleaching and COTS predation (Kotb *et al.* 2008).

Two off-shore patch reefs are detected on the northern Somalia coast to the south of Saylac (Map: 6.2.2.4). However, the spatial resolution of AWiFS data proves to be coarse to bring out significant intra-reef details of these patch reefs.

The frequency of the classes/categories detected for the coral reefs of northern coast of Somalia are represented in Figure 6.2.2.1. Geomorphological zones like reef flat, geomorphological sub-zones like reef edge, reef slope, outer and inner reef flats appear to be commonly detected classes. Geomorphological sub-zones: outer rim and sand patches along with benthic zone class of dune vegetation have been detected only once. Relatively high association of subtidal mudflats, mangrove vegetation and islands is noticed for the coral reef habitats of northern Somalia.

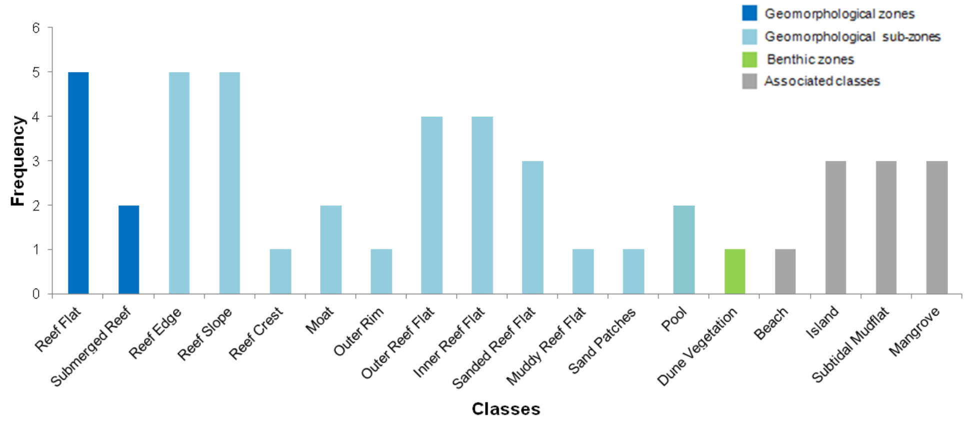


Figure 6.2.2.1 Frequency of classes detected for coral reef habitats of northern coast of Somalia

Areal Extent of Coral Reefs of northern coast of Somalia

The coral reef habitats of northern Somalia coast as mapped from AWiFS data cover a total area of 145.12 sq km. Reef area corresponding to each habitat map is summarized in Table No. 6.2.2.1. The total extent of coral reef area in northern Somalia coast is 145.12 sq km. Coral reef habitats to the west of Saad ed Din Island occupies the highest reef area of 47.26 sq km while the off-shore coral reefs to the south of Saylac occupies the minimum area of 3.60 sq km.

Table 6.2.2.1 Areal Extent of coral reefs in northern coast of Somalia

Map No.	Location	Reef Area (sq km)
6.2.2.1	Coral reef habitats near Loyado	18.59
6.2.2.2	Coral reef habitats to the west of Saad ed Din Island	47.26
6.2.2.3	Off-shore and coastal coral reef habitats of Saylac and surroundings	42.96
6.2.2.4	Coral reef habitat of Saad ed Din	32.71
6.2.2.5	Off-shore coral reef habitats to the south of Saylac	3.60
	Total Area	**145.12**

Summary

Coral reef habitats in the northern coast of Somalia are primarily coastal fringing and off-shore platform and patch reefs. Four coral pinnacles also could be detected and mapped. Significant intra-reef geomorphic details can be delineated for the coastal fringing and off-shore platform reefs. However, detailed mapping of off-shore patch reefs and coral pinnacles of Somalia coast needs high (spatial) resolution data. Formation of hooked-spits in the inner reef flat area is noticed in both coastal fringing and off-shore platform reefs. The coral reef region in the northern coast of Somalia is known to be pristine and productive apart from the natural effects of bleaching and COTS predation (Pilcher and Alsuhaibany 2000). Pressure on coastal resources is relatively low in this coast due to sparse human population (Spalding *et al.* 2001; Kotb *et al.* 2008). Uncontrolled fisheries and international shipping traffic in Gulf of Aden are considered as main anthropogenic threats (Kotb *et al.* 2004) to these coral reef habitats. Saad ed Din, Saba Wanak and Aibat Islands have been surveyed by the Regional Organization for the Conservation of the Environment of the Red Sea & Gulf of Aden (PERSGA) and have been declared as Somalia's first Marine Protected Area (MPA) in 2003 (Kotb *et al.* 2004). The coral reef habitats mapped with 2007-08 AWiFS data cover a total area of 145.12 sq km and appear in *near-pristine* condition.

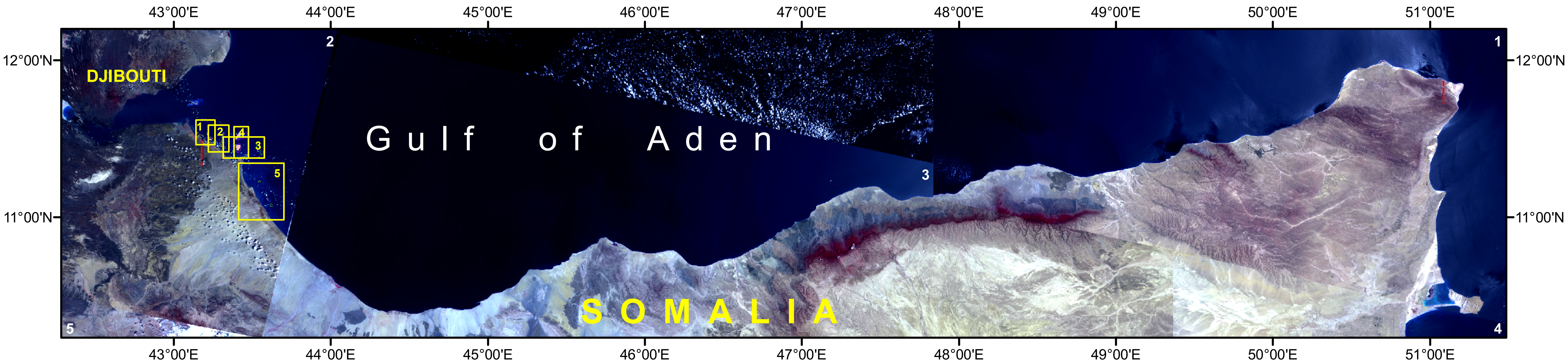
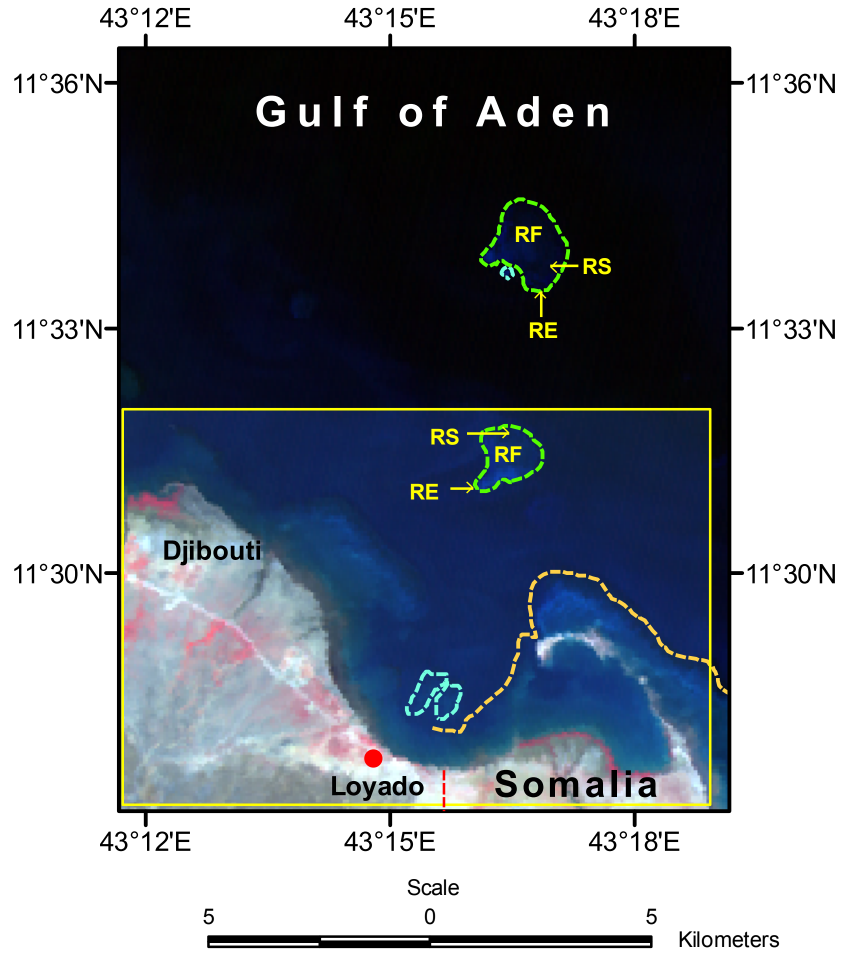
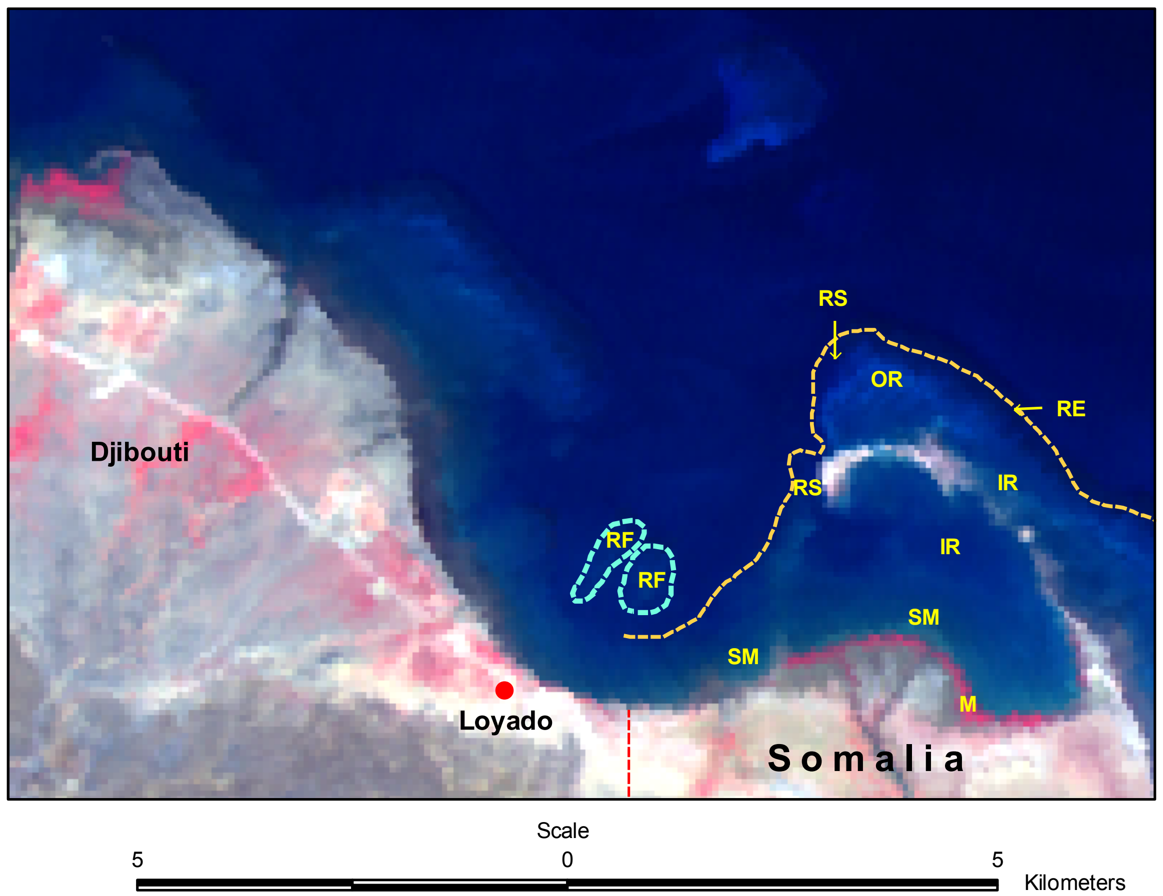


Figure 6.2.2 Index to coral reef habitat maps of Somalia

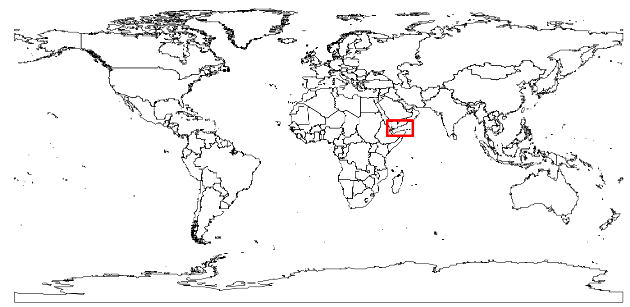


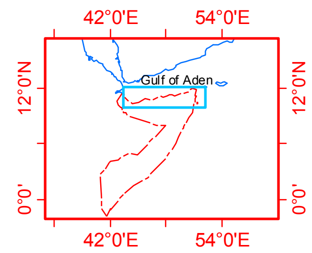


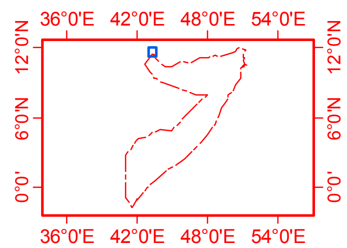
Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Muddy Reef Flat	:	MR
Subtidal Mudflat	:	SM
Mangrove	:	M

Fringing Reef
Patch Reef
Coral Pinnacle



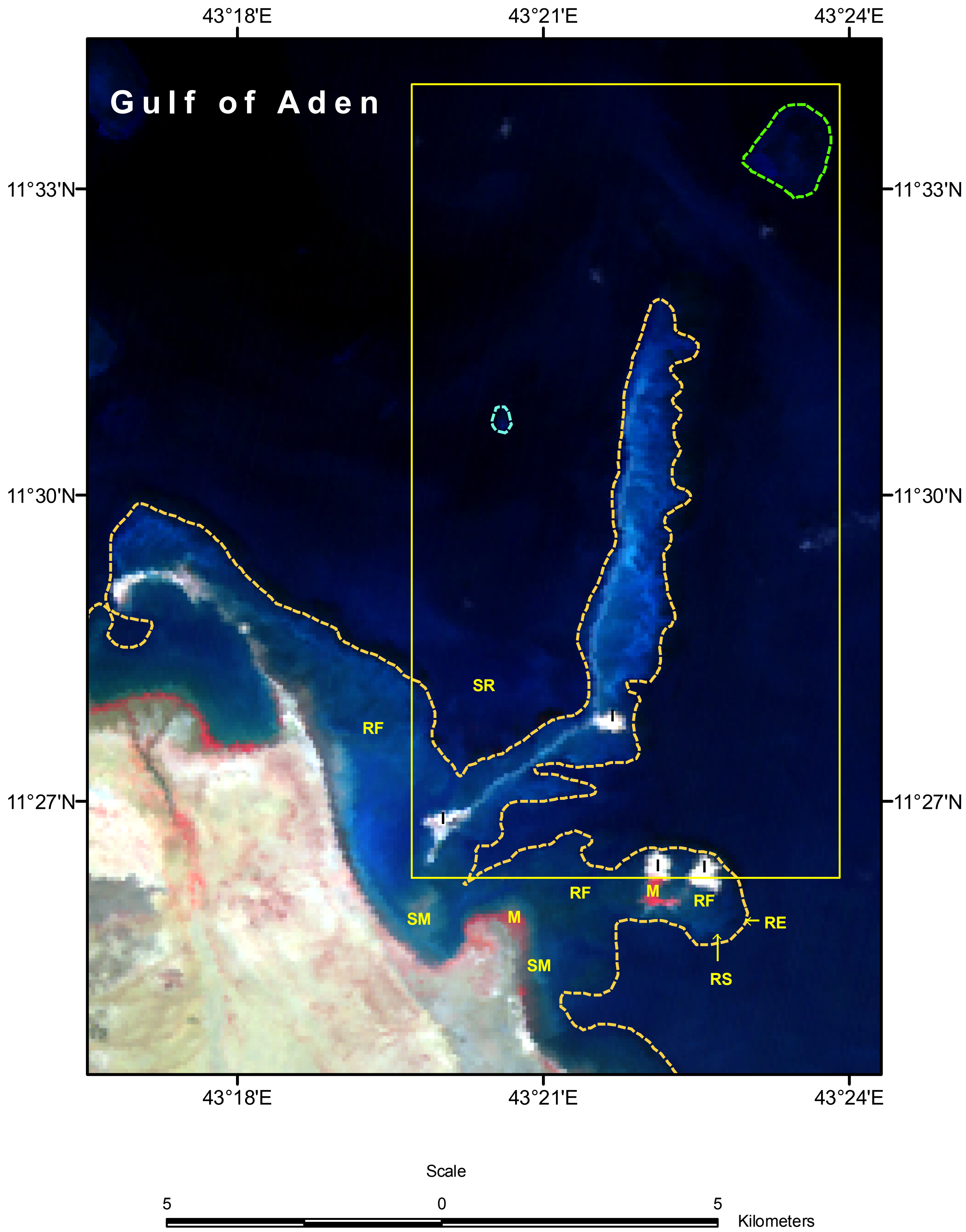


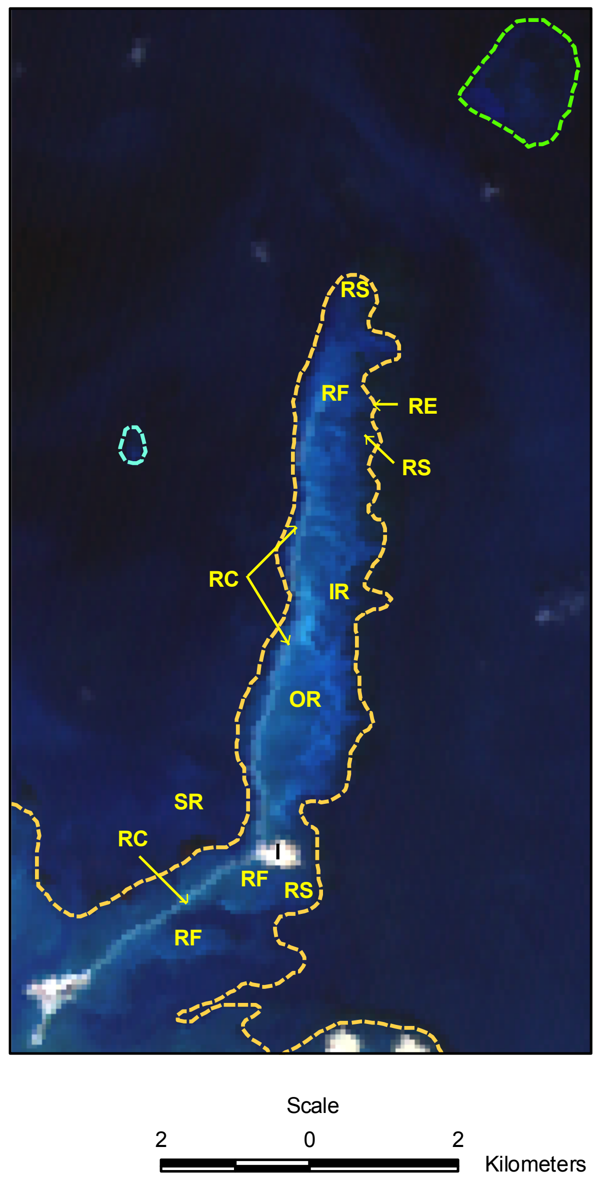


Source : RESOURCESAT-1 AWiFS Data
Dated 12th October, 2008 &
17th November, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.2.2.1 : Coral reef habitats of Somalian coast near Loyado

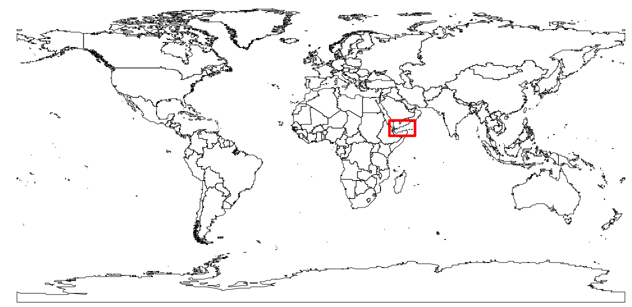


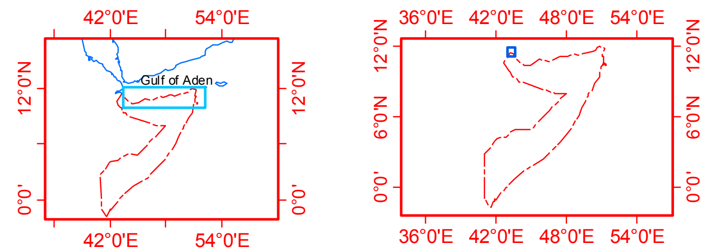


Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Submerged Reef	:	SR
Subtidal Mudflat	:	SM
Island	:	I
Mangrove	:	M

Fringing Reef





Source : RESOURCESAT-1 AWiFS Data
Dated 12th November, 2007

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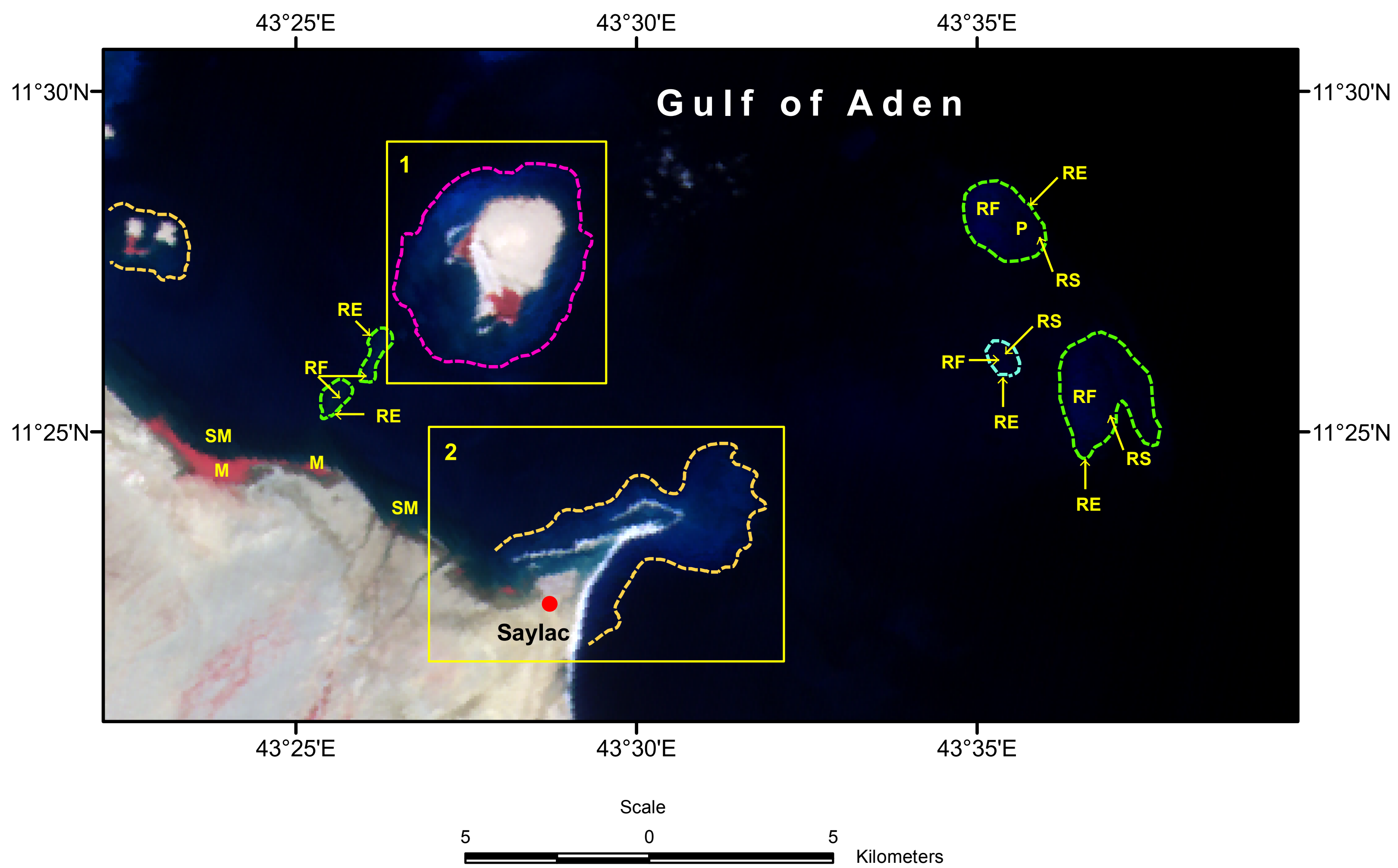
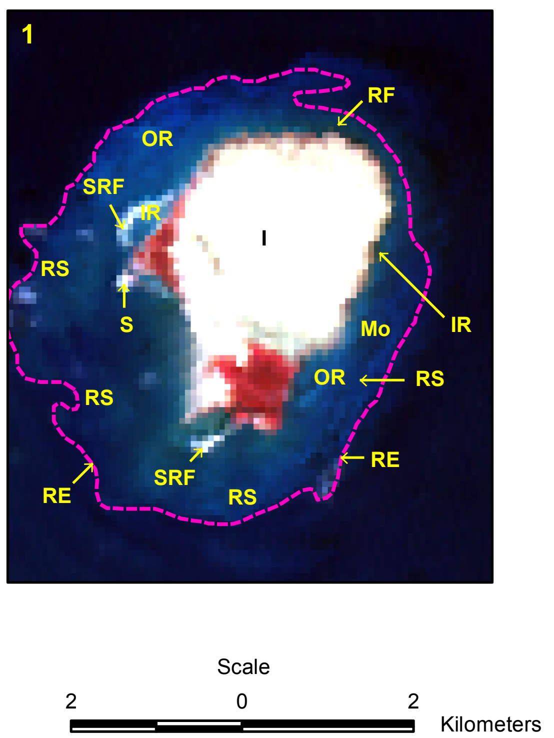
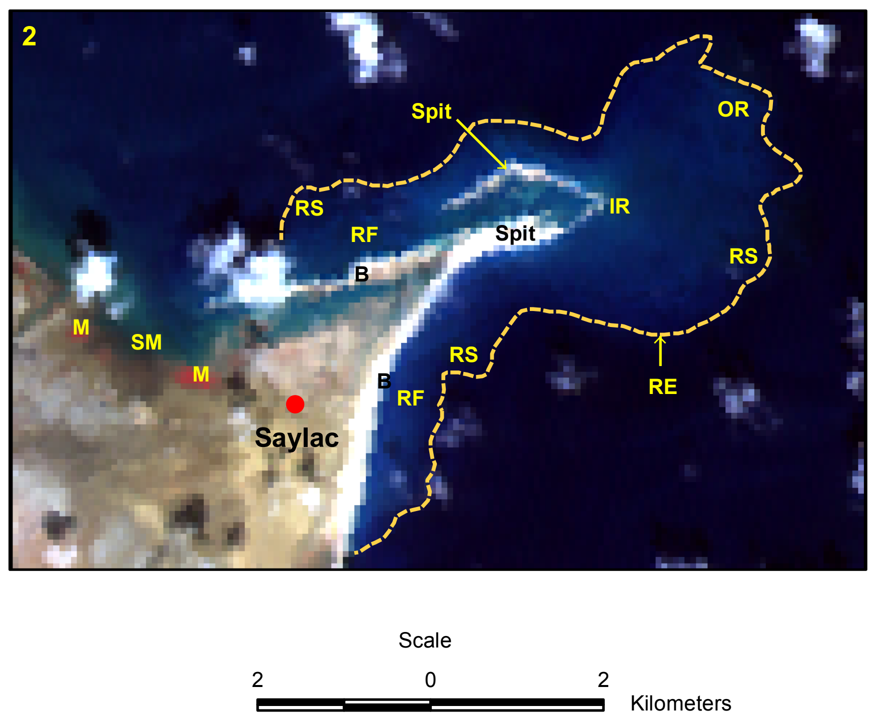
Map 6.2.2.2 : Coral reef habitats of Somalian coast to the west of Saad ed Din Island





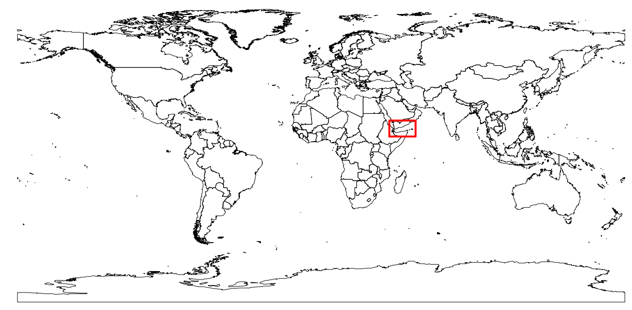


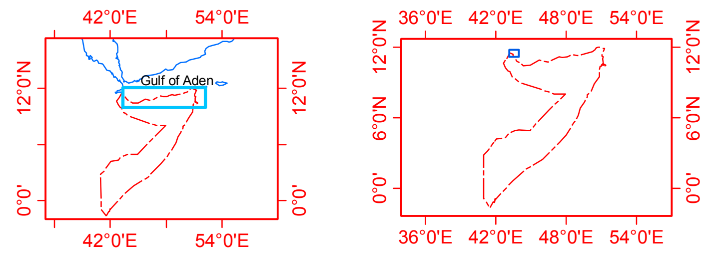
Legend

Reef Edge	:	RE
Reef Slope	:	RS
Moat	:	Mo
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Sand Patches	:	S
Pool	:	P
Submerged Reef	:	SR
Beach	:	B
Island	:	I
Subtidal Mudflat	:	SM
Mangrove	:	M

Fringing Reef
Platform Reef
Patch Reef
Coral Pinnacle

N





Source : RESOURCESAT-1 AWiFS Data
Dated 31st August, 2008 &
12th November, 2007

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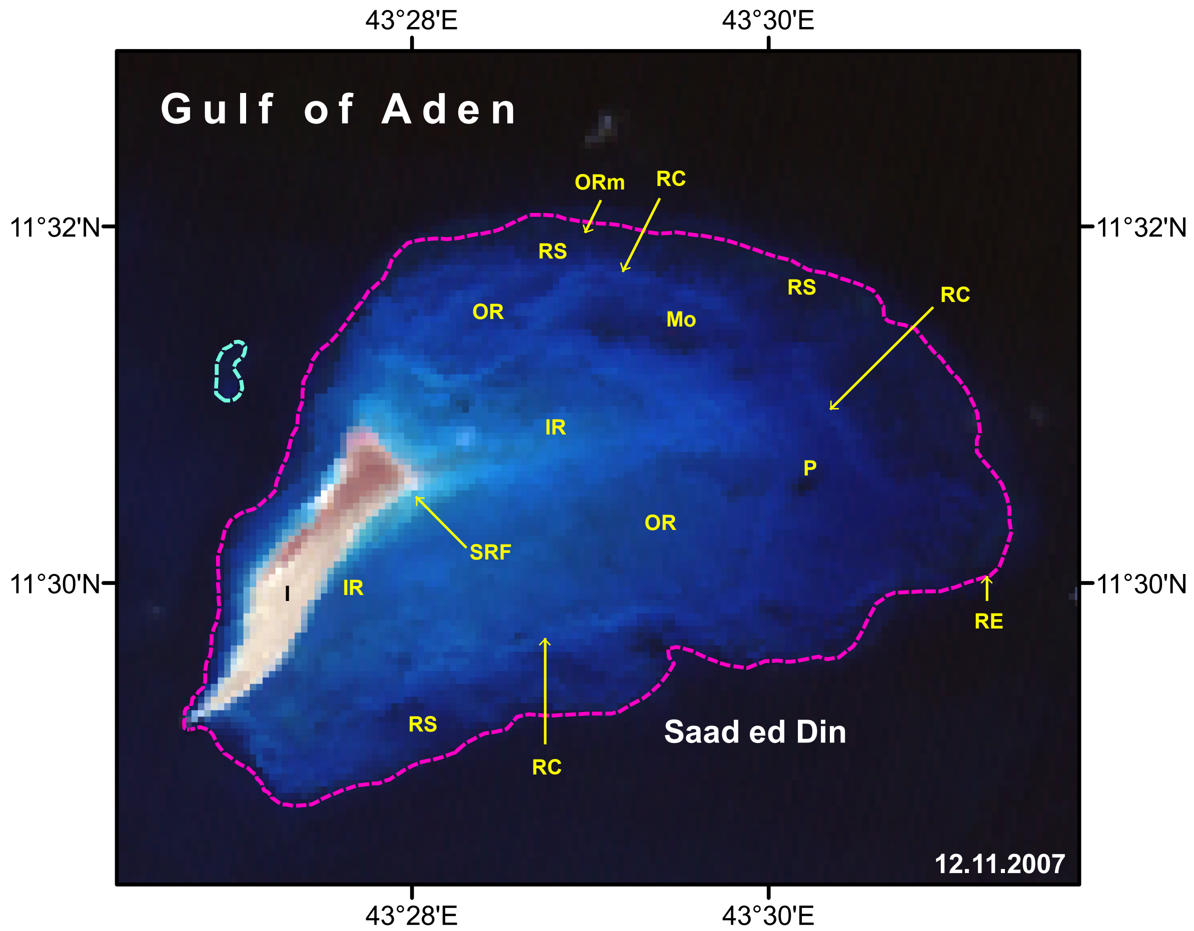
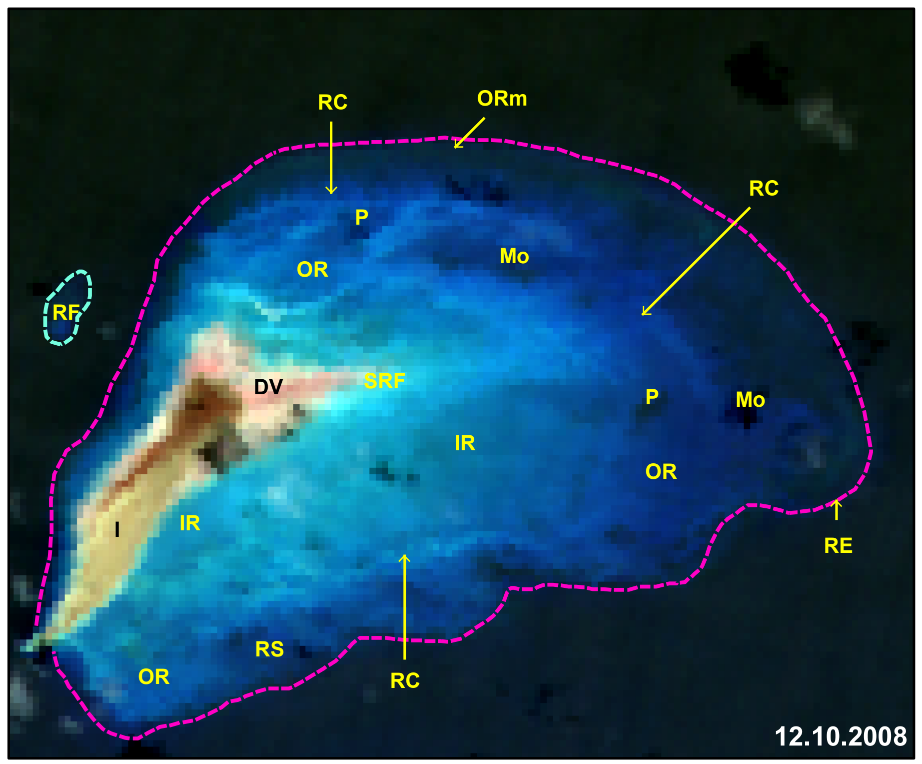
Map 6.2.2.3 : Off-shore and coastal coral reef habitats of Saylac and surroundings



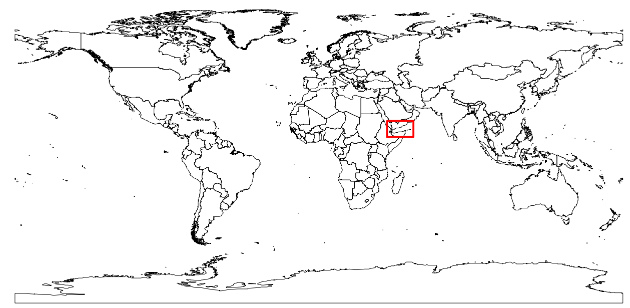


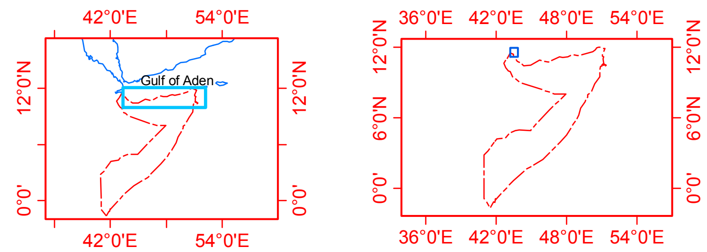
Legend

Reef Edge	:	RE
Reef Slope	:	RS
Reef Crest	:	RC
Moat	:	Mo
Outer Rim	:	ORm
Reef Flat	:	RF
Outer Reef Flat	:	OR
Inner Reef Flat	:	IR
Sanded Reef Flat	:	SRF
Pool	:	P
Dune Vegetation	:	DV
Island	:	I

Platform Reef

Coral Pinnacal

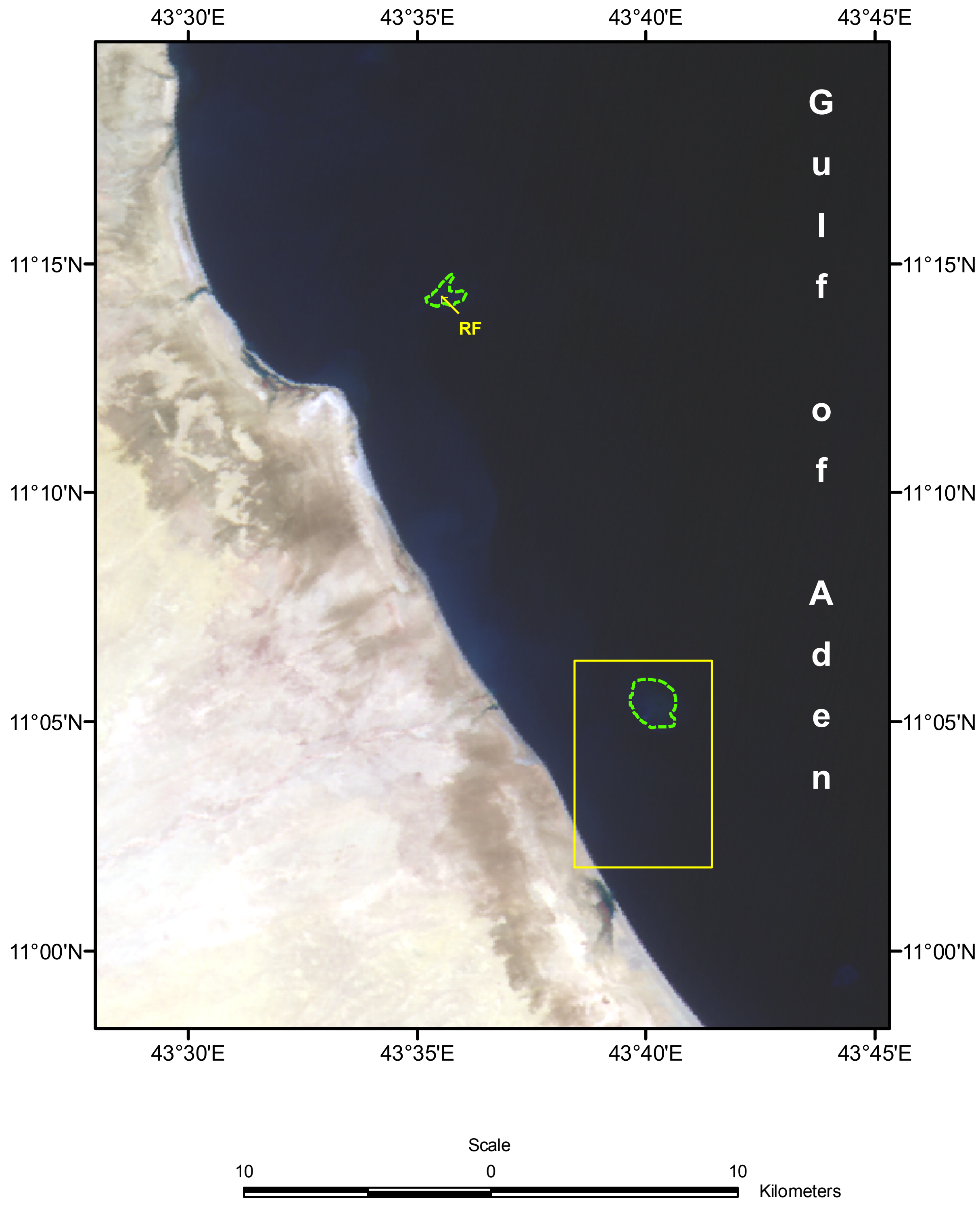


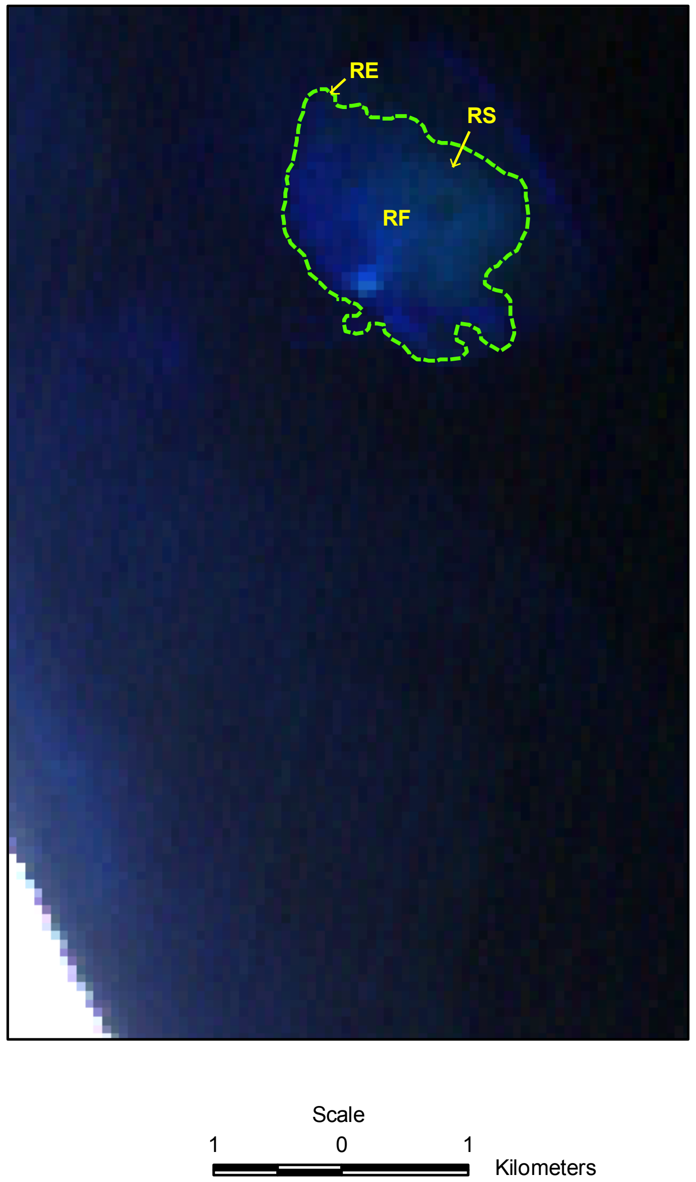


Source : RESOURCESAT-1 AWiFS Data
Dated 12th November, 2007 &
12th October, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.2.2.4 : Coral reef habitat of Saad ed Din

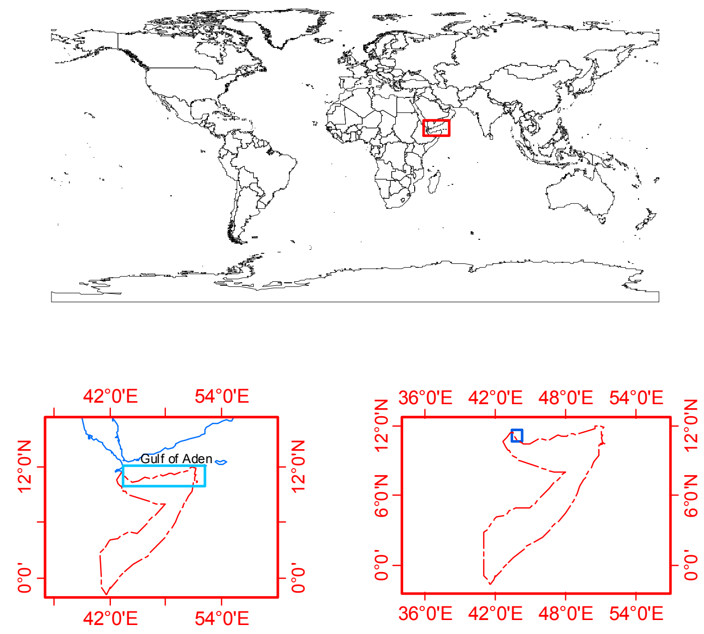




Legend

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF

Patch Reef



Source : RESOURCESAT-1 AWiFS Data
Dated 31st August, 2008

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.2.2.5 : Off-shore coral reef habitats to the South of Saylac

6.2.3. Yemen

Background

Gulf of Aden shares two-thirds of Yemen's 2200 km long coastline and a continental shelf area of 20,225 sq km (Pilcher and DeVantier 2003). The mainland coast of Yemen facing Gulf of Aden occurs within the geographical limits of 12°38'- 16°40'N latitudes and 43°30' - 53°05'E longitudes. The southern coast of Yemen that faces Gulf of Aden and Arabian Sea region extends from the narrow strait of Bab el Mandeb in the west to the border of Oman in the east. This coast of Yemen is characterized with rocky cliffs generally terminating in shallow waters, alternating with stretches of sandy beaches. Large expanses of unfavourable sandy substrate and low temperatures due to seasonal upwelling limit coral growth in this coast. The cold water upwelling during the summer South-West monsoons promotes macroalgae growth on the hard substrates especially to the eastern part of this coast (Kotb *et al.* 2004, 2008). Only 5% of this coast is known to support fringing coral communities or reefs (Pilcher and DeVantier 2003).

Information about the coral communities of Gulf of Aden coast is still sparse. There are few, extensive and high-cover coral communities in the sheltered and moderately sheltered areas in this coast with 50% coral cover or up, even up to 100% at the best sites (Kotb *et al.* 2008) which may spread for hundreds of metres. Corals are reported from Perim Island, near Aden (Khor Umairah/Omera, Little Aden), Ghuraira and Shuqra. The volcanic headlands and small rocky islands near Aden are covered with highly diverse coral communities, including branching, foliose, encrusting and massive corals often covering 100% of the rocky surfaces (Kotb *et al.* 2008). More extensive coral reef areas occur further east, towards Al Mukalla, particularly Balhaf and Burum and a group of six small islands lying off Bir Ali (Pilcher and DeVantier 2003). The reefs in these sites are dominated by branching, foliose, encrusting and massive coral forms as well as soft corals (Kotb *et al.* 2008). Some of these coral communities include wide areas of monospecific stands of *Pocillopora* and *Montipora* (Spalding *et al.* 2001). Balhaf and Bir Ali are the most important coral reef and seagrass areas (biodiversity hotspots) in the eastern Gulf of Aden with extensive fringing reefs supporting major fishing areas. Hard coral cover ranged from 15% in Al Mukalla to 69% in Balhaf which rapidly declined after the 1997-98 bleaching event. The monospecific coral communities in northern Gulf of Aden suffered almost 100% mortality during this bleaching event and showed few signs of recovery (Kotb *et al.* 2004).

The Gulf of Aden coast of Yemen includes the off-shore island group of Socotra which lies 400 km south of the Arabian peninsula, at the entrance of Gulf of Aden. This island group comprises of four islands and two rocky islets, isolated from the mainland, surrounded by deep waters, exceeding 3,000 m depth at some places (Pilcher and DeVantier 2003). Socotra island group is highly exposed to the monsoon climate of Indian Ocean. Most of the island coasts consist of rocky cliffs and sandy beaches with occasional gravel shorelines. These islands, renowned for their rich terrestrial and marine biodiversity with many endemic species are considered as 'biogeographic crossroads' due to their unique biogeographic affinities to Arabia, east Africa, the Red Sea and greater Indo-Pacific (Kotb *et al.* 2004, 2008). Corals are widespread throughout the Socotra archipelago. Coral growth is affected by cold water upwelling during the south west summer monsoons and corals form small discrete communities rather than true reef structures. Two hundred and fifty hard coral species, over 120 species of macroalgae and 730 species of reef fishes have been reported from this island group (Kotb *et al.* 2004). Corals were affected by the 1997-98 bleaching event; however, considerable recovery of surviving corals and new recruitments have steadily contributed to an average live coral cover around 30% (Kotb *et al.* 2004).

Coral Reefs: Distribution and Habitat Characteristics

Coral reefs of Yemen have been mapped with Resourcesat-1 AWiFS data (4 scenes; dated: 24th March, 2006, 16th April, 2006, 12th November, 2007 and 22nd August, 2008). Habitat characteristics of these reefs have been depicted in 4 habitat maps (Maps: 6.2.3.1 to 6.2.3.4). Coastal fringing reefs have been detected in discontinuous patches in the mainland coast of Yemen within the geographical limits of 12°40’ to 14°00’ N latitudes and 44°25’ to 48°27’ E longitudes (Figure 6.2.3). From west to the east, these coastal fringing reefs occur in three major locations: near Port Aden, near Shuqra and near Balhaf and Bir Ali. The off-shore fringing reefs occur in Socotra island group within the geographical limits of 12°09’ to 12°35’ N latitudes and 52°00’ to 54°30’E longitudes.

The coastal fringing reefs occur in two discrete patches surrounding two individual headlands to the west of Little Aden (Map: 6.2.3.1). In case of Shuqra, the reef fringes the coastline for a length little less than a kilometer (Map: 6.2.3.2) while in case of Balhaf and Bir Ali, the reefs fringe the coastline again in discontinuous patches following the natural headland-bay configuration of the coastline (Map: 6.2.3.3). The off-shore reefs of Socotra Island group, fringes four individual islands, namely Abd al Kiri in the west, Socotra in the east, and two small islands of Semha and Darsa between Abd al Kiri and Socotra (Map: 6.2.3.4).

The reef categories detected and delineated for Yemeni reefs in general are limited to few geomorphological zone and sub-zone (Level 2 and Level 3) categories. Among the level 2 classes, reef flat and submerged reef categories have been detected while reef edge and reef slope are the common level 3 classes that could be detected for these reefs. One interesting feature is the vast coralline shelf (level 2 category) of Abd al Kiri island (Map: 6.2.3.4). AWiFS data helped only in detection and boundary delineation for the coral reef habitats of Yemen. The spatial resolution of this data proves to be coarse to bring out significant intra-reef details of these narrow fringing reefs.

The frequencies of the classes/categories detected for the coral reefs of Yemen are represented in Figure 6.2.3.1. Reef flat, reef edge and reef slope categories appear to be the commonly detected categories for coral reefs of Yemen.

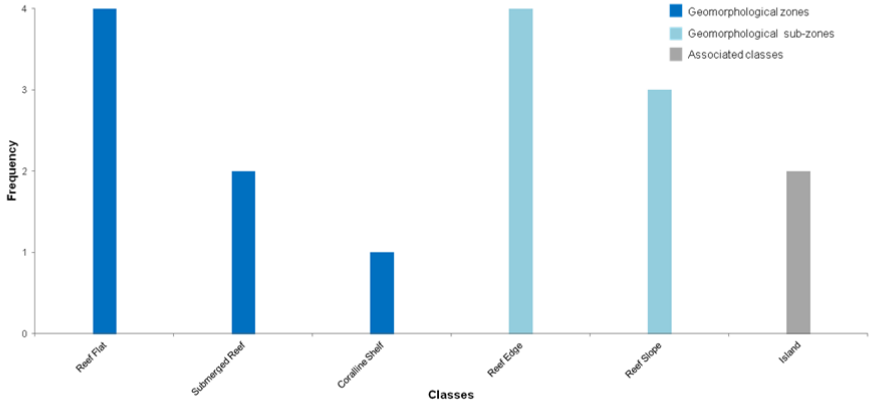


Figure 6.2.3.1 Frequency of classes detected for coral reef habitats of Yemen

Areal Extent of Coral Reefs of Yemen

Coral reef habitats of the Gulf of Aden coast of Yemen as mapped from AWiFS data cover a total area of 277.17 sq km. Reef area corresponding to each habitat map is summarized in Table No. 6.2.3.1. Socotra Island group occupies the highest reef area of 258.84 sq km while the coastal fringing reefs of Aden and surroundings occupy the minimum area of 1.64 sq km. The coralline shelf of Abd al Kiri occupies an area of 124.60 sq km.

Table 6.2.3.1 Areal Extent of coral reefs in the Gulf of Aden coast of Yemen

Map No.	Location	Reef Area (sq km)
6.2.3.1	Coral reef habitats of Aden and surroundings	1.64
6.2.3.2	Coral reef habitats of Shuqra and surroundings	10.90
6.2.3.3	Coral reef habitats of Balhaf, Bir Ali and surroundings	5.79
6.2.2.4	Coral reef habitats of Socotra Archipelago	258.84
	Total Area	**277.17**

Summary

Coral reef habitats of the Gulf of Aden coast of Yemen are fringing reefs either occurring in discontinuous patches in the mainland coast or in off-shore settings of Socotra archipelago. Detailed mapping of these narrow fringing reefs demands very high resolution data. AWiFS data helped only in detection and boundary delineation of these reefs. The status of corals in these reefs of Yemen is known to be in good condition other than localized impacts around the major cities of Aden and Al Mukalla **(**Kotb *et al.* 2008). Human impacts on Yemen's coral reef habitats are relatively minimal, except from fishing (Spalding *et al.* 2001). Port of Aden has been associated with pollution, problems of sewage discharges and solid waste disposal, shipping and associated spills. Localized tourism is also been reported to affect the coral reefs of Shuqra (Kotb *et al.* 2008). 1997-98 bleaching event has been reported to damage Yemen's reefs followed by a steady recovery (Kotb *et al.* 2004, 2008). The Socotra Island group is an officially protected area with natural World Heritage Site status (since 2008) while six other areas have been proposed for protection

(PERSGA/GEF. 2003). These coral reef habitats as mapped with 2006-08 AWiFS data cover a total area of 277.17 sq km. However, much detail on reef health condition could not be inferred due to coarse resolution of the data.

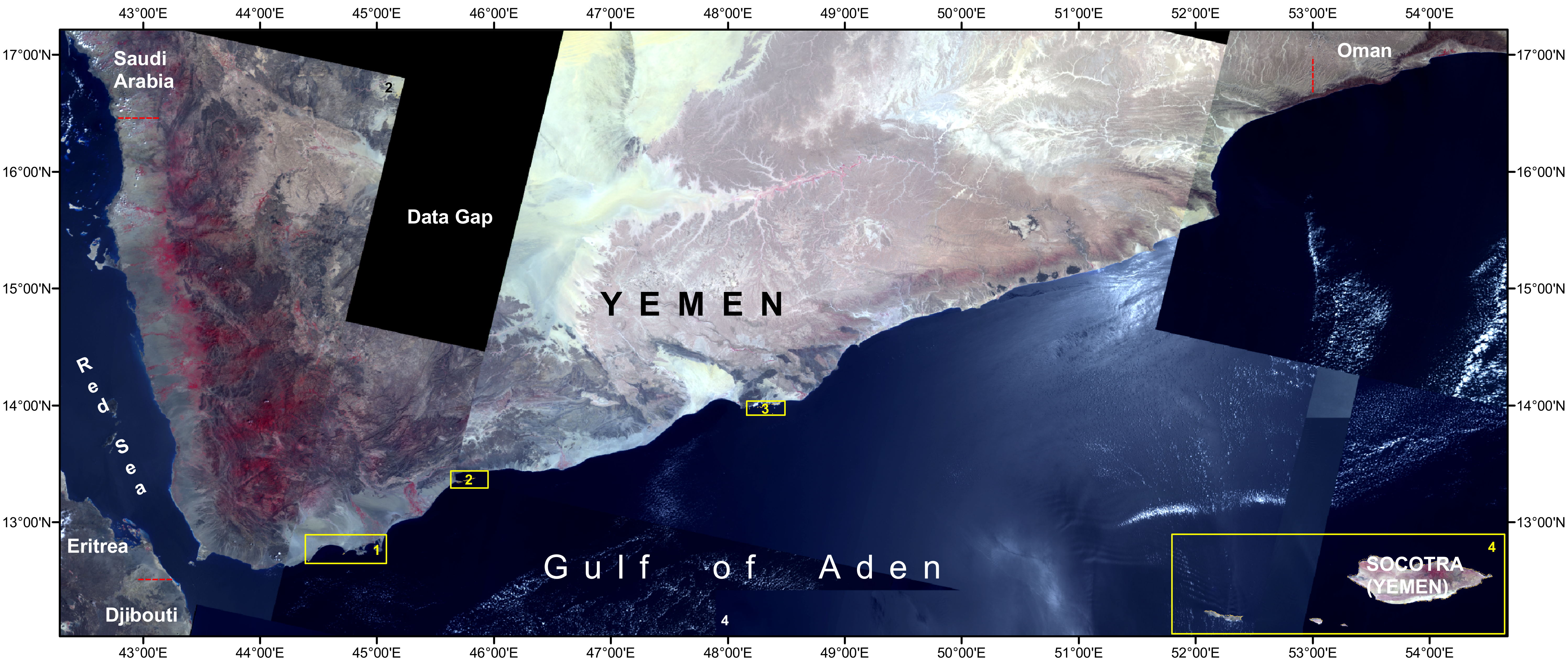
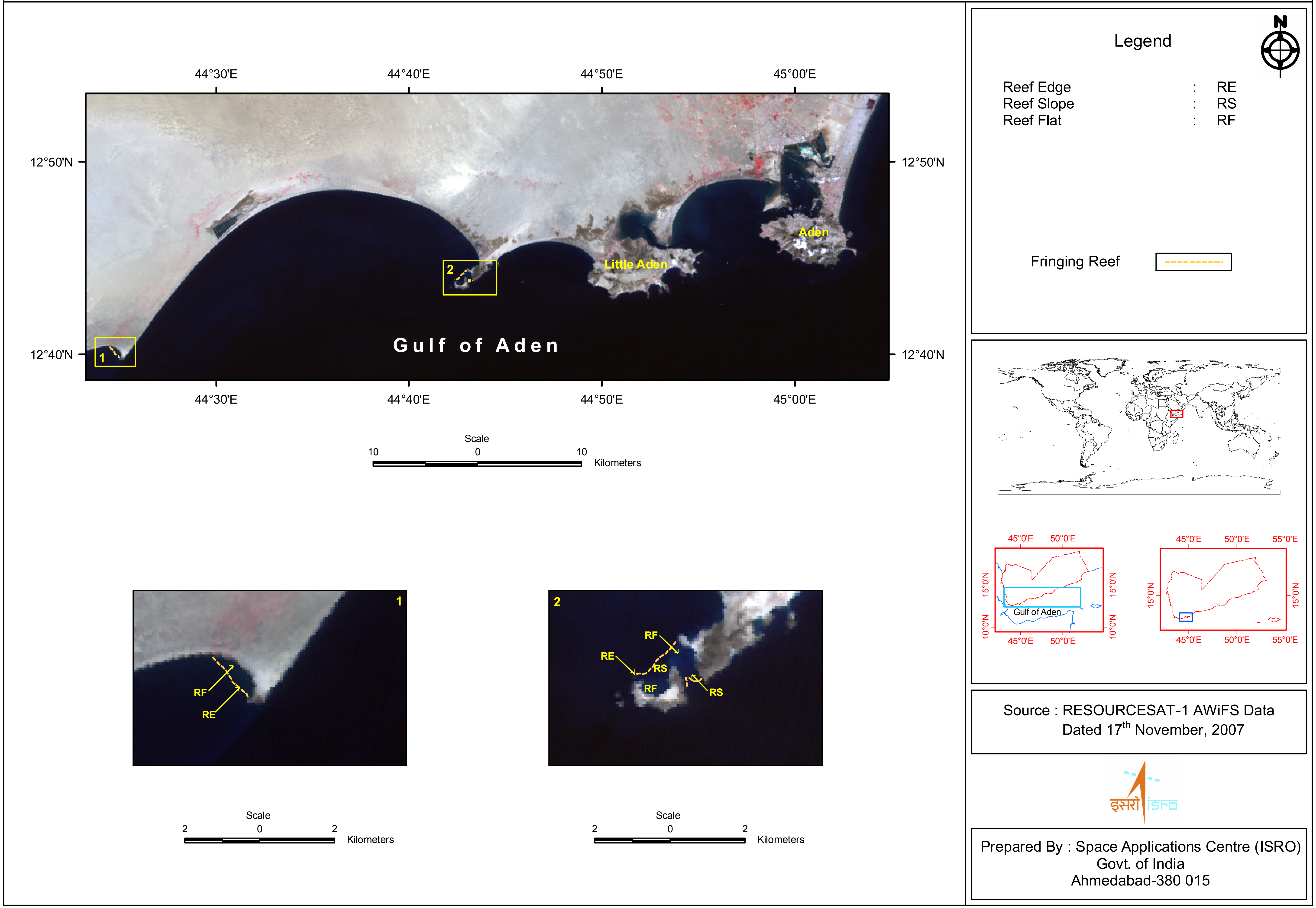
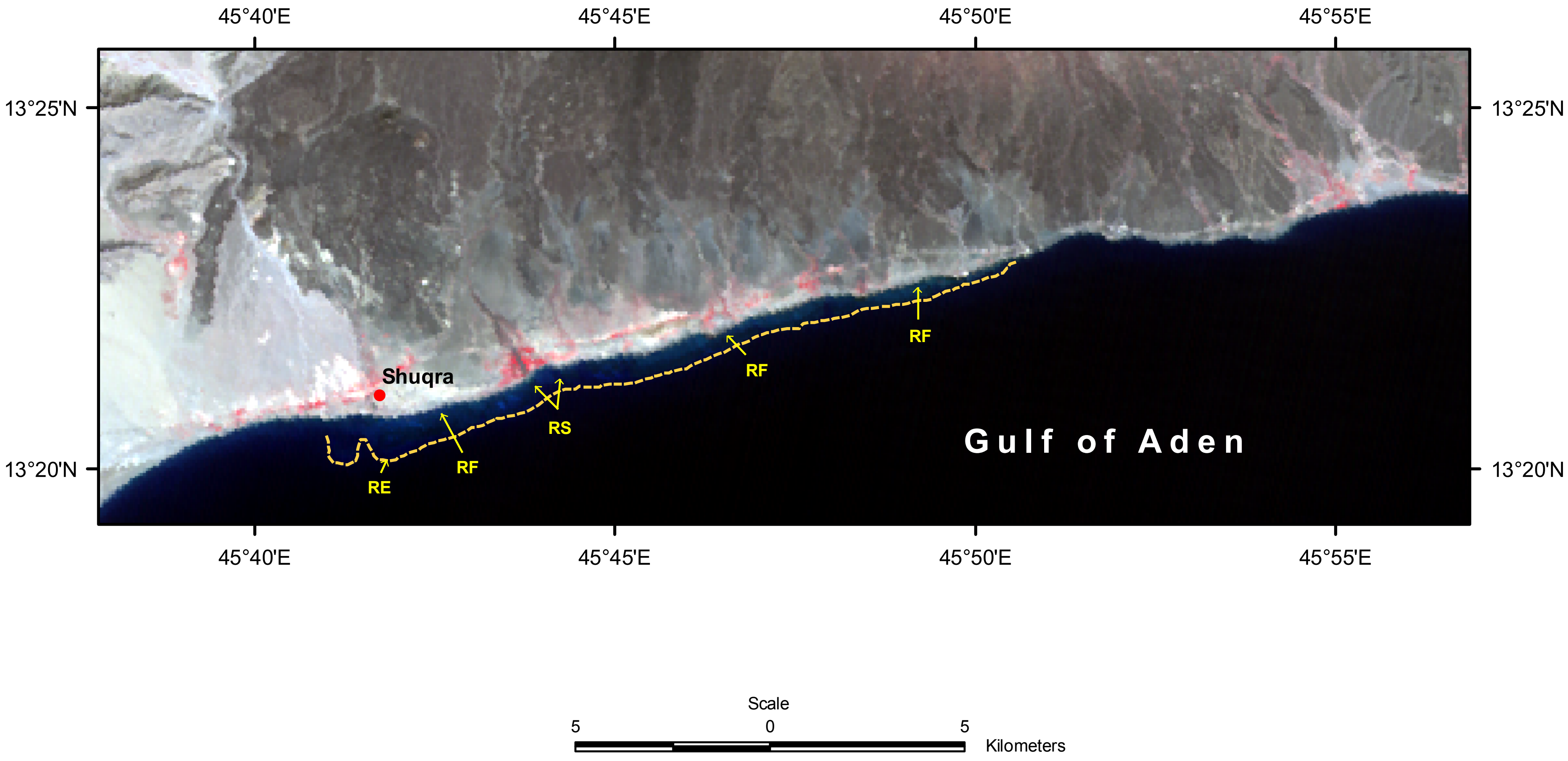


Figure 6.2.3 Index to coral reef habitat maps of Yemen



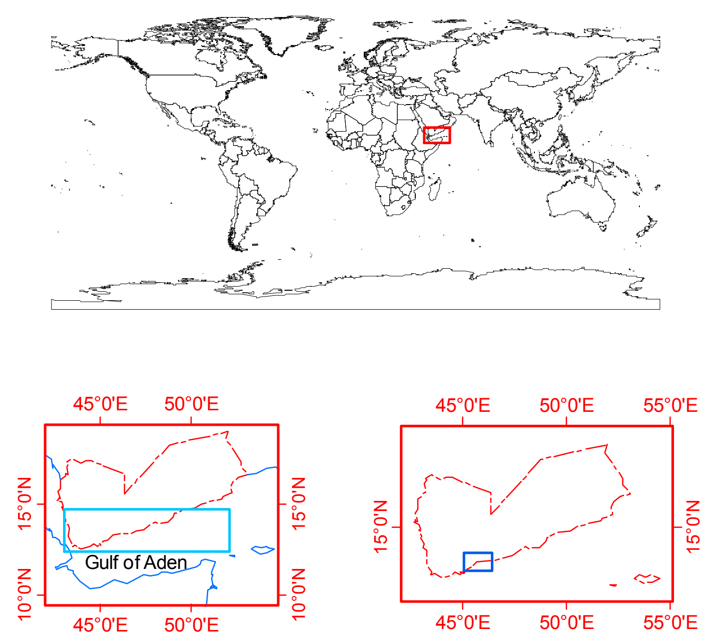
Map 6.2.3.1 : Coral reef habitats of Aden and surroundings



Legend

Reef Edge : RE
Reef Slope : RS
Reef Flat : RF

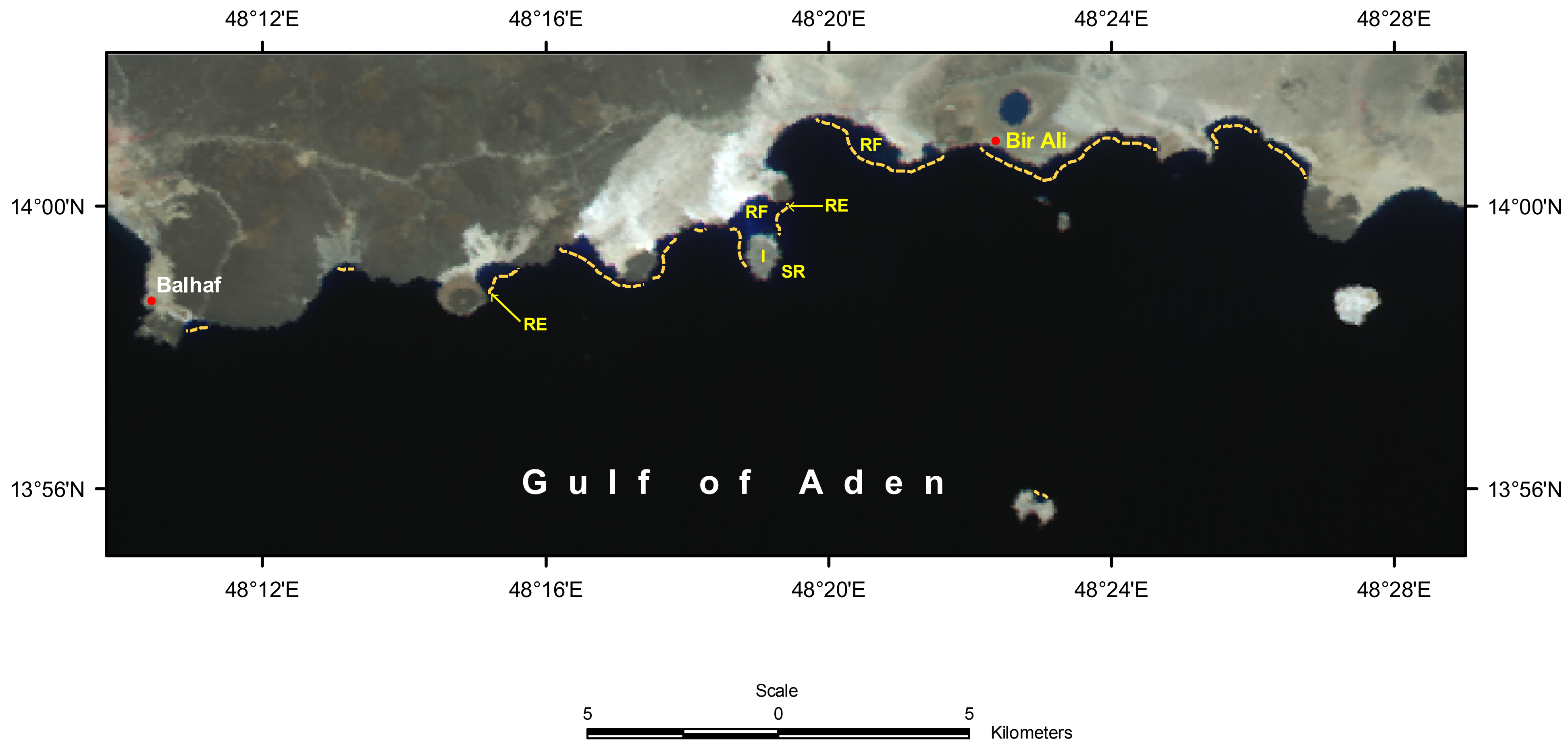
Fringing Reef



Source : RESOURCESAT-1 AWiFS Data
Dated 17th November, 2007

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

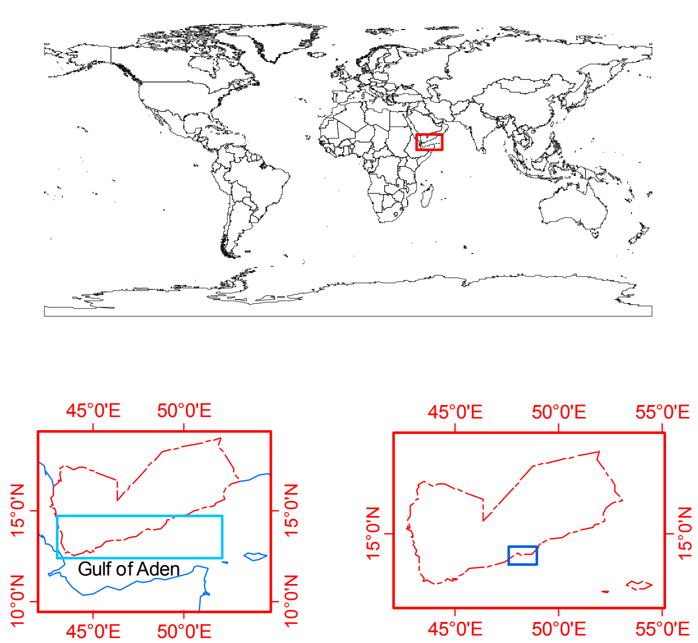
Map 6.2.3.2 : Coral reef habitats of Shuqra and surroundings



Legend

Reef Edge : RE
Reef Flat : RF
Submerged Reef : SR
Island : I

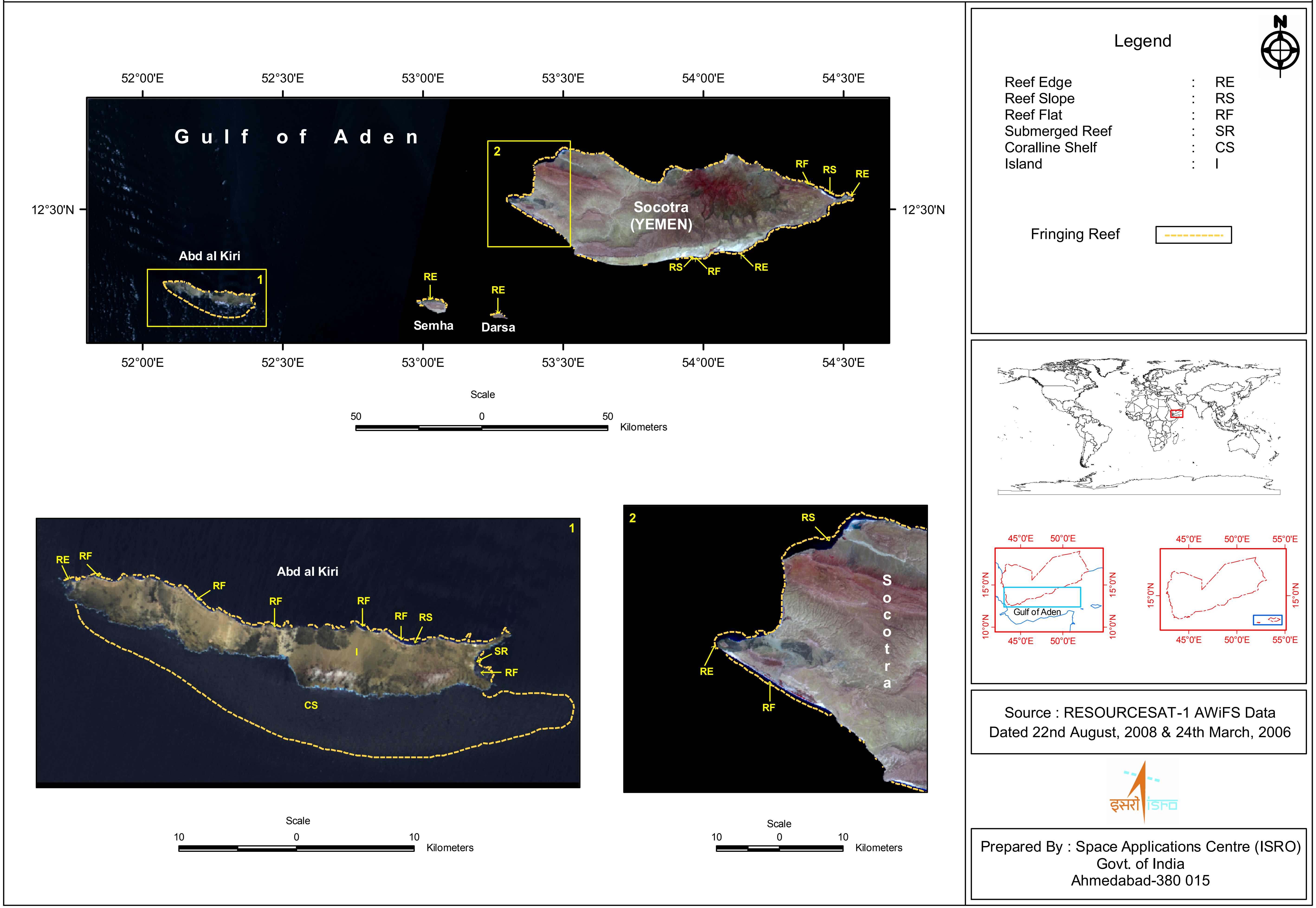
Fringing Reef



Source : RESOURCESAT-1 AWiFS Data
Dated 16th April, 2006

Prepared By : Space Applications Centre (ISRO)
Govt. of India
Ahmedabad-380 015

Map 6.2.3.3 : Coral reef habitats of Balhaf, Bir Ali and surroundings



Map 6.2.3.4 : Coral reef habitats of Socotra Archipelago

Validation

Country-wise satellite-based coral reef area statistics were compared (Table 7.1) with the national level statistics based on hydrographic charts as presented in the World Atlas of Coral Reefs by Spalding *et al.* (2001). At the basin level, considering Red Sea and Gulf of Aden as a single unit, there is a net difference of 11.30 percent in terms of total coral reef area. As per the World Atlas of Coral Reefs, total coral reef area is 17400 sq km while the national reef area aggregate from the same source comes to 17640 sq km (considering Jordan has a reef area equivalent to 50 sq km instead of an open ended class of less than 50 sq km; Spalding *et al.* 2001). As per our exercise, the total coral reef area for Red Sea and Gulf of Aden is 15646.17 sq km based on Resourcesat-1 AWiFS data of 2004-09 timeframe.

This difference in area statistics can be attributed mainly to the function of mapping scale. In case of World Atlas of Coral Reefs, global coral reefs have been mapped at 1:1000000 scale based on US Defense Mapping Agency Operational Navigational Chart series prepared during 1960s and 1970s whereas our mapping endeavour is at 1:25000 scale based on Resourcesat-1 AWiFS data of 2004-09 period. At a coarser scale of 1:1000000, 1 cm on map represents a ground distance of 10 km and accordingly 1 sq cm grid represents an area of 100 sq km. On the other hand, at a finer scale map of 1:25000 scale, 1 cm on map represents 0.25 km on ground and accordingly 1 sq cm on map represents an area of 0.0625 sq km on ground. Spalding *et al.* (2001) have mentioned the fact of exaggeration of the total reef area from the ones actually shown on the maps by this method of simplified calculation of 1 sq km grid as reef or non-reef. From this perspective, satellite-based estimates are more accurate as the mapping exercise has been carried out at a finer scale and that too from satellite observations. The area computed also came from a GIS database. However, low tide exposures of coral reefs during AWiFS imaging time, detectability of the reef patch vis-à-vis the local illumination condition, omission errors due to the Minimum Mapping Unit (MMU) at 1:25000 scale (i.e. 0.56 sq km at 1:25000 scale) still remain major mapping constraints and thus affect reef area estimation. Moreover, the reef area computed represents the two-dimensional area of the reef surface exposed during the imaging time and not necessarily the three-dimensional area of the reef.

Evolution of satellite borne multispectral sensors with respect to increasing spatial and spectral resolutions along with integration of high-resolution multispectral data with different sensor and mapping technologies (e.g. hyperspectral imaging, SAR imaging, LiDAR imaging and acoustic data) will usher in more accurate coral reef maps in the future.

Table 7.1 Coral Reef Area of Red Sea and Gulf of Aden Countries at 1:1000000 and 1:25000 scales

Sr. No.	Country	Coral Reef Area (in sq km) at Mapping Scales		Area Difference (in sq km)	Area Difference (in %)
		1:1000000	1:25000		
1.	Egypt	3800	1469.39	2330.61	61.33
2.	Sudan	2720	1582.35	1137.65	41.83
3.	Eritrea	3260	5346.18	-2086.18	-63.99
4.	Jordan	<50	1.05	48.95	97.90
5.	Saudi Arabia	6660	5832.91	827.09	12.42
6.	Yemen	700	1070.24	-370.24	-52.89
7.	Djibouti	450	198.93	251.07	55.79
8.	Somalia*	0	145.12	-145.12	0.00
	Total	**17640**	**15646.17**	**1993.83**	**11.30**

*= Coral reef area for Somalia has been considered as 0.00 sq km as the World Atlas of Coral Reefs gives coral reef area only for Southern Somalia and not for Northern Somalia.

8. References:

Al Saafani, M. A., 2008. Hydrography and water masses in the Gulf of Aden. In: Physical oceanography of the Gulf of Aden. Pp.43-87. Accessed from: drs.nio.org/drs/bitstream/2264/1395/6/chap3.pdf

Andrèfouët, S., Kramer, P., Torres-Pilliza, D., Joyce, K, E., Hochberg, E. J., Garza-Pérez, R., Mumby, P.J., Riegl, B., Yamano, H., White, W. H., Zubia, M., Brock, J. C., Phinn, S. R., Naseer, A., Hatcher, B. G., Muller-Karger, F. E., 2003. Multi-site evaluation of IKONOS data for classification of tropical coral reef environments. *Remote Sensing of Environment* **88**: 128-143.

Andréfouët, S, Muller-Karger, F.E. Robinson, J.A. Kranenburg, C.J., Torres-Pulliza, D. Spraggins, S.A and Murch, B. 2006. Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. *Proceedings of 10th International Coral Reef Symposium,* 1732-1745.

Bahuguna, A., Ray Chaudhury, N., Bhattji, N., Ajai and Navalgund, R. R., 2013. Spatial inventory and ecological status of coral reefs of the Central Indian Ocean using Resourcesat-1. *Indian Journal of Geo-marine Sciences.* **42**(6): 684-696.

Behairy A.K.A., Sheppard, C.R.C. and El-Sayed, M.K. 1992. A Review of the geology of coral reefs in the Red Sea. *UNEP Regional Seas Reports and Studies No. 152*. UNEP 1992. 41p.

Buddemeier, R. W., Kleypas, J. A. and Aronson, R. B. 2004. *Coral reefs and global climate change.* Pew Center Global Climate Change Report, 56 p.

Burke, L., Reyter K., Spalding, M. and Perry A. 2011. *Reefs at risk revisited*. World Resources Institute, Washington DC, 114 p.

El-Gamily, H. I., Nasr, S. and El-Raey, M. 2001. An assessment of natural and human-induced changes along Hurghada and Ras Abu Soma coastal area, Red Sea, Egypt. *International Journal of Remote Sensing*. **22**(15), pp. 2999-3014.

Gischler E. 2011. Blue Hole In Hopley D. (ed.) *Encyclopedia of Modern Coral Reefs Structure, Form and Process.Springer, Science+ Business Media B. V.* 2011, 164-165 pp.

Green, E.P., Mumby, P.J., Edwards , A.J. and Clark, C. D., 1996. A Review of Remote Sensing for Tropical and Coastal Resources Assessments and Management, *Coastal Management* **24**(1): 1-40.

Green, E.P., Mumby, P.J., Edwards, A.J., Clark, C.D., 2000. *Remote sensing handbook for tropical coastal management*. Coastal Management Sourcebooks 3, ed. A.J. Edwards, UNESCO, Paris.x+ 316 p.

Holthus, P. F. and Maragos, J. E., 1995. Marine ecosystem classification for the Tropical island Pacific, *In Marine and Coastal Biodiversity in the Tropical island Pacific region*. ed. J. E. Maragos, M.N. A. Peterson, L.G. Eldredgeh, J. E. Bardach and H. F. Takeuchi, East-West centre, Honolulu, 239-278.

Hopley, D., 1982. *The Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reef.* John Wiley & Sons, New York. 453 p.

Hopley, D., 2011. *Encyclopedia of Modern Coral Reefs Structure, Form and Process.Springer, Science+ Business Media B. V.* 2011, 1205 p.

Jameson, S.C., Karr, J.R. and Potts, K.W., 2003. A classification system for the diagnostic monitoring and assessment of coral reefs. USEPA Office of Water, Washington D.C. 27p. http://www.coralseas.com/pubs.asp

Klaus, R., Kemp, J., Samoilys, M., Anlauf, H., El Din, S., Abdalla, E.O., Chekchak, T., 2008. Ecological patterns and status of the reefs of Sudan. *Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida*, 7-11, 716-720.

Kleypas J.A., McManus, J.W., Menez, L.A.B., 1999. Environmental limits to coral reef development: Where do we draw the line? *American Zoology,* **39**, 146-159.

Kotb, M., Abdulaziz, M., Al-Agwan, Z., Al-Shaikh, K., Al-Yami, H., Banajah, A., DeVantier, L., Eisinger, M., Eltayeb, M., Hassan, M., Heiss, G. Howe, S., Kemp, J., Klaus, R., Krupp, F., Mohamed, N., Rouphael, T., Turner, J. and Zajonz, U., 2004. Status of coral reefs in the Red Sea and Gulf of Aden in 2004. In: *Status of the coral reefs of the world: 2004.* ed. C. Wilkinson, Global Coral Reef Monitoring Network (GCRMN), Australian Institute of Marine Science, Townsville, Queensland. **1**:137-154.

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

Kuchler, D.A., 1986. *Geomorphological Nomenclature: Reef Cover and Zonation on the Great Barrier Reef.* Great Barrier Reef Marine Park Authority; Technical Memorandum, GBRMPA-TM-8, Townsville, Australia.http://www.reefhq.wm.au/data/assds/pdf-file/0004/3478/tm008.full.pdf

Medio D., Sheppard, C.R.C., Gasgoine, J. 2000. In McCLanahan T. R., Sheppard, C.R.C. and Obura D. (ed.) *Coral reefs of the Indian Ocean: Their ecology and conservation*. Oxford University Press, New York, pp. 231-251.

Mohammed, T. A. A. 2012. Rapid assessment of coral reefs along the Egyptian Red Sea Coast. *International Journal of Environmental Protection*. **2**(4), 25-33.

Mumby, P.J. and Harborne, A. R., 1999. Development of Systematic classification Scheme of Marine Habitats to Facilitate Regional Management of Caribbean Coral Reefs. *Biological Conservation* **88**(2): 155-163.

Mumby, P.J., Green, E.P., Edwards, A. J. and Clark, C. D., 1997. Coral reef habita mapping: how much detail canremote sensing provide? *Marine Biology* **130**: 193-202.

Navalgund, R. R., Ajai, Bahuguna, A., Ray Chaudhary, N., Madhupriya, N., Sharma S., Parihar, J. S., Panigrahi, S., Chakrabirty, M., Dwivedi, R. M., Ramdass, S. and Swaroop, P., 2010. *Coral Reef Atlas of The World*. Vol-I Central Indian Ocean. Space Applications Centre (ISRO) Govt. of India. 281 p.

Nayak, S., Bahuguna, A., Deshmukh, B., Shah, D. G., Rao, R. S., et al., 2003. *Eco-morphological Zonation of Selected Coral Reefs of India Using Remotely Sensed Data*. Scientific Note. Space Applications Centre, Ahmedabad, SAC/ RESIPA/ MWRG/MSCEDITED/SN/16/2003, 108 p.

Nayak, S. R. and Bahuguna, A., 1997, *Coral Reef Atlas of India*. Coastal Studies Project (Dept. of Ocean Development, Govt. of India), Space Applications Centre. SAC/RSA/RSAG/DOD-COS/OD/13/97, 96 p.

NRSA, 2003. IRS-P6 Data User’s Handbook, Technical Report No. IRS-P6/NRSA/NDC/HB-10/03 October 2003, 141 p.

Pandolfi J.M. 2011. The paleoecology of coral reefs. In Dubinsky Z. and Stambler N. (ed.) *Coral reefs: An ecosystem in transition.* Springer Science + Business Media B.V. 2011, pp. 13-24.

Pandya, M. R., Murli, K. R. and Kiran Kumar, A. S., 2013. Quantifiction and comparison of spectral characteristics of sensors on board Resourcesat-1 and Resourcesat-2 satellites. *Remote Sensing Letters*. **4**(1-3): 306-314.

PERSGA/GEF., 2003. *Coral Reefs in the Red Sea and Gulf of Aden. Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No. 7. PERSGA, Jeddah. 137 p.

Phinn, S. R., Roelfsema, C. M. and Mumby, P.J., 2012. Multi-scale, object-based image analysis for mapping geomorphic and ecological zones on coral reefs. *International Journal of Remote Sensing*. **33** (11-12): 3768-3797.

Pilcher, N. and Abdi, N. D., 2003. Coral reefs of Djibouti. In *Coral reefs in the Red Sea and Gulf of Aden. Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No.7 (PERSGA/GEF, 2003), PERSGA, Jeddah, 27-41.

Pilcher N. and Abou Zaid M.M. 2003. Coral reefs of Egypt. In *Coral reefs in the Red Sea and Gulf of Aden Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No.7 (PERSGA/GEF, 2003), PERSGA, Jeddah, pp: 1-12.

Pilcher, N. and Al-Moghrabi, S.M., 2003. Coral reefs of Jordan. In *Coral reefs in the Red Sea and Gulf of Aden. Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No.7 (PERSGA/GEF, 2003), PERSGA, Jeddah, 117-124.

Pilcher, N. and Alsuhaibany, A., 2000. Regional status of coral reefs in the Red Sea and the Gulf of Aden. In: *Status of the coral reefs of the world: 2000.* ed. C. Wilkinson, Global Coral Reef Monitoring Network (GCRMN), Australian Institute of Marine Science, Townsville, Queensland, 35-54.

Pilcher, N. and DeVantier, L., 2003. Coral reefs of Saudi Arabia. In *Coral reefs in the Red Sea and Gulf of Aden. Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No.7 (PERSGA/GEF, 2003), PERSGA, Jeddah, 93-116.

Pilcher, N. and DeVantier, L., 2003. Coral reefs of Yemen. In *Coral reefs in the Red Sea and Gulf of Aden. Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No.7 (PERSGA/GEF, 2003), PERSGA, Jeddah, 71-92.

Pilcher, N. and Nasr, D., 2003. Coral reefs of Sudan. In *Coral reefs in the Red Sea and Gulf of Aden. Surveys 1990 to 2000 Summary and Recommendations.* PERSGA Technical Series No.7 (PERSGA/GEF, 2003), PERSGA, Jeddah, 13-25.

Riegl, B. and Piller, W.E., 1999. Coral frameworks revisited - reefs and coral carpets in the northern Red Sea. *Coral Reefs* **18:** 241-253.

Schleyer, M. H. and Baldwin, R., 1999. Biodiversity assessment of the northern Somali coast east of Berbera. IUCN Eastern Africa Programme, IUCN Contract No. EARO/75561/417, 43 p.

Shaked Y. and Genin A. 2011. Red Sea and Gulf of Aqaba. In Hopley D. (ed.) *Encyclopedia of Modern Coral Reefs Structure, Form and Process.Springer, Science+ Business Media B. V.* 2011, 839-843 pp.

Spalding, M. D., Ravilious, C. and Green, E. P., 2001. *World atlas of coral reefs.* University of California Press, 233-258.

Turak, E., Brodie, J. and DeVantier, L., 2007. Reef building corals and coral communities of the Yemen Red Sea. *Fauna of Arabia* **23**: 1-40.

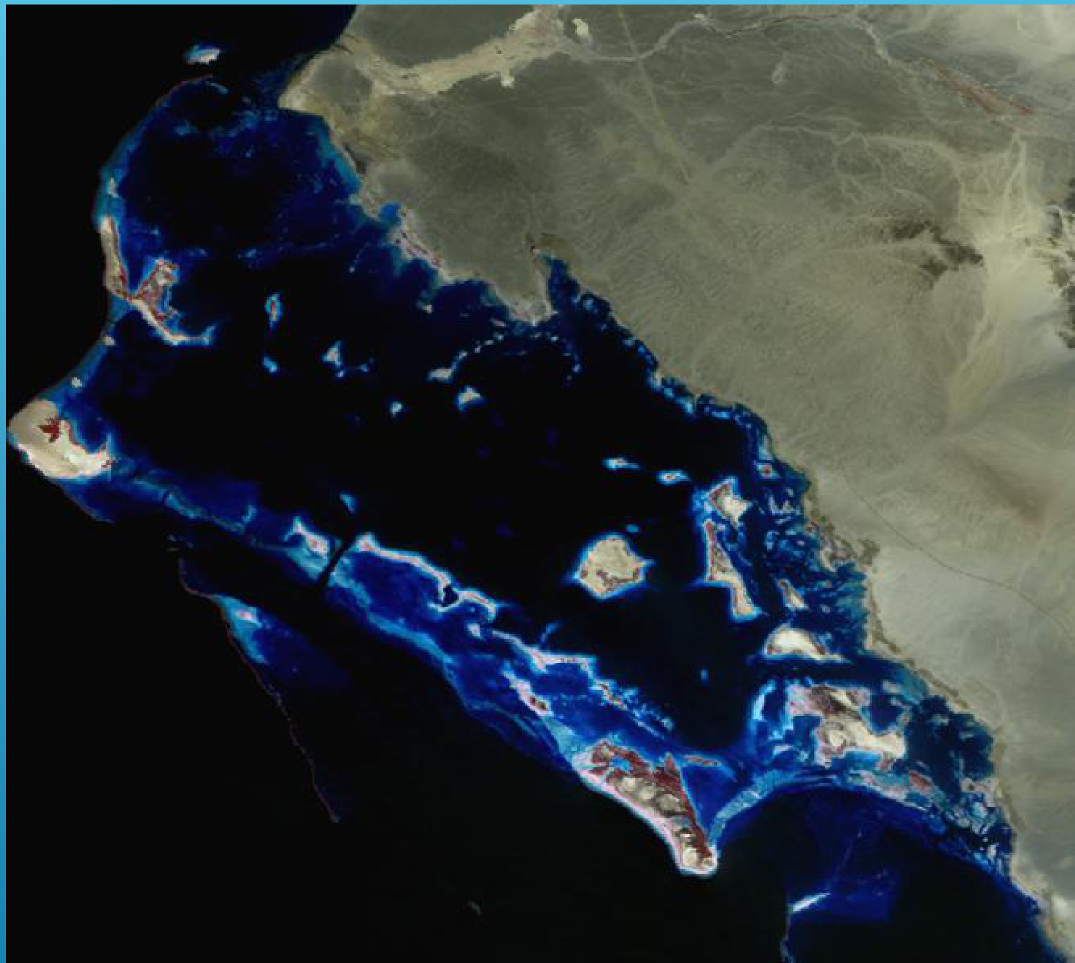
Websites referred:

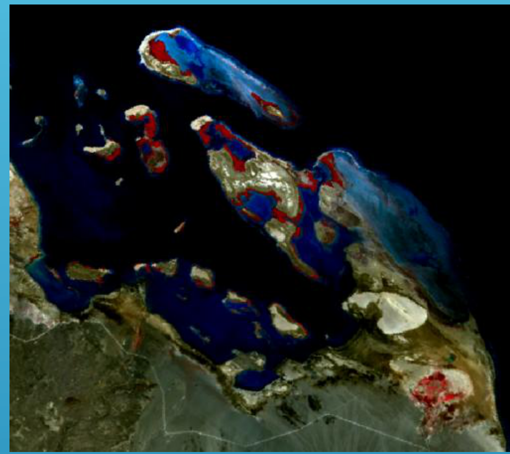
http://www.coral.noaa.gov/reefmaps/volume...

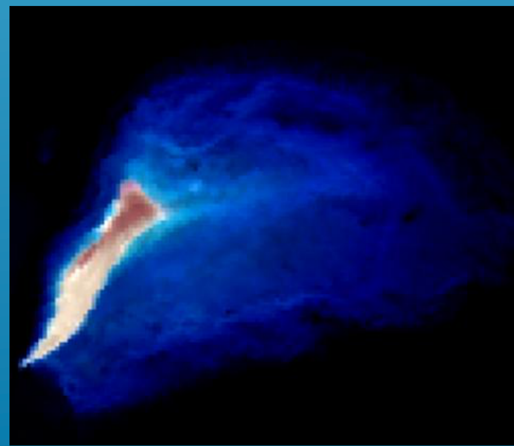
www.nrsc.gov.in

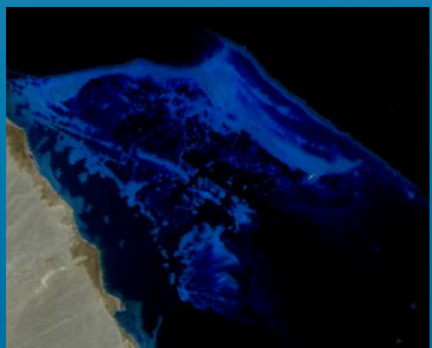
www.reefbase.gov

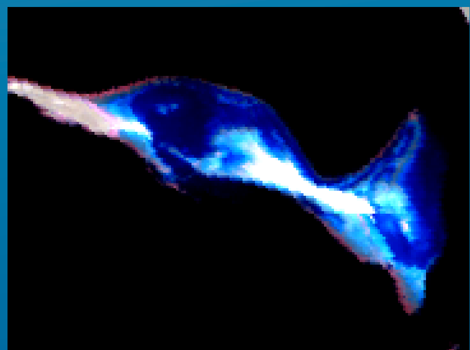
http://www.state.gov/e/oes/ocns/opa/&/6065.html

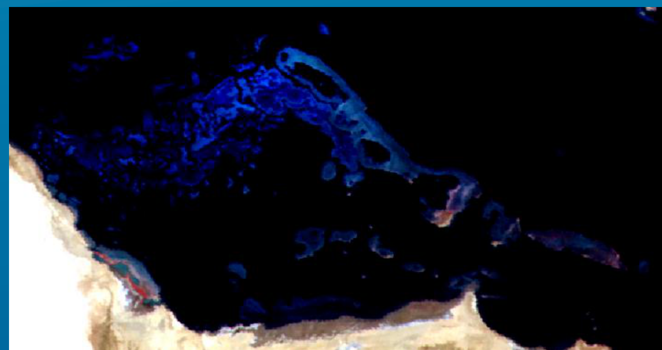












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