UNIVERSITY OF SOUTHAMPTON

LONG TERM CHANGES OF SUVA REEF FLAT COMMUNITIES FROM CONVENTIONAL *IN SITU* SURVEY AND REMOTE SENSING METHODS

by

Veikila Curu Vuki

A dissertation submitted in candidature for the degree of Doctor of Philosophy at the University of Southampton.

March 1994

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

OCEANOGRAPHY

DOCTOR OF PHILOSOPHY

LONG TERM CHANGES OF SUVA REEF FLAT COMMUNITIES FROM CONVENTIONAL *IN SITU* SURVEY AND REMOTE SENSING METHODS.

by *VEIKILA CURU VUKI*

This work is concerned with the combined use of conventionally-gathered data and remote sensing methods to study the communities of Suva Reef, Fiji. A principal objective was to observe coral reef processes that could not be studied effectively by either approach individually. The *in situ* surveys have provided detailed information on reef community dynamics at a small scale while the airborne images have been able to reveal the longer term general patterns.

The results of *in situ* surveys show massive changes to the reef substratum caused by *Echinometra mathaei* excavations. The disturbance caused by *E.mathaei* was associated with increases of turf algae. Four decades of habitat changes were documented from airborne images. The magnitude and spatial extent of these changes were related to likely causes. In particular, the long term patterns of spatial changes of seagrass beds revealed that there were oscillations in the regrowth and losses. Seagrass beds extended towards the lagoon in some years and regressed in others.

Other disturbances have also made significant contributions in shaping community structure of Suva reef flat between 1945 to 1991. Major causes of disturbances were tsunami and cyclone damage, flood damage, *Acanthaster planci* predation and effects of human activities. Tsunamis have probably caused more damage to the structure of the reef than any other disturbance occurring between 1945 and 1990.

This investigation has demonstrated the effectiveness of the combined observational approach in improving our ability to interpret the long term significance of reef changes. The understanding arising from the study will be able to underpin the development of scientifically based plans for conservation and management of reefs.

To Maika

ACKNOWLEDGEMENTS

I am grateful to the many people and institutions who have given generous assistance in this research. I would particularly like to thank my supervisors Dr. Ian Robinson and Dr. Paul Tyler for their guidance and encouragement. Both were generous in their help in reading, checking and editing the drafts of this thesis.

Dr.Leon Zann generously made available his unpublished data and gave valuable advice and support. I am also indebted to him and Susan for their financial assistance which enabled me to carry out field work in 1991. The Staff of the Marine Studies Programme at the University of the South Pacific assisted me during my fieldwork. My special thanks to Ed Lovell for his help in re-checking my study sites.

I gratefully acknowledge the contributions of those who assisted in acquiring aerial photographs used for this research. J.Seeto, E.Lovell and G.Green were most generous with advice and support and were able to locate some of the aerial photographs that were not known to me. The staff of the N.Z. National Archives and the Royal N.Z. Air Force Museum did extensive search of photographs during the World War II.

I also wish to thank the Ministry of Fijian Affairs for their financial support and for generously extending my scholarship to cover for the period of my illness. The French Embassy in Suva provided me with the SPOT satellite data.

My sincere thanks to Susi, Suzanne and Kate for their help in the preparation of the figures. I am also indebted to Dr.Weeks, Suzanne and Steve for their help in proof reading. My friends Moni, Sigrid, Jacyra, Clare, Alison, Miguel and Jose' and all the members of the remote sensing group gave me support and encouragement. The Manuels, Duncalfes, Waqanikas, Maraiwais and the Yabakis gave me support and were always too willing to open their homes and listen to a distraught student. Milika and Helen encouraged me through letters. Kini and Susi Maraiwai were so willing to take care of me during the last stage of my study.

I am most of all grateful to my husband, Maika, whose encouragement made me believe I could go on writing and whose patient love and support has enabled me to complete this task. I also wish to thank all my relatives from Ono and Saqani for their support and prayers. My grandmother Kalolaini Midra and uncle Josefa Tukai did not live to see this thesis completed. My uncle gave me the vision of doing a PhD and I will always be grateful to my grandmother for introducing me at an early age to see the reef in a different light.

Finally, I thank the Almighty God for His grace.

LIST OF CONTENTS

Chapter 5 General Discussion of Results

Chapter 6 Conclusions, Summary and Future Directions

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

GENERAL INTRODUCTION

1.1 CORAL REEFS AND NEEDS FOR LONG TERM MONITORING

Coral reefs are one of the most productive and diverse of natural ecosystems. They protect tropical and subtropical coastlines against waves and storm surges, prevent erosion, and contribute to the formation of sandy beaches and sheltered harbours. They are, however, vulnerable to siltation, overfishing, coastal development, sand dredging, industrial and agricultural pollution and natural disasters. Thus, they need to be managed effectively in order to withstand stress caused by human and natural forces.

Effective management requires knowledge of the extent and distribution of coral reefs, coral communities, status of reef health and resources, effects of pollutants and coral resource potential. The inaccessible location of most coral reefs and their large area of distribution causes great difficulty for conducting *in situ* surveys to assess the impacts of human activities and natural disasters.

Earlier this century, scientists who studied corals and other reef dwelling organisms were restricted to the reef flat because of its accessibility at low tide. The introduction of scuba diving to coral reef research has changed the course of research from the flat to reef slope and lagoon. Research on the reef flat, ironically, has fallen behind when compared to those on the reef slope because the reef flat can only be accessed at very low tide. Diving on the reef flat, except during very calm weather is almost impossible. It is therefore understandable that the vast majority of reef monitoring studies are carried out subtidally even though the reef flat is particularly vulnerable to anthropogenic effects and direct impact by human activities (recreation reef walking and shell collecting; and gleaning) (Wells 1988). Anecdotal reports also suggest that reef flats have been subject to most degradation during the last 50 years. The research described in this thesis is therefore concerned with the study of reef flat communities. A major part of it examines the use of aerial photographs and *in situ* surveys to reconstruct the history and change of community structure of Suva Reef from 1945 to 1991.

More generally, there has been increasing concern about declining reef "health" (Glynn 1984, Lessios *et al.* 1984, Dustan & Halas 1987, Brown 1987, Palca 1987, Williams *et al.* 1987, Brown 1988 and Done *et al.* 1991). Despite this concern there has been much debate on the cause(s) of reef damage over the last 30 years (review by Potts 1981, Moran 1986). Some consider all reef damage to be a result of natural events caused by cyclone damage or terrestrial run-off and that these events have occurred throughout geological time (Grassle 1973, Walbran *et al.* 1989). Alternatively, it has been argued that disturbances to reefs are anthropogenic in origin (Chesher 1969) resulting from chemical pollution (Randall 1972), overfishing (Johannes 1975) or by removal of natural predators (Endean 1969). Clearly the importance of understanding the ecological history of reefs is critical to the interpretations of the specific impacts of a particular physical, biological or anthropogenic disturbance.

It has long been recognised that coral reef community structure varies and is also known to be influenced by processes occurring on a range of temporal and spatial scales (Naylor and Hartnoll 1979, Jackson 1991). Generally, predation (reviewed by Glynn 1990, Knowlton *et al.* 1990), diseases (Antonius 1981, Bak and Criens 1981, Gladfelter 1982) and hurricanes (Stoddart 1974, Porter *et al.* 1981, Woodley *et al.* 1981) are processes that may occur on coral reefs at varied scales of space and time. To quantify controlling influences on community structure observations over relevant time scales are needed. At the very least, the appropriate time scales must encompass the lifespan of the dominant members of the community. For coral reefs, structurally important members may live for centuries (Hughes and Jackson 1985) and important ecological influences may be manifested only on decadal time scales (Done 1992a). Sampling must therefore occur on multiple temporal and spatial scales. Data are needed which are characterised by both fine-grained resolution and large scale, and the monitoring programme must provide means of acquiring both if the ability to answer the most critical questions is not to be lost.

While the need for long term data sets is obvious (Likens 1987, D'Elia *et al.* 1991) no co-ordinated long term monitoring has been developed for coral reefs. With very little long term data available for reef community structure it is difficult to determine what changes have actually occurred on reefs over the last few decades. In the absence of long term studies, changes on reefs that may occur during the next few decades of anticipated increasing anthropogenic pressure and global climate change will be hard to predict.

In Fiji, the existence of long term base-line *in situ* data are scarce because there are very few scientists available to carry out surveys. It is also difficult to assess most reefs because of their isolation. The availabilities of aerial photographs and records of environmental history (Fig.1.1, Table 1.1 and Table 1.2) help to assess long term damage to coral reefs and develop techniques that can detect changes at an early stage.

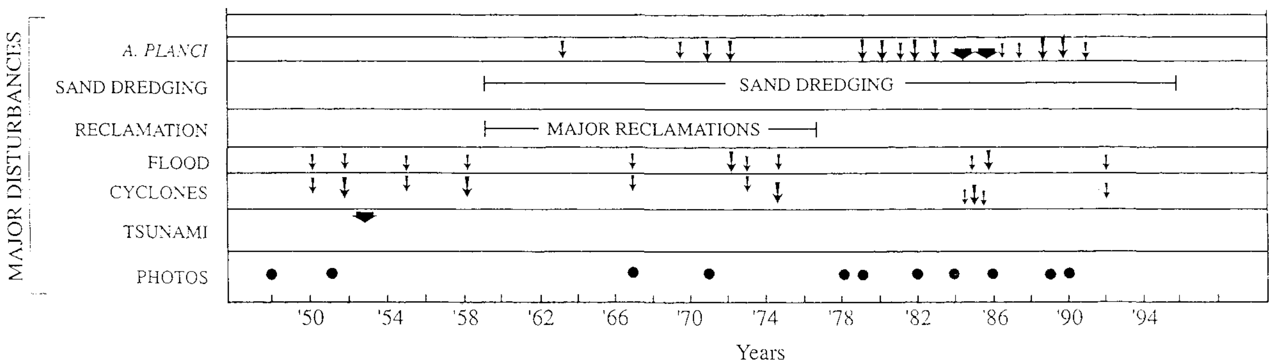


Fig.1.1 Summary of available photographs and major disturbances

Therefore the underlying questions that are being addressed in this research programme are:

(1) Can remote sensing methods be used to assess long term changes on coral reefs?

(2) What indicators of long term coral reef changes can be used to assess coral reef status?

(3) What are the causes of reef disturbance? Are they anthropogenic or natural? Can we separate anthropogenic impacts from natural changes?

(4) What does long term mean? Is a decade enough to determine changes taking place on reefs?

Years	TYPES	INTENSITY	RECORDED DAMAGE
1950 (30th March)	CYCLONE	MODERATE	FLOOD
1951	-	-	-
1952 (28th Jan.)	CYCLONE	SEVERE	FLOOD
1953 (Sept.)	TSUNAMI	SEVERE	Tidal waves and damage to corals
1955 (27th-28th Jan.)	CYCLONE	SEVERE	Flood
1958 (2nd-3rd Dec.)	CYCLONE	SEVERE	Flood
1967 (9th-10th Apr.)	CYCLONE	SEVERE	Flood
1972 (23rd Oct.)	HEAVY RAINFALL	-	Flood
1973 (2nd Feb.)	CYCLONE	SEVERE	Flood
1975 (31st Jan-2nd Feb.)	CYCLONE	MODERATE	Flood
1985 (25th-26th Dec.) (16th Jan) (10th-18th March)	CYCLONES (3)	SEVERE MODERATE MODERATE	Flood
1986 (21st June)	HEAVY RAINFALL	-	Flood
1990	-	-	-

Cyclone, Tsunami and Heavy Rainfall Occurrence in the Suva Area, from 1950 to 1990. (Sources: Dickie *et. al.* 1990 & Met. Office)

YEARS	ABUNDANCES, SECTIONS OF SUVA REEF AND NOTES
1963	Common, Western Suva Reef at vicinity of transect 5, slight damage.
1969	Common to abundant on Suva Reef (section not specified), dead standing corals.
1971-72	Abundant on reef slope of Western Suva Reef, several thousands were killed.
1972-82	Few on Western Suva Reef
1979	Abundant on Eastern Suva Reef, within the vicinity of transect 2.
1980	Abundant on Eastern Suva Reef, within the vicinity of transect 2.
1981	Common on Eastern Suva Reef.
1982-83	Abundant on Western Suva Reef, within the vicinity of transect 5, >1,000 were killed.
1984	Aggregations at Eastern Suva Reef, within the vicinity of transect 2.
1985	Outbreaks on Suva Reef, Western Suva Reef, near transect 4.
1986	Decline on Suva Reef, within the vicinity of transect 2.
1987	Very few adults on Suva Reef within the vicinity of transect 2.
1988	Juveniles common on Eastern Suva Reef.
1989	Adults abundant on Eastern Suva Reef within the vicinity of transect 3 and at backreef.
1990	Adults abundant at vicinity of transect 3 and near backreef near transect 2.
1991	Common within vicinity of transect 3 and 4.

Abundances of *Acanthaster planci* on Suva Reef from 1963-1991. (Sources: Zann *et. al.* 1990, this study).

1.2 OBJECTIVES AND REASONS FOR THIS RESEARCH PROGRAMME.

The primary question to be addressed in this research is whether remote sensing methods can be used to determine long term changes on coral reef flats in Fiji?".

The objectives of the project are :

(1) to determine long term temporal and spatial ecological changes using both conventional *in situ* survey methods and remote sensing method. A suitable methodology based on Geographical Information Systems (GIS) and image processing techniques to assess the changes from airborne images was developed.

(2) to evaluate the value of remote sensing methods and conventional *in situ* survey methods in assessing long term ecological patterns. Both the magnitude and the nature of these changes were assessed.

Subsidiary questions include :

(1) Are there dramatic changes occurring on Suva Reef? Are there any shifts in dominance of habitats?

(2) Is there any decline in major habitats from 1951 to 1991? What are the causes of decline?

The intention in this study is to integrate *in situ* and remote sensing techniques for rapidly assessing long term changes on coral reefs at different scales but primarily at a community level. Therefore in describing the ecology of the reef, broad categories have been established. This approach does not negate the importance of species but helps to put high resolution information into a broader context. In addition, homogeneous groups of communities are easier to detect from remote sensing methods.

1.3 SCOPE OF THIS RESEARCH PROJECT

The methods utilised can be broadly categorised at two levels. Aerial photography can survey reefs at a meso-scale level and *in situ* observations are at micro-scale levels. For the purpose of this research, the aerial photographs provide sampling relatively regularly over a longer period while the *in situ* surveys are occasional.

The way in which these methods relate to one another are illustrated in Fig.1.1. *In situ* observations provided occasional "snapshots" in 1984, 1989 and 1991 of six transects on Suva Reef. These observations should show temporal and spatial variability of reef communities at specific transects. The questions that must be asked are; to what extent is this information representative of the entire Suva Reef? and how representative of a given year is a single field sampling?

On the other hand, aerial photographs should fill the gaps in space and time that cannot be provided by *in situ* observations because of the regular sampling by aerial surveys between 1945 and 1990. *In situ* observations should also help to calibrate aerial photographs. For future applications *in situ* data and aerial photographs should assist in the calibration of satellite data and airborne thematic data for large scale and long term studies on coral reefs, although insufficient satellite data was available for useful analysis within this project.

1.4 STRUCTURE OF THE THESIS

In Chapter 1, the needs for long term monitoring of coral reefs and major aims of this study are being addressed. Chapter 2 presents a review on community studies, disturbance and stability. It also discusses the concept of indicators of reef health. The techniques and the technology used for monitoring coral reefs are also reviewed in this chapter.

In Chapter 3, the *in situ* survey methods and results are presented and discussed. The nature of the changes on the reef are interpreted and are related to some causes.

Chapter 4 explores and develops the use of aerial photographs and image processing techniques to document long term changes at different periods.

The discussion of the results of this study are presented in Chapter 5. In Chapter 6, the conclusions are drawn from this study. An assessment on the benefits of combined airborne images with the more conventional methods are carried out. Suggestions are also made for future extensions of this work.

CHAPTER 2

REVIEW OF REEF COMMUNITY STUDIES AND SURVEY METHODS

2.1 REEF COMMUNITY STUDIES, DISTURBANCE AND STABILITY.

Current research on coral reefs can be evaluated in two ways firstly at a community level and secondly at species level. Community studies have been used mainly to describe the status of coral reefs and especially in defining perturbed conditions (Dahl and Salvat 1988).

Reef community structures are complex and dynamic (Dahl & Salvat 1988). They are shaped and maintained by biotic and abiotic events (Witman 1992). When community structures are related to human impacts and natural disasters the task of monitoring is even more difficult since both time and space must be considered. The different components of the reef systems also vary in scale of occurrence. Some may persist for a long time while others may have a high turnover of individuals. These must be borne in mind when discussing suitable indicators of coral reef health and effects of disturbance.

In order to determine the causes of changes in reef community structure it is essential to carry out studies over time scales long enough to document at least one of these events. The events which have been reported to alter reef community structure are hurricanes (Porter *et al.* 1981), severe outbreaks of coral predators (*Acanthaster planci*) (Moran 1986) and coral bleaching phenomena (Glynn and Weerdt 1991, Lang *et al.* 1992) or El Nino events (Glynn 1990).

There are currently two schools of thought about coral reef stability with regard to natural phenomena (Grigg & Dollar 1988). The first proposes that the reef ecosystem is stable because of its ancient origin and its evolution of great complexity where conditions have been uniform over long periods. This complexity has certain "limits" and can be very fragile if pushed beyond these limits (Goreau 1969, Johannes 1975, Endean 1976). The second school of thought states that the reef ecosystem is unstable over time and heterogeneous in space. The present reefs around the world are believed to be in different stages of structure and organisation and are being continually modified by natural perturbations (Grassle 1973, Grigg and Maragos 1974, Connell 1978).

The expected effect of human influence will depend on which view is seen to be important. In the first view, human effects bring changes that are irreversible and will cause rapid destruction of coral reefs. In the second view, human effects are relatively minor when compared to natural perturbations (cyclones, predation and terrestrial run-off) given the instability of the system.

Both views may be relevant and complementary in any assessment but will depend on the scale of community structure being studied. The stability of many reef systems may also be a result of dynamic instability of parts of the system which have the ability to re-establish balance after a natural shock (Dahl & Salvat 1988). On the other hand, at a larger geographical scale, human influences may push the system beyond its limits which may lead to rapid degradation (Dahl 1985).

Distinguishing human from natural effects in a coral reef ecosystem is difficult especially where the scales of interaction are complex in time and space. Reviews of natural events damaging reefs have been provided by Stoddart (1969) and Loya (1976). These natural events were flood, low temperatures and exposure to air. The main anthropogenic effects on reefs have been reviewed by Johannes(1975), Brown & Howard (1985), Salvat (1987), Grigg and Dollar (1988) and Dahl & Salvat (1988). These include sedimentation, dredging, sewage effluent, filling and construction, oil spills & dispersants and heated effluent from power plants. Some human effects may mimic the natural influences, for example siltation from construction or from run-off after heavy rains. Effects may differ in their duration and the size of the area affected.

Given the difficulty in determining causality linking human activities with reef impacts and separating anthropogenic impacts from natural changes, it may be possible to consider aspects that can be measured. In some cases damage can be done directly to the substrate by mechanical activity and changing the reef shape and producing sediments which cover hard surfaces. If the hard surfaces are covered by sediments it will damage living communities on the reef surface and also expose new substrate. Channel blasting and construction activities may have such effects (Smith & Henderson 1976, Nontji 1986). Any new surface created by significant coral mortality will be coral rubble and will be colonised by opportunistic organisms such as algae. This will have a major effect on coral reef community structure and especially on the living coral cover.

2.2 INDICATORS OF REEF HEALTH

The concept of "indicator species" for detecting pollution in the marine environment has been adopted by reef researchers to describe a healthy reef community. Percentage cover and species diversity indices have been used as indicators of reef health (Dustan & Halas 1987, Done 1981, 1982, 1987, Hughes & Jackson 1985, Hughes *et al.* 1987). The sensitivity of such indicators in describing environmental impacts on coral reefs were questioned by Brown (1988). However, results of seven years of study at Key Largo from monitoring the abundance of corals showed significant changes (Dustan & Halas 1987). Although significant changes were apparent they were not as obvious to the same degree as those from photographs and field observations. They argued that a less "myopic" view of the reef in terms of assessment of algae, fish, major invertebrate groups and corals would be more appropriate.

There appears to be a confusion in the literature on the evaluation of species diversity as a valuable and sensitive indicator of coral reef degradation. Some workers argued that species diversity adopted to detect polluted communities are more appropriate for tropical soft bottom communities rather than coral reefs (Gray 1979, Gray & Mirza 1979, Gray 1981, Warwick 1986). Warwick further argued that it is difficult to find suitable ways to assess the coral reef health because of the natural variability and effects of natural disasters and human activities on community structure.

2.3 REVIEW OF REEF SURVEY TECHNIQUES, REMOTE SENSING TECHNOLOGY AND TECHNIQUES AND APPLICATIONS.

2.3.1 *IN SITU* SURVEY METHODS FOR ASSESSING REEF COMMUNITIES.

A variety of different quantitative survey techniques have been developed and applied to the assessment of coral reef sessile benthic communities (Goodwin *et al.* 1976, Kinzie & Snider 1978, Loya 1978, Bouchan 1981, Weinberg 1981, Dodge *et al.* 1982, Birkeland 1984, Marsh *et al.* 1984, UNESCO 1984). These methods are usually modifications of transect or quadrat techniques used for plant ecological surveys. The theoretical backgrounds, strengths and weaknesses of these methods have been discussed by workers on plant communities (Greig-Smith 1964, Kershaw 1964 and Poole 1974).

However, there is no consensus as to which method are most appropriate for reef communities surveys. Loya (1978) reviewed plotless and transect methods for reef surveys and recommended the use of plotless methods. Weinberg(1981) evaluated different methods and recommended quadrat methods. Dodge *et al.* (1982) found no significant differences between three plotless methods and photographic belt quadrats while Bouchan (1981) found no significant differences between quadrats and plotless (line) methods. Birkeland (1984) advocated the point quarter method for large individuals or colonies and the planar point intercept method for taxa such as algae. UNESCO(1984) recommended the use of both transect method and the plotless point quarter technique.

There is a need to compare the methods commonly used to assess reef communities. Such evaluations are vital for ascertaining the most suitable and time efficient techniques for reef surveys.

2.3.2 DEVELOPMENT OF REMOTE SENSING TECHNOLOGY, METHODS AND APPLICATIONS TO CORAL REEFS

In the past researchers have relied mainly on *in situ* data to provide information on the coral reef environment. The advantage of using remote sensing as a tool for gathering information for the coral reef environment is that it provides a synoptic view of a large area which cannot be provided by any other means (Goetz & Rowan 1981). The remote sensing method is repetitive and provides a quick collection of spatial and temporal information that could be utilised to detect important changes (Kuchler 1985a). The generally clear waters that exist on coral reefs make it possible to explore them by remote sensing methods that were originally developed for landuse.

Aerial photography has traditionally served as the principal medium of analysis of coastal changes (El-Ashry 1977). However, aerial photographs are still considered to be important in detecting changes because of very high spatial resolution and also they provide many decades of data. In particular, aerial photographs have advantages because they provide the level of detail necessary for detecting change and especially where photogrammetric methods are employed (Leatherman 1993).

It is, however, surprising that after many decades of the availability of high resolution aerial photographs there has been no long term study of coral reefs using this method, although, it is recognised that it cannot replace *in situ* survey methods in understanding some coral reef processes. In this study, the limitations of aerial photography are recognised but the usefulness of the information obtained is considered to be too valuable to discard and may be the only information available on isolated reefs such as those encountered in Fiji.

A review of applications of aerial photography to the coral reef environment is provided in Chapter 4. However, aerial photography has been previously utilised by several investigators for change detection of land and submerged vegetation in the early sixties (Edwards and Brown 1960, Kelly and Conrad 1969, Orgoskey 1978 and Orth *et al.* 1979). Aerial photographs were also used to prepare the Sri Lankan Coastal Zone

Management Plan (Wisumperuma 1989) where five broad classes were categorised into coastal wetlands, lagoons, estuaries, sand dunes and barrier beaches.

The emergence of satellite data provided an alternative for mapping of coastal habitats such as coral reefs. In contrast to aerial photographs, satellite images do not usually provide the level of detail necessary for precise measurements of environmental change because of the limitations of resolution. Landsat Multispectral (MSS) data with 79 m pixels is far too coarse to detect changes except in a qualitative sense or when there is an extremely rapid rate of change (Leatherman 1993). Nevertheless, SPOT imagery can provide 10 m pixel resolution necessary to quantify changes on coral reefs when considered on long term basis. In addition, SPOT multispectral data can provide 20 m resolution which is necessary in differentiating the spectral features of coral reef habitats. In this study, there was only one SPOT image available for Suva Reef. This SPOT image was used for geometric corrections of airborne images and also for additional verifications of different classes categorised from airborne images. The applications of satellite data to the coral reef environment are also discussed in this review.

When data from Landsat series and SPOT satellites became available in 1972 and 1986 respectively, they provided opportunities for studying coral reefs from space. The usefulness of satellite data to coral reef study was first demonstrated in 1975 on the Great Barrier Reef Region by mapping physiographic zones of inshore and offshore reefs using Landsat digital data (Smith *et al.* 1975). In 1976, a bathymetric study using Landsat data clearly showed that such a study could be undertaken in clear waters of the coral reef environment (Polcyn 1976).

However, in 1977, a major breakthrough on the practical use of Landsat data was the revising of the Nautical Chart of the Indian Ocean Chagos Archipelago (Hammack 1977). The results showed that shoals, banks and reef features can be located and positioned on Landsat image data with respect to known surface features. It was not until 1978 that the benefits of using Landsat data for mapping and monitoring isolated reefs was carried out on Apo Reef, Mindoro Island, Philippines (Bina *et al.* 1978). The study produced thematic maps of Apo Reef from Landsat digital data and highlighted a major difficulty in categorising reef covers using digital data because of variability in spectral reflectance.

In 1979, Bina and Ombac noted the inconsistencies of satellite data through time. The inconsistencies resulted from differing water depths associated with tidal stages during the recording time of satellite data. It was later found that spectral changes influenced by tidal variation can be contrasted to environmental changes on coral reefs (Kuchler 1985a).

Furthermore, previous studies on coral reefs indicated that the Landsat spatial resolution allows a correlation with the spatial relationships and patterns observed on coral reefs (Bina 1982, Hibbs 1982, Jupp 1983a, 1983b). More importantly, studies on coral reefs showed that the different zones on the reef can be distinguished on satellite images and as a consequence coral reef resource information can be extracted (Smith *et al.* 1975, Bina *et al.* 1978, Bina 1982, Hibbs 1982, Jupp 1984, Jupp *et al.* 1985, Maniere *et al.* 1985, Kuchler 1987).

In the early 1980's, research activities on the application of remote sensing on coral reefs were centred on the Great Barrier Reef. The problems of obtaining data for the 345,000 km^2 of the Great Barrier Reef and the need for information to manage the thousands of coral reefs that constitute the Marine Park led to various reef studies using remotely sensed data (Jupp 1984, Kuchler 1985a, Kuchler *et al.* 1988).

By using satellite data, a practical and useful Landsat based reconnaissance mapping of the Great Barrier Reef was achieved (Jupp 1983a). As a result of the Great Barrier Reef research, a number of surface ground categories combined into classes were established to resolve elements observed from remote sensors and to further recover resource information. The success of the research on the Great Barrier Reef was attributed mainly to the development of a suitable software for analyses (Micro Brian) and its ability to deal with "category mixtures problem".

The low contrast of satellite data which is caused by the submerged nature of some reefs presents a major problem in applying remote sensing to study coral reefs (Kuchler 1985b). The lack of available Landsat and SPOT satellite data for Fijian reefs is a major limitation in its use in the study of long term changes. In addition, the limited available satellite data were mostly covered by clouds and were not useful when comparing different time scales. The only satellite receiving station in Fiji is for receiving AVHRR data for weather forecasts. This type of data is not suitable for coral reef studies where higher resolution data are required.

Despite the limitations of satellite remote sensing, it has potential for coral reef monitoring. The development of image processing techniques to process satellite imagery for change detection has also been encouraged by the availability of satellite data. These techniques usually involves the use of multi-temporal data sets (Singh 1989) which could discriminate areas of change between sets of images. Several methods have been proposed and a comprehensive summary is given by Singh(1989). These methods required the accurate spatial registration of images used. The three main image processing techniques were image differencing, image ratioing and principal component analyses. These image processing techniques were suitable in change detection for multispectral data (Singh 1989, Zainal 1993).

However, techniques such as various filtering, smoothing, and edge enhancement are also used to improve accuracy in classification, although it was found that image differencing and ratioing performed better (Singh 1989). The choice of image processing techniques used will depend on the nature of information to be extracted from the images whether panchromatic or multispectral (Pilon *et al.* 1988).

Numerous studies have been undertaken to determine the efficiency of several techniques in extracting information from images. Pilon *et al.* (1988) used a multi-component approach starting with simple enhancement techniques to isolate changes followed by classification to identify changes in semi-arid regions of Nigeria. Howarth and Wickware (1981) used simple ratio enhancement techniques which provided a series of vegetation changes. In a more recent study, Zainal (1993) concluded that there is no specific technique or approach that can be applied to ensure its success. He further suggested that testing different techniques and assessing the merit of their results by comparing them with field data is probably the way forward.

As far as the current investigation is concerned, an important difference exists between panchromatic airborne data and multispectral data. Any method used in the analysis of panchromatic data should be able to separate the subtle habitat changes between different dates. For the purpose of this study, the way to achieve reliable results would only be possible by a combination of field data, visual examination of airborne images and using simple change detection functions in the Geographical Information Systems (GIS) routines.

CHAPTER 3

CORAL REEF DYNAMICS FROM 1984 TO 1991 USING CONVENTIONAL BIOLOGICAL SURVEY METHODS.

3.1 INTRODUCTION

Despite early interest in the reefs of Fiji (Gardiner 1898, Agassiz 1899, Davis 1920, Hoffmeister 1925) and their importance in the development of coral taxonomy (Dana 1846), there are still relatively few studies published. The most detailed description of reefs in Fiji to date are those of Ryland(1979, 1981).

The vulnerability of Fijian reefs to disturbance caused by cyclone and human activities are very important considerations when explaining changes on Suva Reef. Coral predators affect the survival of corals and ultimately reef communities. Zann *et al.* (1987, 1990) showed that the outbreaks of the crown of thorns starfish *(Acanthaster planci)* on Suva Reef was the major controlling factor in coral community changes.

The search for patterns of distribution of the diverse organisms found on coral reefs has been an important endeavour of coral researchers (Licuanan & Gomez 1988). Previous detailed reef studies have focused primarily on zonation of scleractinian corals (see Done 1983 for review) without assessing other reef organisms.

Zonation of scleractinian corals has been described on the basis of dominant species (Wells 1957, Rosen 1971) and lack of dominant species (Sheppard 1980). Variables such as diversity, evenness and richness measures were commonly used, along with multivariate methods, to analyse large numbers of species and individuals by sample matrices (Loya 1972, Veron & Done 1979, Done 1982). The recognition of plasticity of coral species (Veron & Pichon 1976, Willis 1985) and taxonomic problems have facilitated the development of assessing zonation on the basis of broad categories such as growth form attributes (Rosen 1971, Pichon 1978).

Reef assessments on the Great Barrier Reef (Dartnall & Jones 1986) and the Philippines (Licuanan & Gomez 1988) have used life form categories, along with taxonomic identifications, to the lowest possible level (for example family and genus level). Bradbury *et al.* (1986) showed that broad level data on the patterns of distribution of organisms on reefs can yield information approximating those collected with species level data. The value of information obtained from broad level data will depend on the goals of the study and whether one is comparing similarities and differences between reefs.

Using a similar approach, this study aims to describe zonation patterns on Suva Reef from 1984 to 1991. By classifying attributes into broad categories the zonation patterns are established. The influence of natural disturbances and human activities are also discussed in relation to changes in the patterns observed on the reef over a seven-year period.

3.2 STUDY AREA

3.2.1 PHYSICAL SETTING

Fiji comprises about 844 islands and are scattered in the area of 15°S to 23°S and 177°E to 178°W (Fig.3.1). The Suva Reef is located south-east of Suva Harbour (18° 08' S, 178° 25' E) on the south coast of Fiji's main island, Viti Levu (Fig.3.2). It is part of the Viti Levu south-eastern reef chain and encloses Suva Peninsula and Laucala Bay.

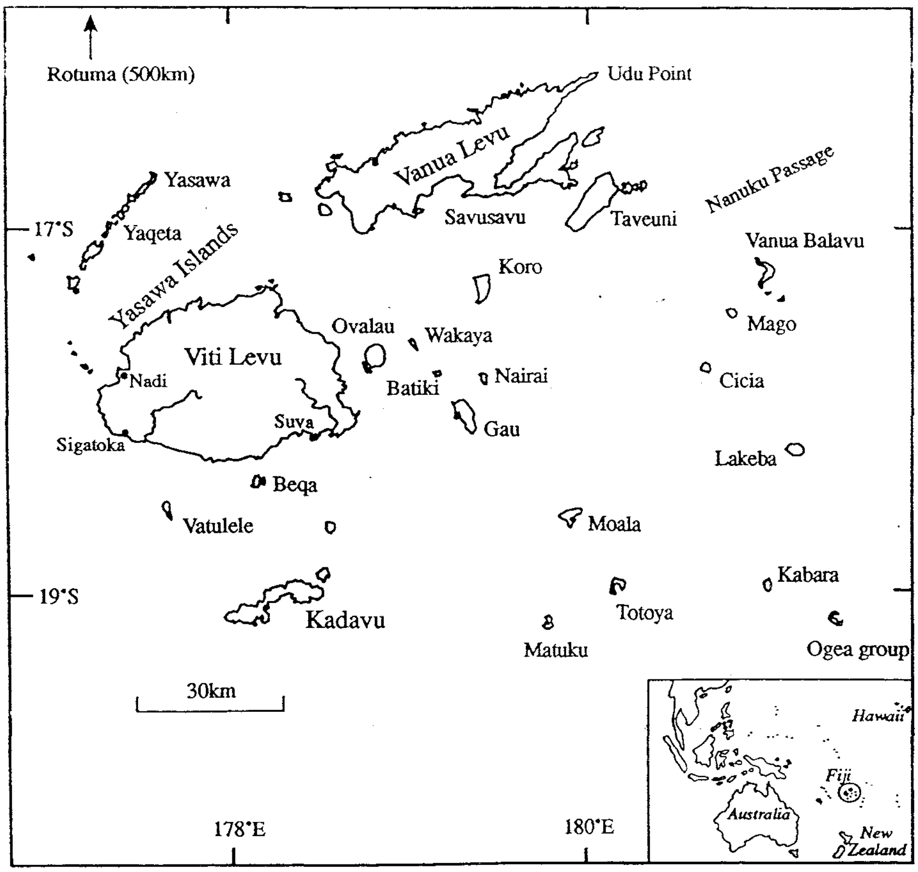


Fig.3.1 Map of Fiji Islands. Inset: Fiji's location in relation to Australia, New Zealand and South-East Asia.

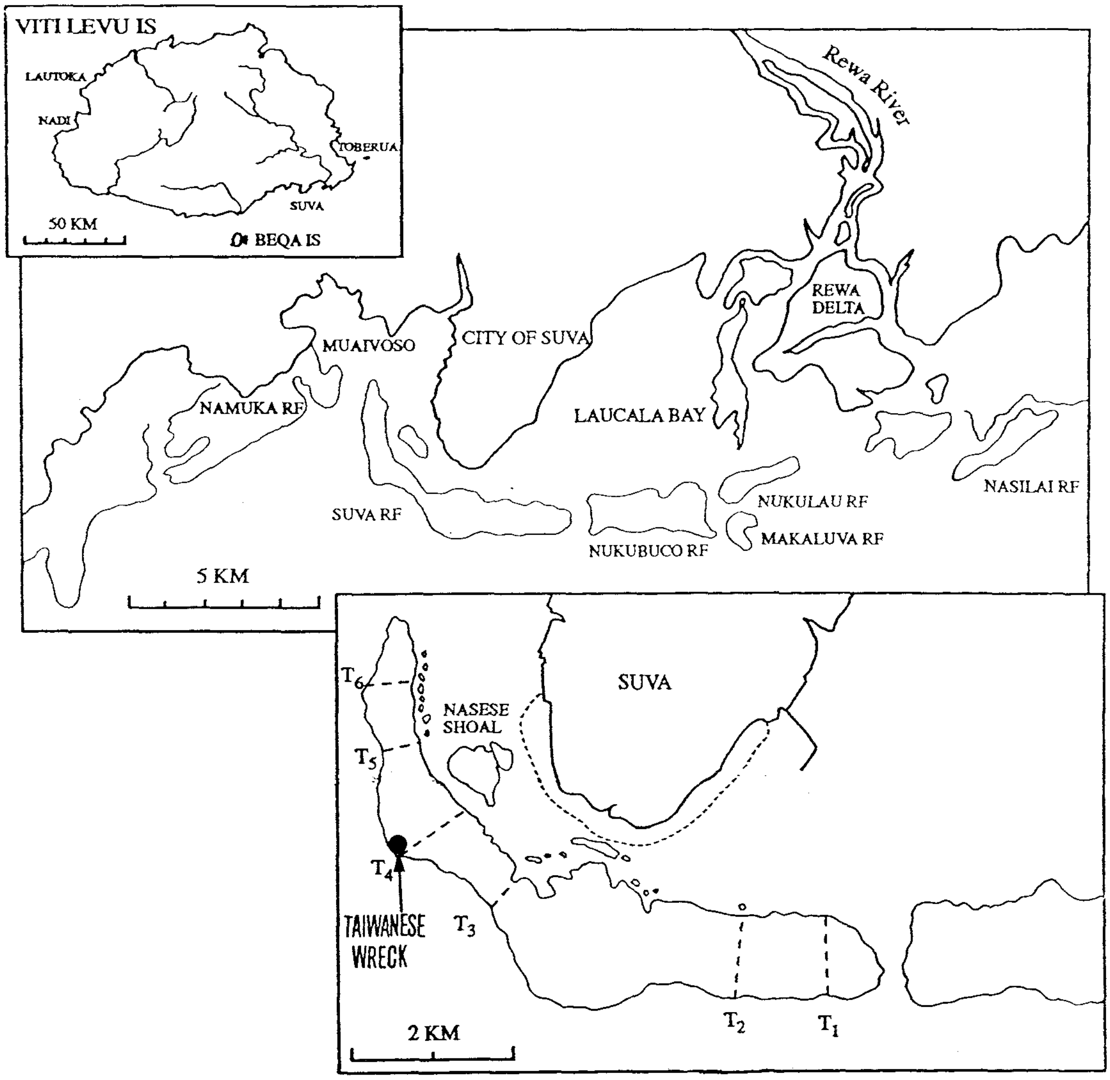


Fig.3.2 Location of Suva Reef. Inset above: Viti Levu Island, Fiji. Inset below: detail of Suva Reef transects.

Suva Reef is a barrier reef and lies between one and five km off the coast of Suva. A narrow lagoon of about 10m deep separates the reef from the city of Suva. Suva has a population of approximately 160,000 (1986 census).

3.2.2 CLIMATOLOGY

Suva Reef is subject to the East and South-East trade winds. These are most persistent from July to December. The western edge of the reef is sheltered but the eastern part is more exposed to wind-driven swells and waves.

The mountainous southeastern part of Viti Levu island has a high annual rainfall, with occasional years of very high summer rainfall associated with tropical cyclones. The annual rainfall is unevenly distributed because of the rain shadow caused by mountains.

High rainfall associated with cyclones often leads to severe floods, land erosion and high sediment loads in local rivers and coastal waters. Rainfall is seasonal with distinct dry (May-October) and wet (November-April) seasons. About 67% of the annual rainfall in the Suva area occurs in the wet season (Dickie *et al.* 1990).

The main river entering the Suva lagoon is the Rewa River which has a mean annual discharge equivalent to 160 $x10^6$ m^3. A discharge of over 10,000 x 10^6 m^3 were experienced in 1972, 1973 and 1986. However, the largest flood record was estimated at 17,000-19,000 $x10^6$ m^3 in 1931.

The mean monthly air temperatures range from 23°C in July and August to 27°C in January. The summer is hot and wet but the winter months are drier and cooler. Daily sunshine values reached a maximum during December and decline to a minimum during July and September (Penn 1983).

3.2.3 **TSUNAMIS**

Eleven tsunamis have been recorded in the Fiji group since 1877. Only three produced waves of significant heights in the Suva area, rising 2m in 1877, 1.8m in both 1881 and 1953.

During the 1953 Suva earthquake, a tsunami of 1.8m height reached Suva. This occurred at low tide but would have had an even more disastrous effect if it had occurred at high tide. Considerable reef damage was reported after the 1953 tsunami (Wells, 1988).

3.2.4 **OCEANOGRAPHY**

South-easterly swells predominate through the year with significant easterlies occurring from July to December. The wave and swell records in Laucala Bay show a positive correlation with wind data (Dickie *et al.* 1991).

Tidal range is very small, with an annual mean range of 1.1m. Neap tides have a mean range of 0.9m and springs of 1.30m (Ryland 1981). The Suva area experiences predominantly semi-diurnal tides with the lower low water springs falling during the night in summer but during the day in winter.

The annual sea surface temperatures in Laucala Bay vary from 24°C to 31°C during the year. It has an average annual variation of 6°C. The normal salinity is 35‰, and may drop to 10-15‰ after heavy rainfall (Zann *et al.* 1987). During heavy rainfall associated with cyclones large discharge of terrestrial sediments are transported to the sea (Ryland *et al.* 1984). High sediment loads over such a short period caused mortalities of marine organisms in Laucala Bay and also on Suva Reef.

The oceanography of Suva reef has been described by Penn(1983) and Gendronneau(1986). The strongest tidal current in the lagoon was observed three hours before and after low and high tides. In contrast the weakest currents were at low and high tides. Oceanic water enters the lagoon through Nukulau and

Nukubuco passages during flood-tide and leaves by the same route at ebb tide (Fig.3.3).

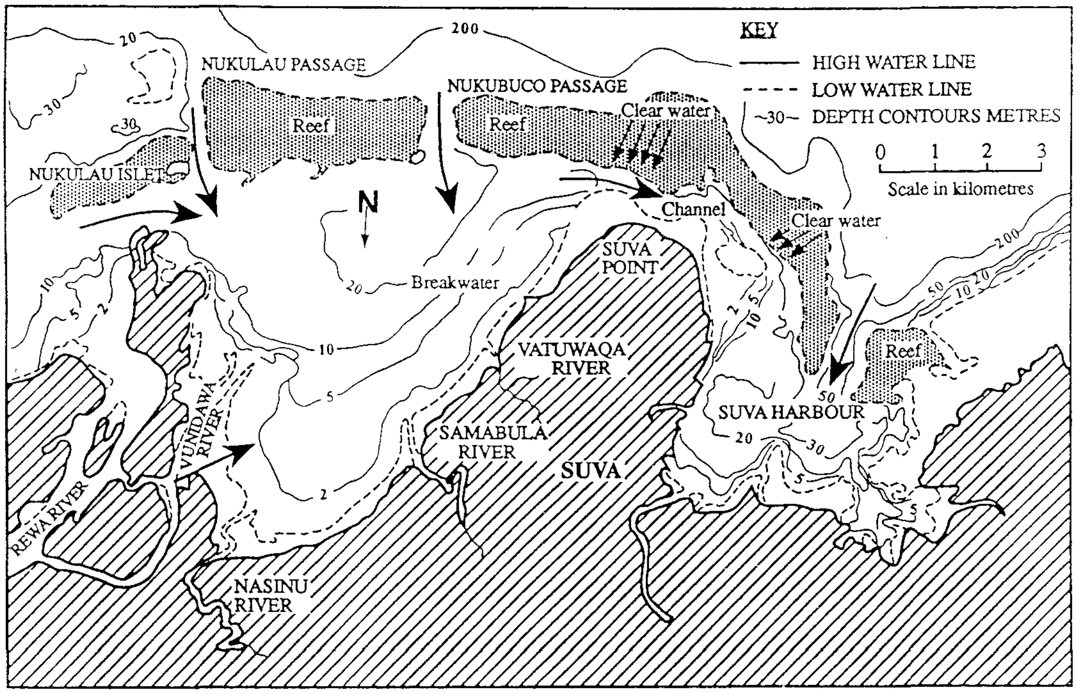


Fig.3.3 Map showing oceanic water entering the Suva Lagoon.

In general, the dynamics and high variability of currents in the lagoon were influenced by four important factors:

(1) the tidal cycle,

(2) flow of Rewa river and other smaller rivers and creeks flowing into the lagoon,

(3) oceanic water entering the lagoon over the reef top and through different passages which depends on tide and surf and

(4) influence of strong and continuous trade winds.

3.3 MATERIALS AND METHODS

3.3.1 SAMPLING DESIGN AND FIELD SAMPLING

Six transects on Suva Barrier Reef were established in 1984 to survey the population of coral predator starfish, *Acanthaster planci* (L.) (Zann *et al.* 1987, 1990) (Fig.3.2). The transects were permanently marked with steel pegs driven into the hard coral rock substratum every 15m to 30m across the reef. The land bearings were also noted for each transect to ensure easier relocation when re-surveyed. Several ways of relocating the permanent steel pegs were used. Some branching corals near the steel pegs were tied with fluorescent ribbons and some of the massive corals were permanently marked with aluminium nails with fishing line. The fishing line was tied to white plastic containers which could be seen from a distance.

In 1984, transects 1 to 6 were surveyed. At each transect, a 15m line was laid from the seaward reef edge and at the beginning of each line a station was established to estimate the % substrate type and the % surface cover of dominant living communities (Zann, unpublished data).

This present survey evolved from the methods used in the above investigation to assess *Acanthaster planci*. From June to August of 1989, a re-survey of the six transects was undertaken for this study. A 15m line was used and at the beginning of each line a station was established. At each station, 5 random replicates of 0.5m x 0.5m quadrats were undertaken. The % substrate type (coral rock, sand and *Acropora* rubble), living communities (turf algae, living corals, soft corals, zoanthids and seagrass) were estimated in each of the five quadrats. The algal assemblages have been differentiated as "turfs", "fleshy" and "coralline" algae. Most reef workers recognise "turf algae" as primarily filamentous algae having a canopy height of 1-10mm (Dahl 1972, Pichon & Morrissey 1981 and Carpenter 1981). Fleshy algae includes larger (canopy heights usually >10mm), erect algae described by Adey *et al.* (1977).

Coralline algae are calcareous crustose coralline reviewed by Steneck(1986).

In addition, a number of selected echinoderms (*Echinometra mathaei, Acanthaster planci, Linckia laevigata, Tripneustes gratilla*) were estimated in each of the five quadrats sampled.

3.3.2 **DATA ANALYSES**

Analyses of data involved a comparison of the abundance (% cover and density) between transects, between years and between stations within each transect. A variety of univariate and multivariate statistical techniques has been used to compare coral reef community structure in this study. The following suite of analytical procedures was adopted and the rationale for each procedure is also described here.

A suite of non-parametric tests was performed. Using Sigmastat Statistical Package the test for normality (Kolmogrov-Smirnov) and the test for equal variance (Levene Median) on different types of transformed data were performed. Data on % cover were transformed using arcsin or sqrt, and $\log_{10}$ and $\log_e$ transformations were also carried out to help transform data for normality and equal variances as required by the assumptions of parametric tests. The transformed data, however, often failed when tested for normality and also for equal variances. In some cases, the transformed data passed the normality tests but then failed the equal variance tests. Since the assumptions for parametric tests were violated, non- parametric tests were adopted in most cases. Unless otherwise stated statistical "significance" refers to the 5% level of significance.

The non-parametric test Kruskal Wallis Anova (analysis of variance) on Ranks (Sokal & Rohlf 1973) was used to compare different attributes within one transect and also with attributes between different years within one transect. The assumption is that the samples were drawn from non-normal populations and do not have equal variances. The Student Newman Keuls (SNK) test (Sokal & Rohlf 1973) was used to further determine any differences in attributes between years if the Kruskal Wallis ANOVA on Ranks test was significant. The Mann-Whitney Rank Sum test (Sokal & Rohlf 1973) was used to determine differences in attributes between stations within each year, since there is no two factor test for non-normal populations. All these tests were performed using the statistical package Sigmastat.

The hierarchical clustering was performed on a euclidean distance dissimilarity index based on the raw data and using the group-average linkage. Cluster analysis was carried out using the statistical package Unistats.
Cluster analysis was performed to broadly categorise different sections of the reef flats within a transect. The analysis of variance tests was used to confirm whether these broad categories were significantly different between years and also between stations.

3.4 RESULTS

3.4.1 MORPHOLOGICAL ZONATION AND GENERAL ECOLOGY AT EACH TRANSECT

A summary of subjective assessements of zonation patterns at each transect is given in Table.3.1.

Table 3.1 Summary of general zonation patterns at each transect (** dominant).

TRANSECT	BACKREEF	MIDDLE AND INNER REEF FLAT	SEAWARD REEF EDGE
1	sand** seagrass ** low coral cover	rubble** boulders** turf** echinoderm** low coral cover	coral pavement** coralline** table corals ** spurs/grooves **
2	sand** seagrass** algae ** low coral cover	rubble** live corals** boulders** turf** echinoderms**	coral pavement** coralline** low coral cover spurs/grooves**
3	sand** seagrass** algae** low coral cover	live corals** boulders** echinoderms**	coral pavement** low coral cover spurs/grooves**
4	sand** seagrass** algae** echinoderms** low coral cover	live corals** rubble** turf** echinoderms**	coral pavement** low coral cover zoanthids** spurs/grooves**
5	sand** seagrass** rubble**	consolidated rubble** low coral cover algae** pools**	coral pavement** low coral cover zoanthids**
6	sand** rubble** seagrass**	consolidated rubble** pools** sand** turf**	coral pavement** low coral cover zoanthids**

At the backreef, seagrass (*Syringodium isoetifolium*) and coarse grained sand dominated all transects. The seagrass beds were only exposed at very low spring tides. The seagrass helps consolidate loose sand and rubble with its extensive rhizome system. Living amongst seagrass beds were sea urchins *Tripneustes gratilla* and *Toxopneustes pileolus*. These sea urchins were particularly common at transect 4. Species of holothurians (*Holothuria scabra, Holothuria atra*) and spider shells such as *Lambis* and *Strombus* sp. were also abundant at this transect.

Algae (*Padina tenuis*) were dominant at transects 2, 3 and 4. In addition, there were low cover (1-5%) of scleractinian corals at transects 1, 2, 3 and 4. These were mainly *Acropora* spp., *Porites* spp., and *Pocillopora* spp. However, at transects 5 and 6, loose rubble and sand were dominant.

At transects 1, 2 and 3, ridges of coral rock dominated by soft corals (*Sarcophyton* spp., *Sinularia* spp., and *Xenia* spp.) separated the backreef from the rest of the reef flat. In contrast, the transitional zones between the reef flat and the backreef at transects 4, 5 and 6 were dominated by sand and rubble.

The inner and the middle reef flats at transects 1, 2 and 3 were dominated by coral boulders and blocks. These coral boulders and blocks resulted from cyclones and tsunami damage. Part of the boulder zone was moated at low tide and provided habitats for invertebrate communities. The upper and lower surfaces of the blocks were encrusted by coralline algae. Encrusting byrozoans, sponges and ascidians were well developed beneath many of these blocks.

Rubble also dominated the inner and the middle reef flats at all transects except at transect 3. These rubble were covered with coralline algae. In addition to loose rubble and rubble bank, consolidated rubble intermingled with patches of coarse sand dominated transects 5 and 6.

There were moderate development of corals at transects 2, 3 and 4. Microatolls (*Porites lobata* and *Porites andrewsi*) and branching corals (*Acropora* spp.) dominated the reef flat at transect 2. The reef flat at transect 2 was infested by *Acanthaster planci* between 1978-1982 which caused a pronounced decline in the coral cover.

At transect 3, the inner and middle reef flat was dominated by living *Acropora* spp. and *Porites* There was also an elaborate growth of other species of living corals such as *Echinopora lamellosa, Hydropora* spp., *Merulina* spp., *Pavona* spp., *Psammocora* spp., *Porites* spp., *Seriatipora* sp. and *Stylophora* spp.

At transect 4, the reef flat was dominated by *Acropora* spp.. Most *Acropora* spp. at the vicinity of this transect was devastated by *A.planci* in 1984, and as a result *Acropora* rubble accumulated over the reef flat.

The inner and middle reef flats at transects 5 and 6 were dominated by consolidated rubble. There were also low coral cover which were scattered across the reef flats and in tidal pools. There was luxuriant growth of algae in tidal pools at transects 5 and 6 The algal vegetation was dominated by *Amphiroa* spp. and *Turbinaria ornata*.

In general, turf algae dominated the algal population of the inner and the middle reef flats at all transects. Turf algae were also distributed at variable proportions at different zones on the reef flat.

The reef flat was dominated by echinoderms at transects 1, 2, 3 and 4. The echinoderms were *Diadema setosum, Echinometra mathaei, Echinothrix calamaris, Tripneustes gratilla, Holothuria atra, Stichopus chloronotus* and *Linckia laevigata*. Other species of echinoderms such as *A.planci*, and several species of holothurians (*Bohadschia* sp. and *Holothuria scabra*) were also present on the reef flat. At transects 4, 5 and 6, large numbers of *Echinometra mathaei* were observed boring into the coral rock reef framework at the inner and the middle reef flats.

However, at all the transects, the seaward reef edges have coral rock pavement. They provided a solid habitat for growth of encrusting coralline algae, zoanthids and other corals (*Acropora* spp. and *Porites* spp.) at the seaward reef edge. The reef edge also had well developed spurs and grooves at all transects. There was low coral cover (5-10%) of *Acropora* spp.., faviids, and *Montipora* spp. at all transects except for transect 1 which had luxuriant growth of table corals (*Acropora hyacinthus*). Zoanthid colonies (*Palythoa* spp., *Zoanthus* spp.) dominated the seaward reef edge at transects 4, 5 and 6.

In general, the seaward reef edge at transects 1, 2, 3 and 4 are more subjected to heavy surf. There were also narrow terraces dissected by surge channels at these transects. Then the reef slope dropped rapidly into deep water. In contrast, the reef edge at transects 5 and 6 were less exposed and were sheltered by the presence of patch reefs just off the reef slope. The patch reefs and their reef slopes were dominated by living corals (*Acropora* spp., *Pavona* spp. and *Pocillopora* spp.).

3.4.2 **SUBSTRATA COMPOSITION ON ALL TRANSECTS DURING 1984, 1989 AND 1991.**

During 1984, 1989 and 1991, the seaward reef edge at all transects consisted of coral rock pavement (Figs. 3.4-3.6). The backreef was either sand or rubble or a mixture of both at all transects during the same period.

There were, however, marked changes in the substratum compositions on the middle reef flats at transects 1, 4 and 5 in 1989 and 1991. This was compared to a more stable substratum at transects 2, 3 and 6. At transect 1, the middle reef flat was a mixture of sand and rubble with a few patches of coral rock in 1984. In 1989 and 1991, they were mostly coral rock with a few patches of rubble. The establishment of coral rock substratum at transect 1 between 1989 and 1991 may be a result of regrowth of *Acropora hyacinthus* at this site which helped stabilise the substratum.

At transects 4 and 5, the middle reef flat consisted mainly of coral rock in 1984 (Figs. 3.5 & 3.6). There were major destructions of coral rock substratum from 1989 to 1991 at these transects. This resulted in a mixture of rubble and coral rock with a few patches of sand during 1989 and 1991. Large numbers of *Echinometra mathaei* were observed at transects 4 and 5 during 1989 and 1991. These sea urchins bore into the coral rock. As a result the coral rock was destroyed and may take some time for the substratum to recover.

Results of Kruskal Wallis ANOVA on Ranks are summarised in Table 3.2. They showed that there were no significant differences in the percentage cover of major substratum (coral rock, sand and rubble) at transects 2 and 3 between years. This indicated that the substratum at these transects were generally more stable. In contrast, there were significant differences in all substratum at transects 4 and 5. The differences in substratum between years may have been caused by *Echinometra mathaei* excavations in 1989 and 1991 which resulted in increased sand and rubble. However, the results of the tests varied for transects 1 and 6.

There were no differences in coral rock and sand at transect 1 but there were differences at transect 6. The differences in the substratum at transect 6 may have been caused *Echinometra mathaei* excavations. Field observations showed that coral rocks excavated by *E.mathaei* were filled with sand and rubble. There were, however, differences in rubble at transect 1 while there were no differences at transect 6. There were regrowth of corals at transect 1 which may have resulted in the extension of the coral rock substratum to the rubble zone.

Further analysis by using the Mann Whitney Rank Sum test for differences in substratum types between the different stations within each transect in any particular year are summarised in Table 3.3. In general, the differences in substratum between stations are the results of distinct zonation patterns across the reef flats.

At transect 1, all substratum showed significant differences between stations in 1984 and 1989. In 1991, coral rock and rubble showed significant differences but no differences in sand in 1991.

At transect 2, there were no differences in sand and rubble. Coral rock showed differences between stations in 1989 and 1991. There were coral recruits at this transect in 1989 and 1991 and may have contributed to the differences in the coral rock substratum at some stations.

At transect 3, there were differences in coral rock between stations. There were also differences in rubble in 1984 and 1991. There were no differences in sand between stations in the three years. The differences in coral rock between stations are the result of distinct zonation patterns at this transect.

At transect 4, all substratum showed differences. The differences between stations in each year showed clearly the distinct patterns of distribution between stations at this transect.

At transect 5, there were differences in coral rock, rubble and sand between stations in 1984. In 1989, there were no differences in coral rock and rubble but differences in sand. All substratum showed no differences between stations in 1991. The results of the analysis showed that there were some major changes occurring at this transect in 1989 and 1991. The changes to the substratum were caused by the rock-boring *Echinometra mathaei* which resulted in massive changes of the substratum from coral rock to rubble and sand.

At transect 6, there were differences in all substratum between stations in 1984 and 1989. In 1991, only rubble showed differences but coral rock and sand showed no differences. These results indicated that the substratum were relatively stable across transect 6 in 1984 and 1989. But in 1991, there were changes caused by *Echinometra mathaei* excavations.

3.4.3 DISTRIBUTION AND ABUNDANCE OF MAJOR REEF COMMUNITIES (CORALS, ZOANTHIDS, ALGAE AND ECHINODERMS) AT EACH TRANSECT IN 1984, 1989 AND 1991.

3.4.3.1 ZOANTHIDS, LIVING CORALS AND DEAD STANDING CORALS

Zoanthids were restricted to the reef edge at all transects except at transect 6 where they were located at the middle of the reef flat (Figs. 3.7-3.9). They also occurred at both the reef edge and the middle reef flat at transect 4 in 1991.

In 1984, a higher cover (40%) of zoanthids was found at transect 1 when compared to lower cover in 1989 and 1991 (<10% and <20% respectively). At transect 2, there were low cover (<10%) in 1984 whereas in 1989 and 1991 there were higher cover (60%) of zoanthids. At transect 3, high zoanthid cover (40-82%) was recorded in all years.

Zoanthids at transect 4 had higher cover (45%) in 1989 than in 1984 and 1991 (<10% respectively). There were no zoanthids recorded at transect 5 in 1984 and 1991. But very low cover (<1%) was recorded in 1989. At transect 6, zoanthids were recorded in 1984 but there were no records in 1989 and 1991.

Living scleractinian corals were distributed across the reef flat at all transects except for transect 6 (Figs.3.7-3.9). On transect 6, corals were restricted to the reef edge. There were generally higher coral cover at the eastern section of the reef when compared to the western section. The eastern section of the reef was the most exposed while the western reef was more sheltered. The highest coral cover was found at transect 3.

Field surveys showed that regrowth of corals was dominated by *Acropora hyacinthus* at transect 1 in 1989 and 1991. This species was mostly located at the seaward reef edge and at the inner reef flats.

The coral cover at transect 2 was very similar in all the three years. However, live corals had slowly recovered by 1991. Field surveys showed that small colonies of *Porites* spp. and *Acropora* spp. were found in 1991 at this transect.

At transect 3, there were relatively higher cover of corals in 1989 and 1991 when compared to those in 1984. There were relatively higher coral cover in 1984 and 1991 at transect 4 when contrasted with those in 1989.

At transect 5, live corals were located at the seaward reef edge in 1991. In 1984, they were situated at the middle reef flat and backreef. There was a decline in live corals by 1989 and these corals were restricted to the backreef.

However, dead standing corals were recorded at all transects. There were generally higher cover of dead corals where there were higher cover of live corals. These dead corals were not restricted to any section of the reef.

At transect 1, dead corals were recorded in 1984 and 1991. There were no dead corals in 1989. At transect 2, there were no dead corals in 1984 but there were some in 1989 and 1991. Dead corals were recorded for all the years at transect 3 and 5. However, at transect 3, there were losses of corals at the reef edge in 1989 and 1991 at the seaward reef edge and the middle reef flat. These losses were attributed to large numbers of *A.planci* present at the vicinity of this transect. Dead standing corals in this area had scar marks caused by *A.planci.*

At transect 4, dead corals were recorded in 1984 and 1991 but there were none in 1989. Large stands of dead corals recorded in 1984 resulted from *A.planci* predation (Zann *et al.* 1987). The dead corals were branching *Acropora* spp., a preferred diet of *A.planci* (Zann *et al.* 1990). Low cover of dead corals was recorded at transects 5 and 6 in 1991 but there were no dead corals at both these transects in 1984 and 1989.

The results of the Kruskal Wallis ANOVA on Ranks which tested for the differences in zoanthids, live corals and dead corals between years are summarised in Table 3.4. The results showed that there were no significant differences in zoanthids cover between years at all transects. This showed the persistence of zoanthids from one year to the next without any significant changes in abundance.

There were no differences in live corals between years at transects 1, 3 and 6. There were, however, significant differences in live coral cover between years at transects 2, 4 and 5. The differences in live corals between years at these transects were the result of *A.planci* predation.

There were no differences in dead coral cover between years at transects 1, 2, 3 and 5. At transect 4, there were differences in dead coral cover. The differences in dead coral cover at transect 4 were attributed to large aggregations of *A.planci* in this area in 1984. Field observations showed that dead corals had *A.planci* scar marks on them. There were higher dead coral cover present in 1984 than in 1989 or 1991.

The Mann Whitney Rank Sum tested for the differences in zoanthids, live corals and dead corals between stations within each transect. The results of these tests are summarised in Table 3.5.

The results showed significant differences in zoanthid cover between the different stations at all transects in all the years. This was expected since zoanthids were almost exclusively recorded at the seaward reef edge.

However, at transect 1, there were differences in live corals between stations in 1984 but no differences in 1989 and 1991. This further indicated that in 1989 and 1991, the distributions of live corals between stations were similar. Fig. 3.7 shows that there were high cover of live corals because of regrowth during 1989 and 1991.

At transect 2, there were differences in live corals between stations in 1984 and 1991 but no differences in 1989. At transect 3, there were differences in live corals between stations in 1984 and 1989 but not in 1991.

Live corals showed differences between stations at transects 4, 5 and 6. These differences were the result of patchy distributions of live corals between different stations. Live corals were restricted to sections of the reef such as seaward reef edge at transect 6 (Fig.3.9).

Dead corals were significantly different between stations at all transects in all the years. Dead corals were restricted to areas where live corals are distributed. In addition, live corals killed by *A.planci* may be isolated patches and those damaged by increased wave activities may be restricted to the seaward reef edge. Dead corals located at the backreef may be the result of several factors such as *A.planci* predation, sand dredging, siltation or lowered salinity.

3.4.3.2 **ALGAE AND SEAGRASS**

Coralline algae dominated the algal population in all years at all transects (Figs.3.10-3.12). Coralline algae were distributed across the reef flat, although they were abundant near the reef edge. The presence of coral rock pavement at the seaward reef edge provided suitable habitats for encrusting coralline algae.

High cover of coralline algae was recorded in 1984 at most transects. There were also high cover of coralline algae recorded in 1991. In contrast, low cover of coralline algae were found at most transects in 1989 (Figs.3.10-3.12).

Fleshy algae were distributed across the reef flat. In some years they were restricted to the seaward reef edge and in other years they were present at the middle reef flat or backreef (Figs.3.10-3.12). There were no major changes in fleshy algal cover at most transects between years. There was, however, generally higher cover in 1984 at most transects.

Turf algae were not restricted to any section of the reef flat. They were widely distributed at the seaward reef edge, inner reef flat, middle reef flat and backreef. There were no records of turf algae at any transect in 1984. Field surveys showed, however, that there were limited growth of turf algae present on the reef over non-transect areas. There were higher cover of turf algae in 1991 at transects 1, 4, 5 and 6 when compared to those in 1989. High cover of turf algae at these transects may be a result of disturbances caused by *E.mathaei* excavations. It is possible that high turf algal cover at transect 1 may have been enhanced by terrestrial run-off from the Rewa River. At transects 2 and 3, there were similar turf algal cover in 1989 and 1991.

The Suva Reef flora was dominated by the seagrass *Syringodium isoetifolium*. Seagrasses were recorded at the back reef in 1989 and 1991 at transects 1 and 5. At transect 6, they were only recorded at the backreef in 1991. There was high cover (100%) of seagrass at the back reef in transects 1, 5 and 6. The results showed that there were no records of seagrass in 1984 for all transects.

In addition there were no records of seagrass at transects 2, 3, and 4 in 1989 and 1991. There were also no records of seagrass at transect 6 in 1989. There are several reasons why they were not observed on these transects. It is possible that seagrass had declined in 1984 and was replaced by sand or corals. The sparse distribution of seagrass in these areas may have been missed. There are also limitations to the use of coverage where quadrats may have been placed in areas where seagrass were not found because of random distribution of quadrats. The results of aerial photographs (see Chapter 4), however, showed that seagrass occurred at all these transects in 1984, 1989 and 1990.

The Kruskal Wallis Anova on Ranks and Mann Whitney test results of the differences in coralline algae, fleshy algae, turf algae and seagrass between years are summarised in Tables 3.6 and 3.7. The Kruskal Wallis test showed that there were significant differences in coralline algae between years at all transects except for transect 3 where there were no differences between years. Coralline algae were restricted to areas where there were coral pavement and also to areas where there were coral rubble. The distribution of coralline algae are affected by the fluctuations in rubble on the reef flat since coral pavement are a more stable substratum. At transect 3, the coralline algae were restricted to the seaward coral pavement platform.

There were no differences in fleshy algae at all transects except at transect 3 where there were differences between years. There were no differences in turf algae between years at transects 1 and 2. In contrast, there were significant differences in turf algae between years at transects 3 to 6. There were generally high turf algae at these transects in 1991 which may have been the result of disturbances caused by *E.mathaei*. There were no differences in seagrass between 1989 and 1991 at transects 1 and 5.

The Mann Whitney Rank Sum test was used to test for differences in algae and seagrass between stations across the reef flat. The test was carried out for each transect and for each year. The results are summarised in Table.3.8.

There were no differences in coralline algae between stations at transect 1 in 1984 and 1991 while there were differences in 1989. There were differences in turf algae and seagrass between stations in 1989 and 1991.

At transect 2 and 3, there were differences in coralline algae and fleshy algae between stations for all the years. In addition, there were differences in turf algae between stations in 1989 and 1991. This indicated that fleshy algae were patchily distributed at different sections of the reef flat.

At transect 4, there were no differences in coralline algae between stations in 1984. There were, however, differences in coralline algae between stations in 1989 and 1991. There were differences in turf algae in 1989 but no differences between stations in 1991.

At transects 5 and 6, there were differences in coralline algae between stations in 1984 and 1989 but no differences in 1991. In addition, there were differences in turf algae between stations in 1989 and 1991. There were also differences in seagrass between stations in 1989 and 1991 at transect 5.

At all transects, there were differences in fleshy algae between stations for all the years. This may be an indication of patchy distribution of algae on the reef flat or restriction in their distribution to sections of the reef for example at the seaward reef edge. There are also differences because of their seasonal cycle of development. It is likely that marked seasonal changes of fleshy algae may have contributed to differences between stations at each transect. However, turf algae were observed to exist throughout the year and did not exhibit seasonal patterns. The differences in cover between stations in some transects may be caused by disturbances such as eutrophication or *E.mathaei* excavations on the reef substratum.

3.4.3.3 **ECHINODERMS**

The sea urchin, *Echinometra mathaei* was the dominant echinoderm in all the years at all transects (Figs.3.13-3.15). Relatively low densities of other echinoderm species were present on all transects. These echinoderm species were *Acanthaster planci, Bohadschia argus, Culcita granulatus, Diadema setosum, Echinothrix calamaris, Holothuria atra, H.echinites, H.leucopistilata, Linckia variegata, Stichopus chloronotus* and *Tripneustes gratilla.* Most of these echinoderm species were patchily distributed across the reef flat at all transects in the three years.

The sea urchin *Echinometra mathaei,* was most prominent across the reef flats at different transects in different years. There were large numbers of *E.matheai* at transect 2 in 1984 and transect 3 in 1991. Large numbers aggregated at transect 4 in 1989 and 1991. These sea urchins bore into the coral rock and had disastrous effects on the reef framework.

The results of Kruskal Wallis ANOVA on Ranks to test for major echinoderm groups (echinoids, asteroids and holothurians) on Suva Reef at each transect between years are presented in Table.3.9. There were no significant differences in echinoids, asteroids and holothurians between years at transect 1. At transect 2, there were no differences in the echinoids and asteroids but there were differences in holothurians. These were the results of the patchy distribution of holothurians across the reef flat in some years and their absence and presence in other years.

At transects 3, 4, 5, and 6 there were significant differences in echinoids between years. The sea urchin *Echinometra mathaei* was a major contributor to the differences between years. In some years they were present in large numbers while other years there were only a few numbers. However, there were no differences in asteroids and holothurians at transects 3, 4 and 5 between years. The results of the Kruskal Wallis ANOVA on Ranks tests for each echinoderm species at each transect between years are shown on Table.3.10. In general there were significant differences in *E.mathaei* at transects 2, 3, 4 and 5 between years. This was supported by the Student Newman Keuls test which showed differences ($p < 0.05$) between the three years at these transects (Table.3.11). There were no differences in *E.mathaei* at transects 1 and 6 between years. All other species of echinoderms showed no differences at all transects between years. Therefore most of these echinoderms were present in low densities and were very similar in densities between years at all transects.

The results of the Mann Whitney Rank Sum test for differences between stations within each transect in any particular year are shown on Table 3.10. All species of echinoderms showed significant differences between stations in any given year at all the transects. These results indicate that all species of these echinoderms were not evenly distributed across the reef flat at any given time. It must be noted that some of these echinoderms aggregated at sections of the reef where there were suitable habitats or where there were abundant food. For example *A.planci* were most abundant where there were high cover of live corals.

3.4.4 CLUSTER ANALYSES

Cluster analyses of cover (live corals, sand, coral rock, rubble, algae, zoanthids and dead corals) by Euclidean measure and average within groups strategy were used to determine similarities between stations within each transect for a given year. The results showed that there were generally four clusters recognised within each transect. The clusters were broadly categorised as seaward reef edge, inner reef flat, middle reef flat and backreef. Fig.3.16 shows an examples of cluster analyses results from transect 3. There were four clusters recognised on Fig.3.16. These clusters were relatively stable from 1984 to 1991 within transect 3.

However, in most transects, there were no consistent clear cut divisions of some stations because of transitional zones. These transitional zones were scattered across the reef flats.

In general, the cluster analyses showed general zonation patterns on the reef. Although the reef flats have diverse substratum and communities, the patterns of their distribution are generally very distinctive.

3.5 DISCUSSION

The results indicate that Suva Reef flat has well differentiated zones from the seaward reef edge to the back reef. The zones were identified according to dominant living communities such as vegetation and fauna and major substrate features. The different zones can be broadly categorised as:

(i) back reef - sand and seagrass
(ii) middle reef flat - rubble, sand and echinoderms
(iii) inner reef flat - consolidated rubble and boulder zone
(iv) seaward reef edge - coral rock pavement, coralline algae zoanthids and hard corals

Similar zones on the Great Barrier Reef (sand & seagrass, sand & rubble and rubble & pavement) were classified by Rutzler & MacIntyre (1982).

Furthermore, results of quantitative studies indicated that zonation at each transect on Suva Reef can be refined by combining all factors that determine the zonation. Previous studies (Pichon & Morrissey 1981, Dai 1988) have used scleractinian corals to be the main determinant of zonation patterns on reefs studied. However, scleractinian corals are not the only component of coral reefs, although they can provide a broad line of zonation.

In this study, the cluster and multivariate statistical analyses demonstrated clearly that the pattern of zonation becomes more evident when the major groups within the reef community are included in the analysis. Groups of major primary producers (fleshy and turf algae) are important in subdividing reef flat communities. Other major benthic reef dwelling organisms such as zoanthids and echinoderms are important components of the zonation patterns on the reef. These findings suggested that the structure and zonation patterns of reef communities would be best defined by taking into account more than one benthic group.

Apart from scleractinian corals, algal cover appeared to be one of the most important benthic features. Amongst reef benthic algae, the turf algae was the most significant component. The tall fleshy macroalgae, however, were not present on Suva Reef and this feature usually characterises most inshore reefs (Morrissey 1980, Vakamoce 1987, Done 1990). Crustose coralline algae are important on Suva Reef and are characteristics of exposed barrier reefs (Stephenson *et al.*, 1931, Pichon & Morrissey 1981). This algal community reflect the exposed nature of the reef flat. Suva Reef had therefore some inshore influences because of its proximity to land and terrestrial input and also some characteristics of exposed hydrodynamic conditions which characterise barrier reefs. Sometimes the zonation patterns were not clear on some transects and this could be attributed to samples being taken across heterogeneous transitional zones and will therefore affect all the different parameters concerned in classifying zones.

In general, details of reef zonation varied according to the degree of wave exposure at each site on Suva Reef. Transects 1 and 2 have high wave energy reef edge and inner reef flat because of prevailing south-east trade winds. In contrast, the western reef edge and reef flats (transects 5 and 6) were more sheltered. The temporal and spatial variations observed in this study indicated that reef zones on Suva Reef must be monitored over many years to establish patterns and processes of zonation and population dynamics.

The reef framework was vital for the stability of reef community structure. In this study, the reef substrata was used as an indicator of stability of reef framework. The Kruskal-Wallis tests showed no significant differences in the coral rock, sand and rubble at most transects between 1984, 1989 and 1991. This demonstrated a relatively stable reef framework on Suva Reef over seven years. Alternatively, it is possible that short term variation in the reef substrata during the aftermath of cyclones in 1985 as described by Zann *et al.* (1987) could have been missed in this study. There were, however, significant differences in the substrata at transects 4 and 5 between years. Observations during field surveys showed that there large numbers of *Echinometra mathaei* present on these areas between 1989 and 1991. These sea urchins were probably one of the major contributor to changes occurring at these transects.

Although there were no significant differences in the reef substrata at most transects over seven years, there were significant differences in the reef substrata across the reef flat for almost all the transects for the three different years. Clearly, the differences in the reef substrata across the reef flat was one of the main reasons in the differences in the zonation patterns on the reef flat.

The refuge substratum of many juvenile species of echinoderms were found to be the inner reef flat. The inner reef flat had boulders and coral blocks. The blocks and boulders had coralline algae on the underside which provided a food source at early juvenile stages for some of the echinoderms. The boulder zone is therefore very important for successful recruitment of echinoderms. Damage to the boulder zones by cyclones could destroy nursery grounds for juvenile reef animals.

However, the paucity of corals on the inner reef flat were mainly a result of *Acanthaster planci* predation (Zann *et al.* 1990). Results of 10 years of studying *A.planci* on Suva Reef indicate that the decline in coral cover at some sites were due to starfish predation. It was further suggested that damage to corals by *A.planci* was progressive and had entered a chronic phase of "moderate to low coral cover and moderate to high *A.planci* abundances". A re-survey of the sites in 1989 and 1991 in this study indicate a low population of *A.planci* at most sites. In addition, the community structure has also not shifted from a community dominated by low biomass algal turfs and corals to one dominated primarily by macroalgae as a result of starfish predation as reported by several authors (Carpenter 1990, Done 1990).

In Southern Japan (Birkeland 1989), second order effects of *A.planci* outbreaks include increases in numbers of rock boring urchin *Echinometra* *mathaei*. Large numbers of *Diadema setosum* and *E.mathaei* were found on Suva Reef in 1984, 1989 and 1991. The high abundances of rock boring echinoderms at some sites in this study may be a result of *A.planci*. It also implied an unusually high settlement of larvae and successful recruitment. Factors that may have contributed to a successful recruitment are favourable conditions for larvae, presence of reproductive populations, fertilization success and favourable winds and currents. Echinoderms may vary greatly in reproductive success, both temporally and spatially (Yamaguchi 1973, Ebert 1983).

Ogden *et al.* (1973) and Hay (1984) had speculated that abnormally high population densities of *Diadema antillarum* in some areas of the Caribbean were the result of overfishing and the removal of sea urchins predators and competitors. On Kenyan reefs, McClanahan & Muthiga (1989) found high fishing pressure to be the major cause of reduction in predators which allowed *E.mathaei* to increase. Although overfishing is important to some degree on a local scale on Suva Reef, there is lack of data to correlate sea urchin population and human population densities. It is suggested that a combination of processes may be responsible for the overall increase in the sea urchins on Suva Reef.

Reef destruction by borers will alter and destroy reef frameworks (Neumann 1966, Scoffin *et al.* 1980, Hutchings 1986 and Kiene 1988). On Suva Reef, degradation of reefs may be a result of a combination of several factors such as increase in boring activities, predation, cyclones and human activities. A single explanation of reef degradation is therefore unlikely. Damage to reefs resulting from predation, rock boring activities and cyclone may occur on a macroscale level for some years and isolated on others.

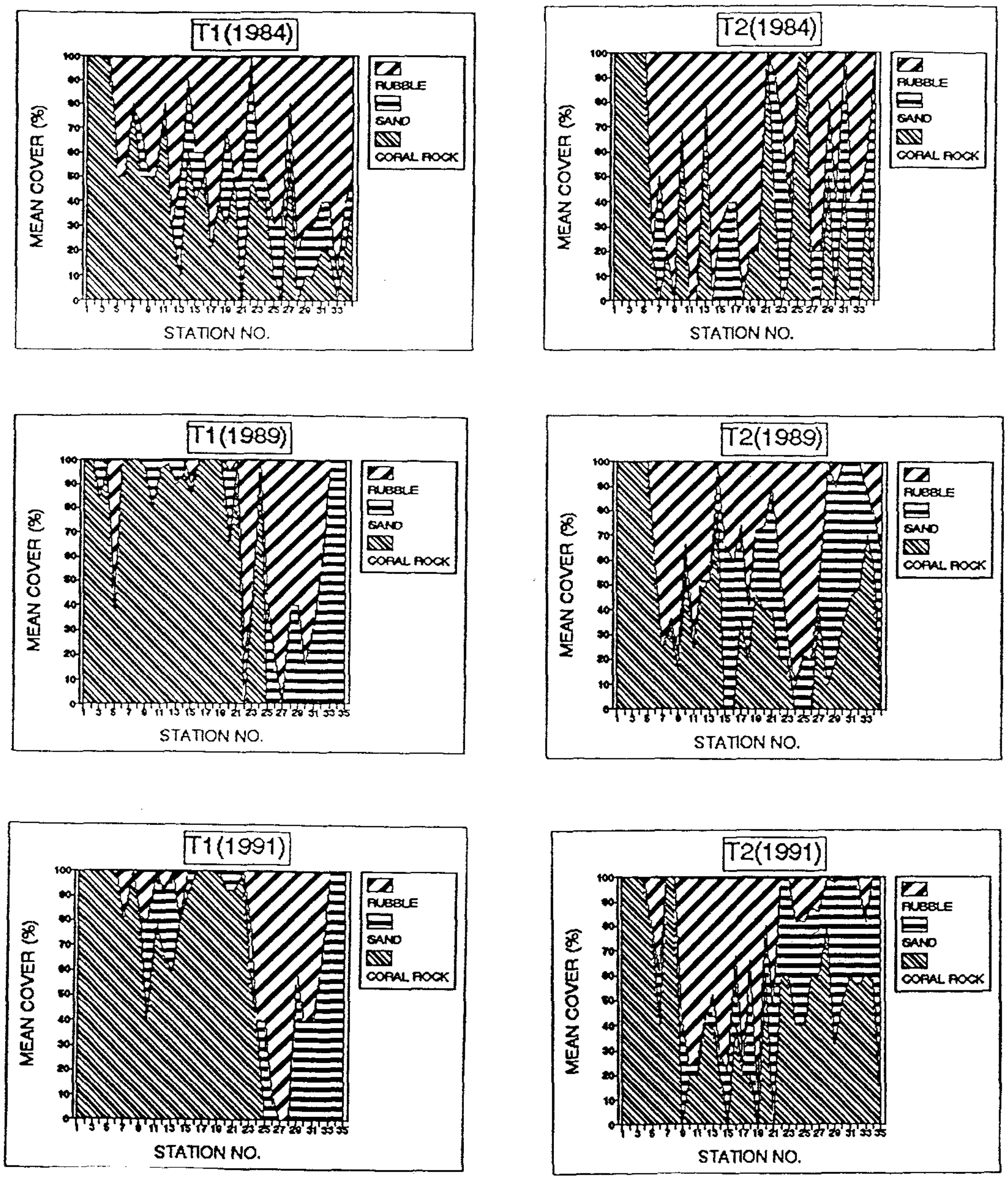


Fig. 3.4 Distribution of substrata across stations at transects 1 and 2.

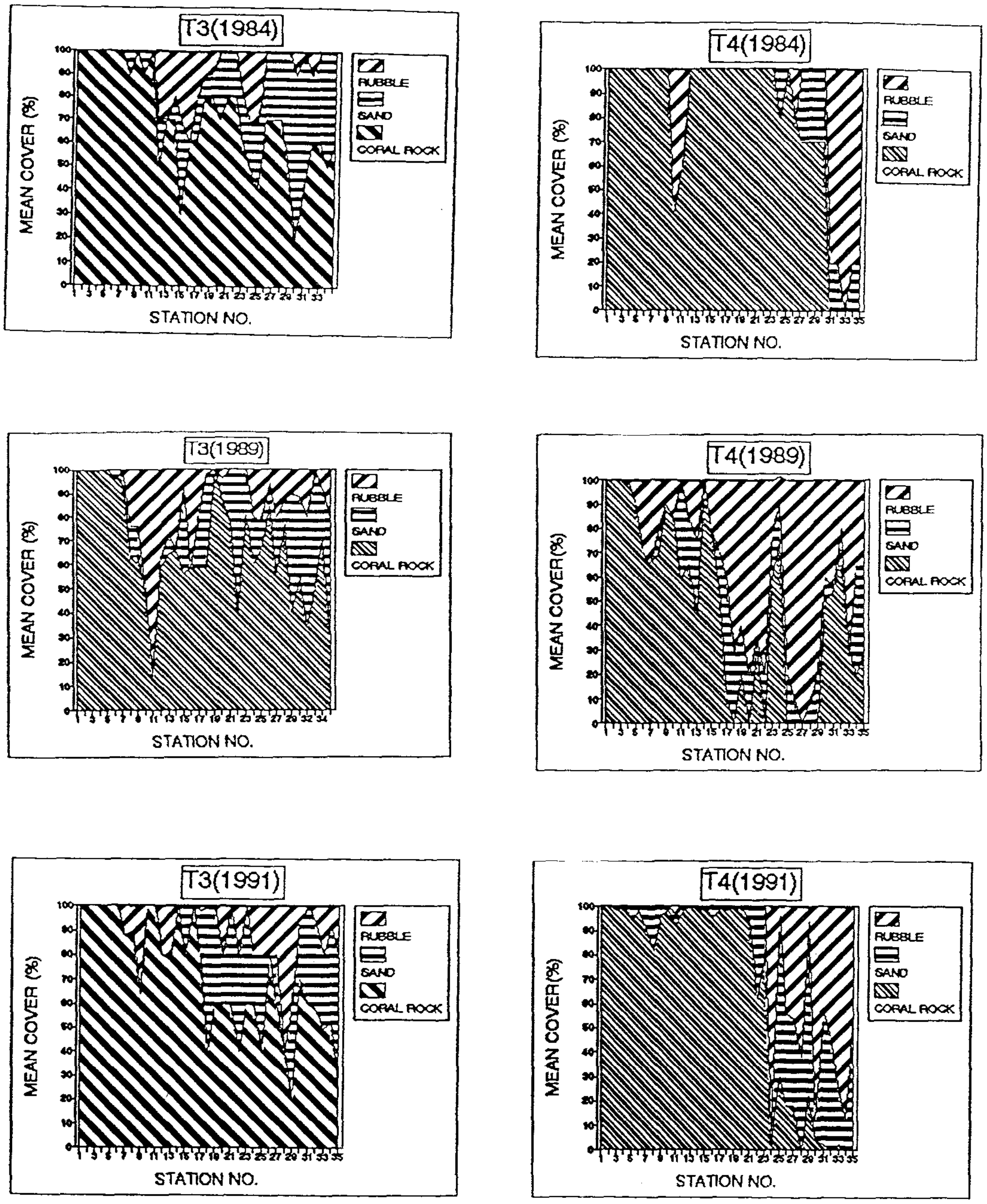


Fig. 3.5 Distribution of substrata across stations at transects 3 and 4.

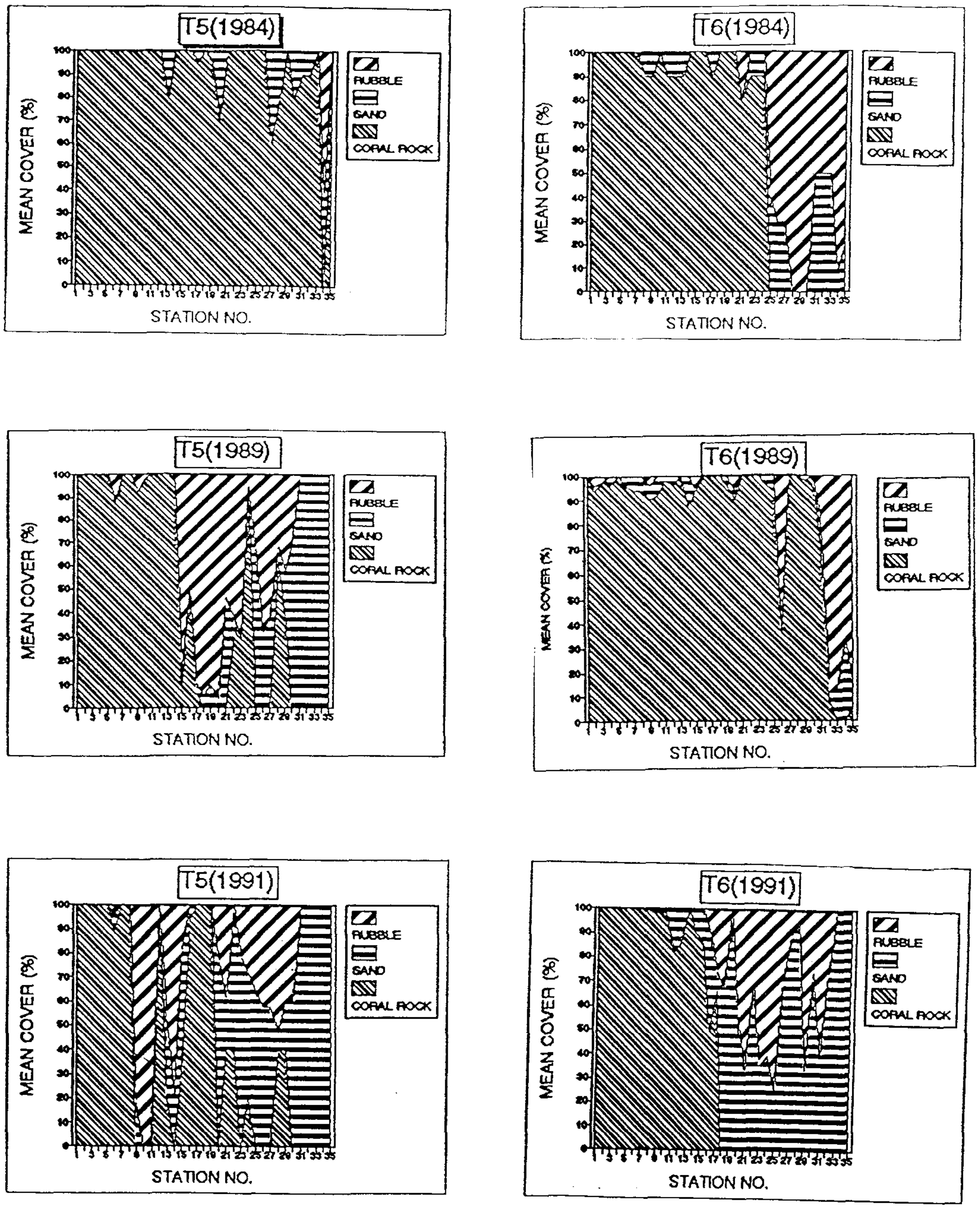


Fig. 3.6 Distribution of substrata across stations at transects 5 and 6.

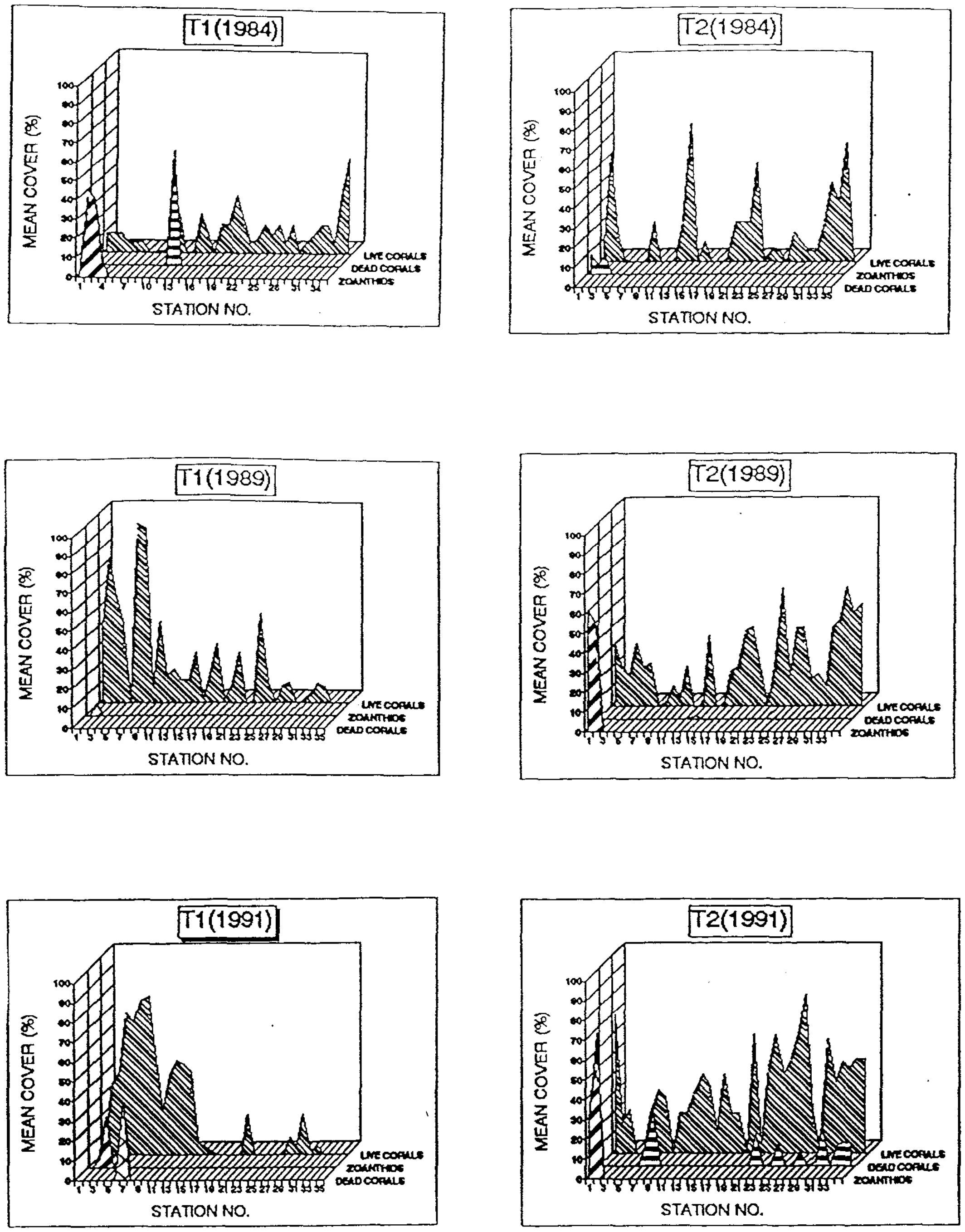


Fig. 3.7 Distribution of corals and zoanthids at transects 1 and 2.

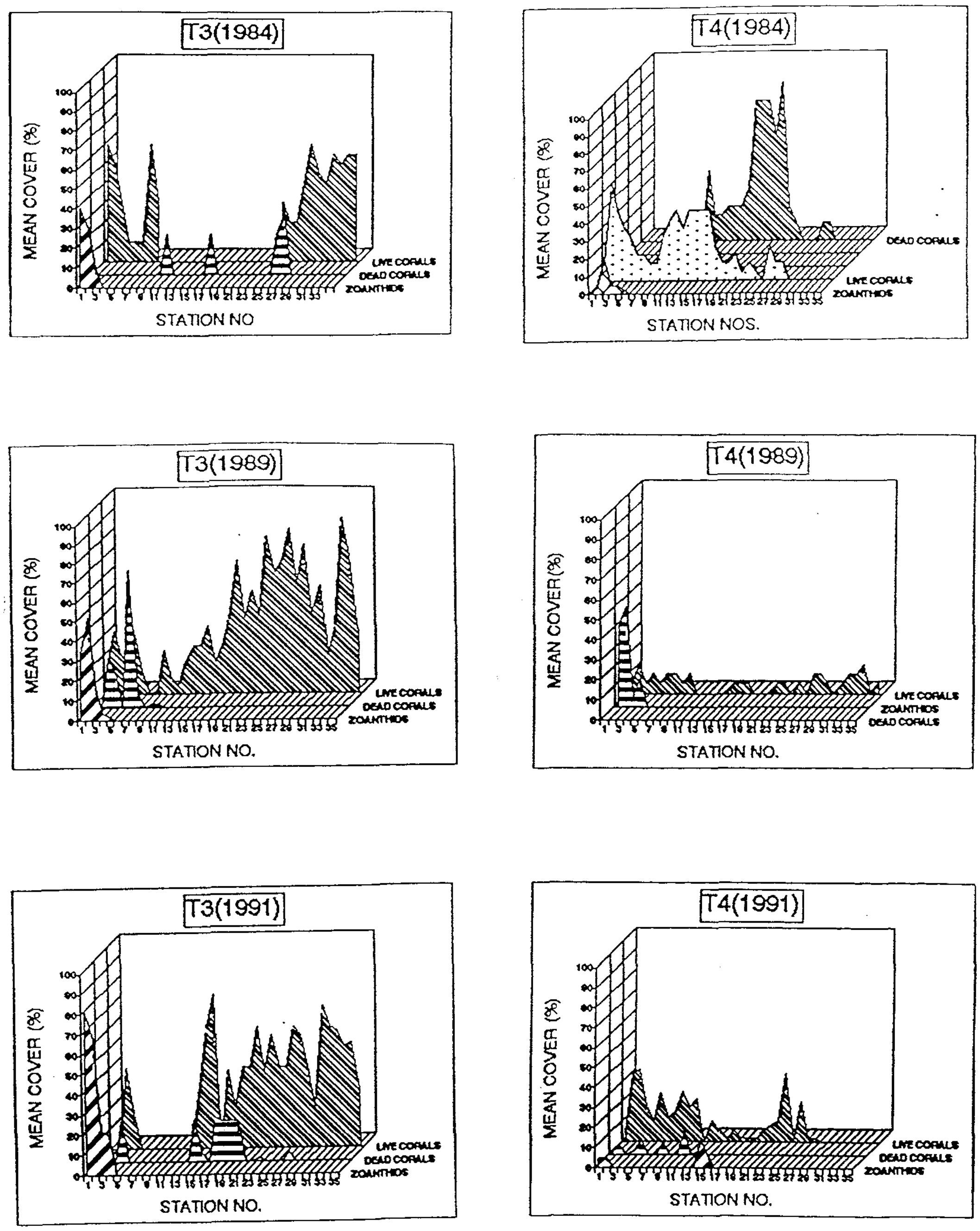


Fig. 3.8 Distribution of corals and zoanthids at transects 3 and 4.

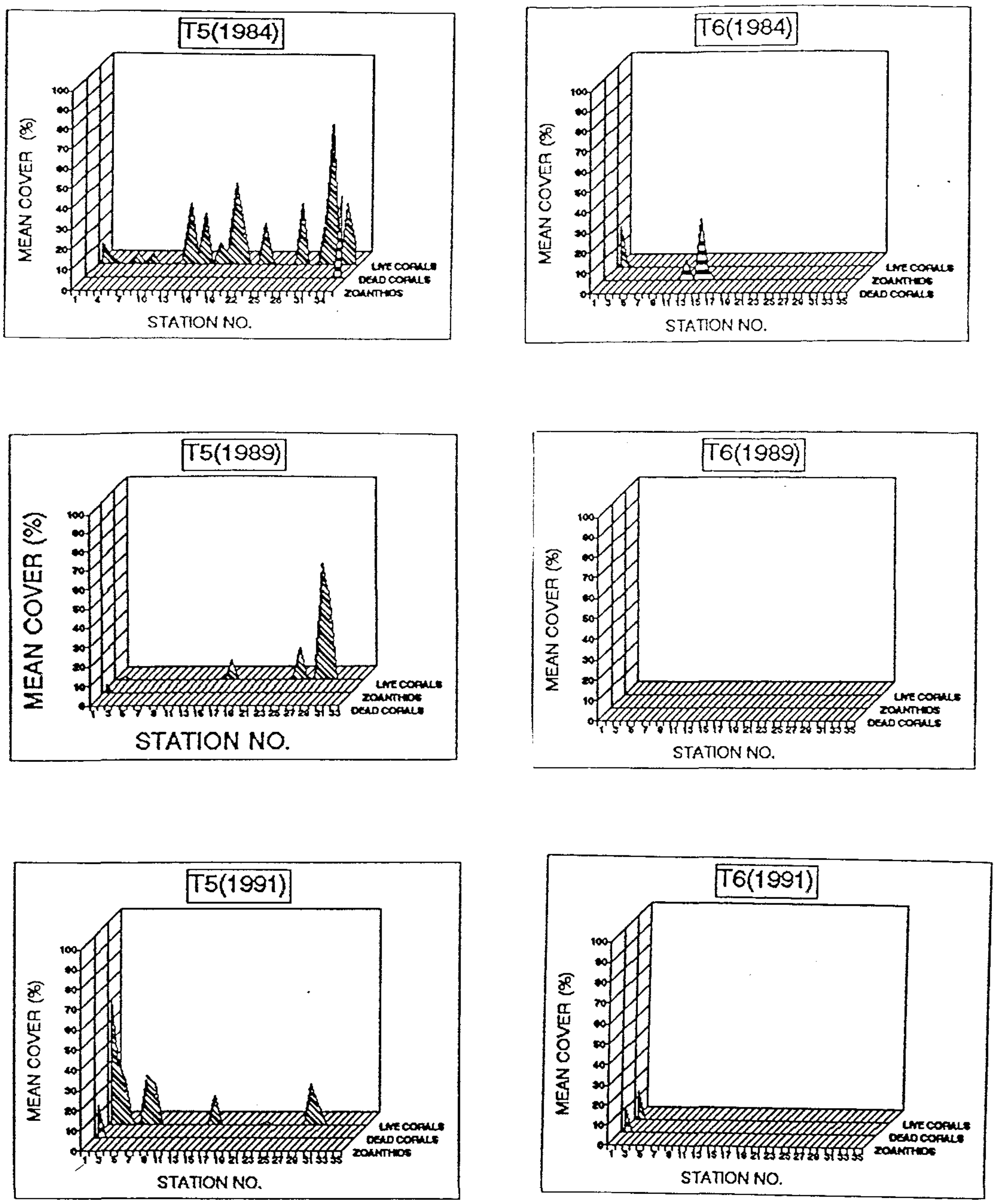


Fig. 3.9 Distribution of corals and zoanthids at transects 5 and 6.

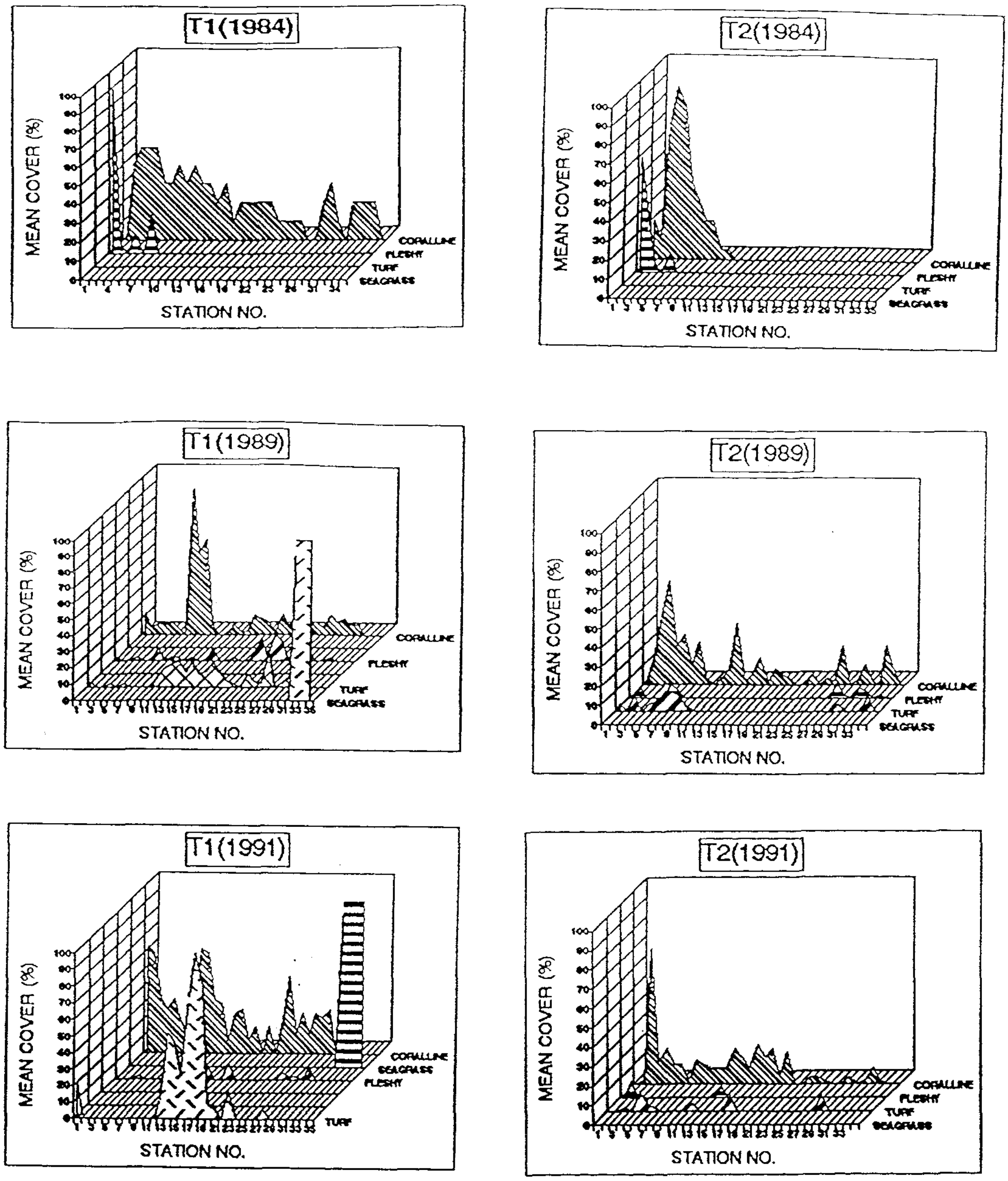


Fig. 3.10 Distribution algae and seagrass across stations at transects 1 and 2.

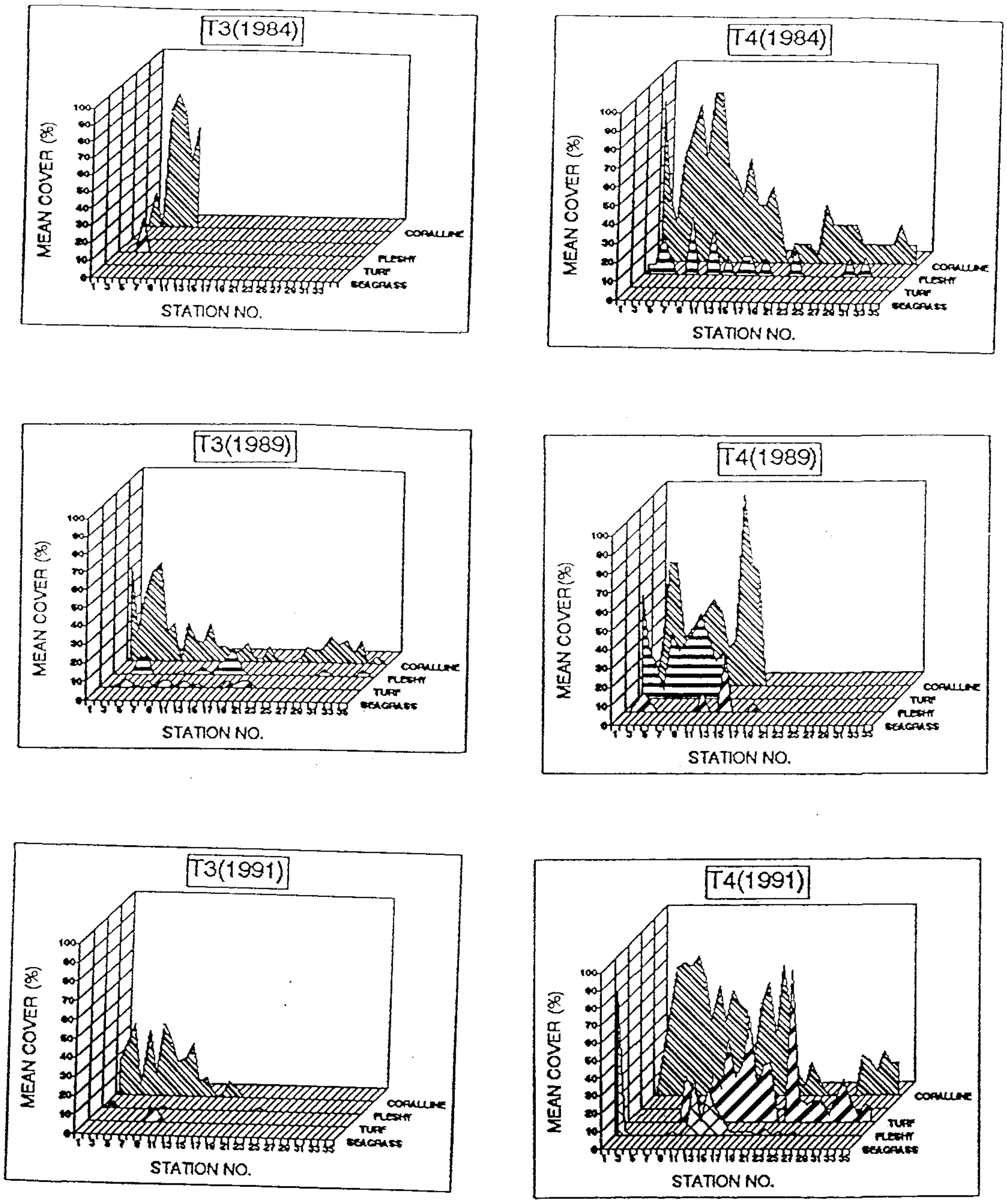


Fig. 3.11 Distribution of algae and seagrass across stations at transects 3 and 4.

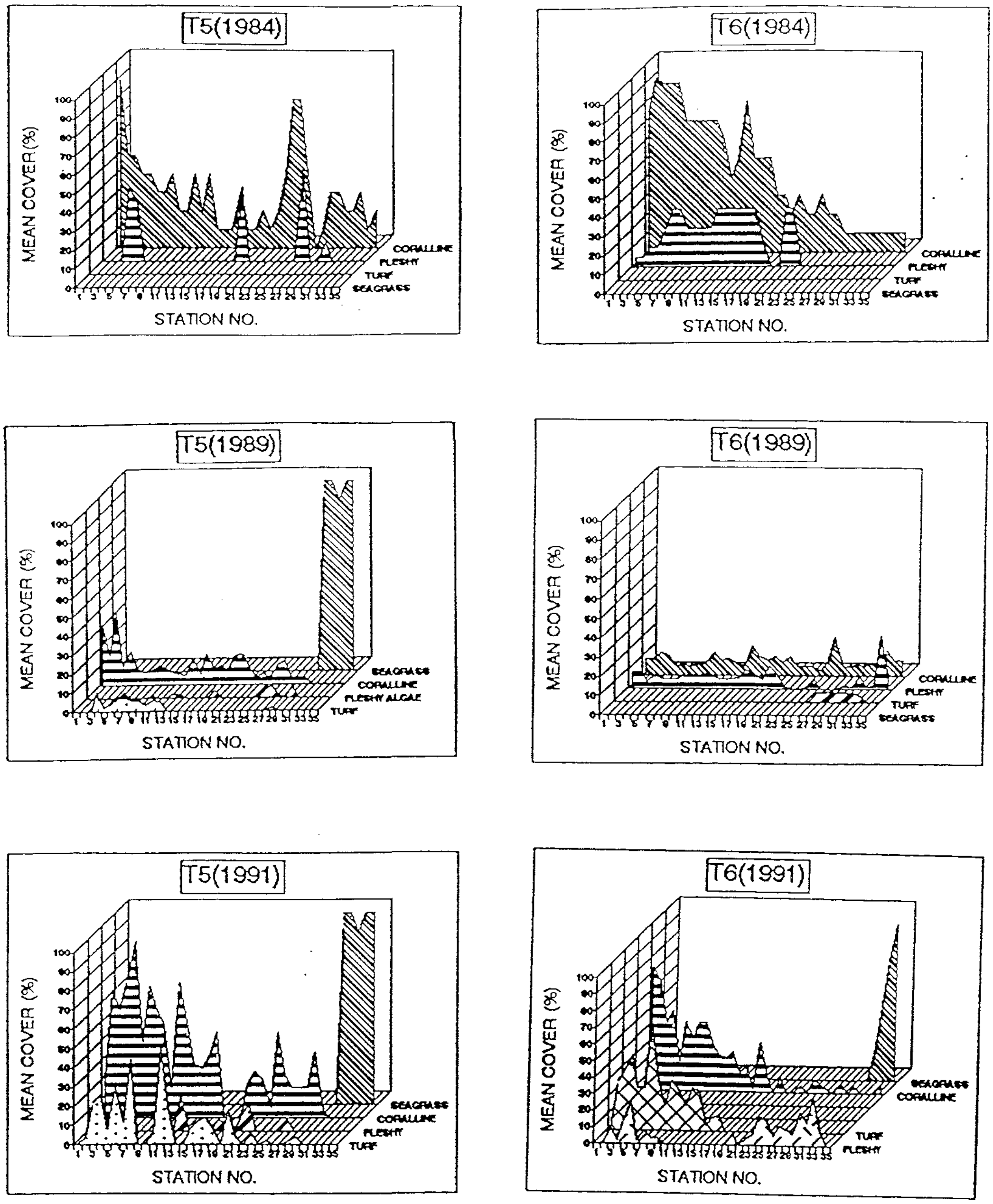


Fig. 3-12 Distribution of algae and seagrass across stations at transects 5 and 6.

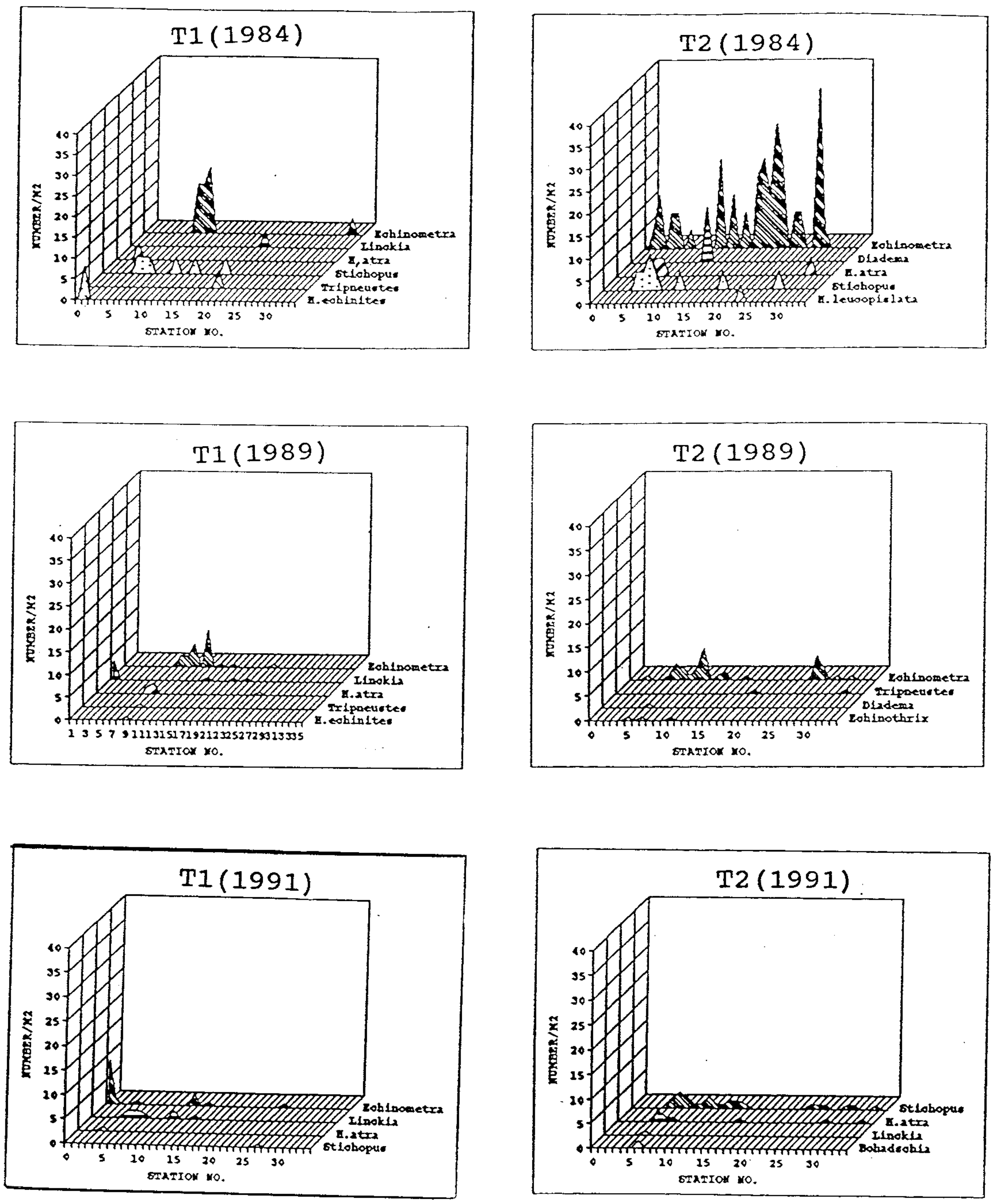


Fig. 3.13 Distribution of echinoderms across stations at transects 1 and 2.

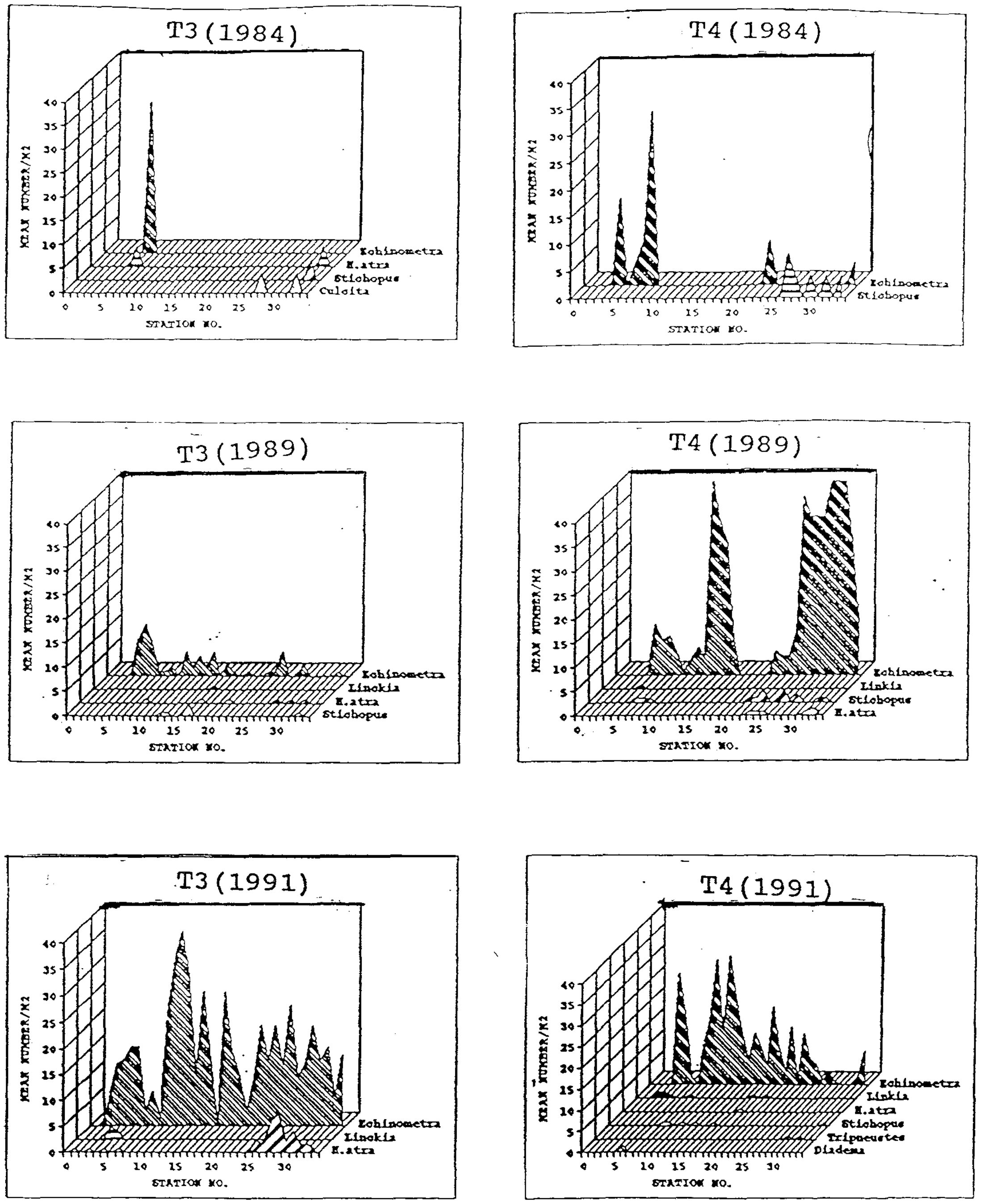


Fig. 3.14 Distribution of echinoderms across stations at transects 3 and 4.

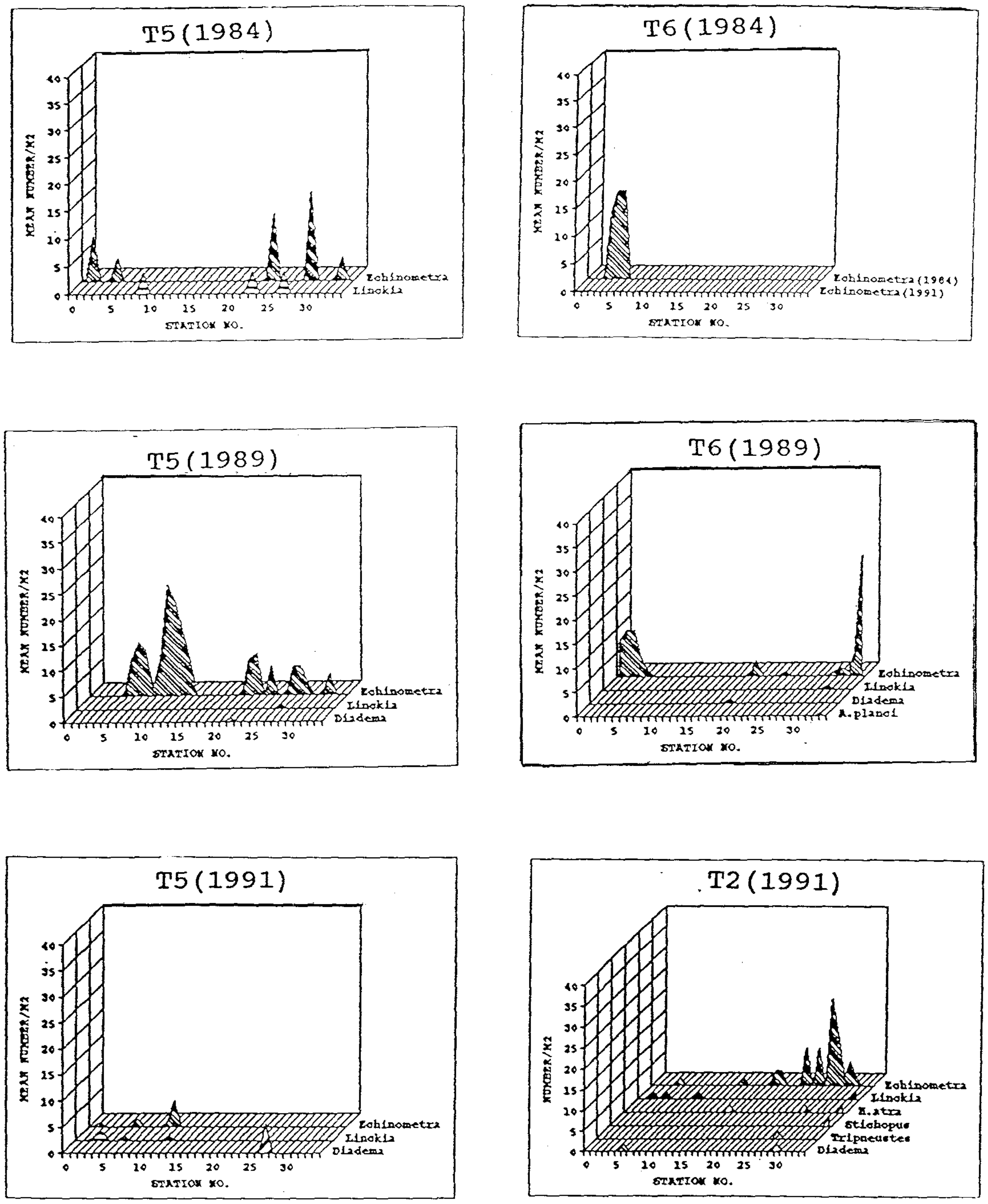
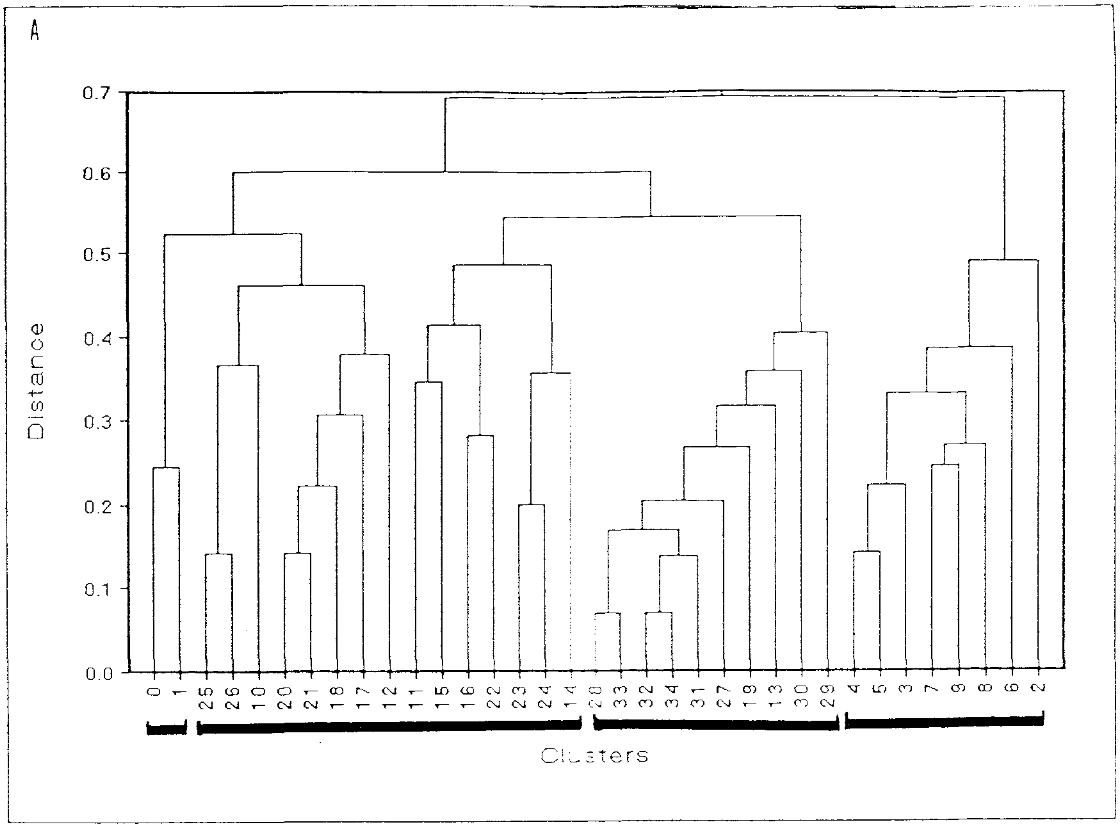


Fig. 3.15 Distribution of echinoderms across stations at transects 2, 5 and 6.



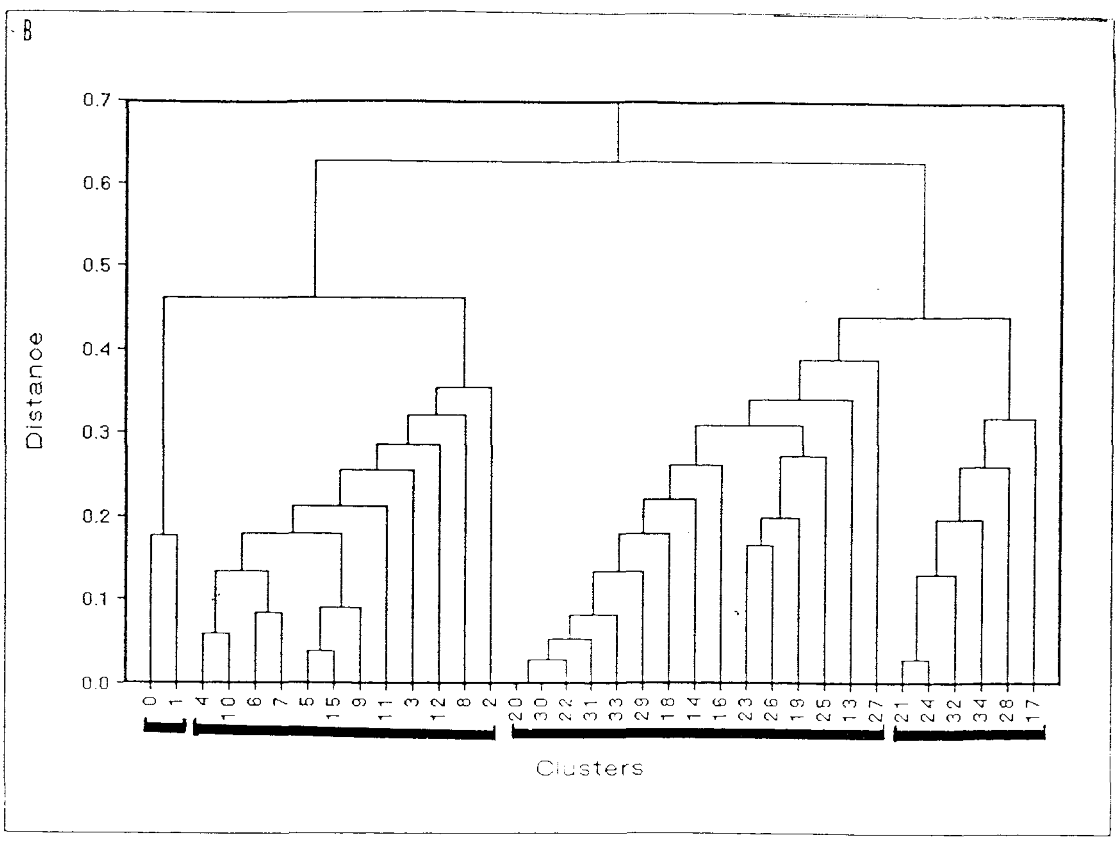


Fig.3.16 Dendograms of stations classifications at transect 3.
A. 1984 B. 1991

Table:3.2 Results of Kruskal Wallis ANOVA on Ranks testing for differences in coral rock, sand and rubble between years.

Transect	Substrate	p	significance ($p<0.05$)
1	Coral rock	0.231	not significant
	Sand	0.959	not significant
	Rubble	0.001	significant
2	Coral Rock	0.088	not significant
	Sand	0.118	not significant
	Rubble	0.056	not significant
3	Coral Rock	0.510	not significant
	Sand	0.790	not significant
	Rubble	0.119	not significant
4	Coral Rock	<0.001	significant
	Sand	0.002	significant
	Rubble	<0.001	significant
5	Coral Rock	<0.001	significant
	Sand	0.005	significant
	Rubble	<0.001	significant
6	Coral Rock	0.006	significant
	Sand	<0.001	significant
	Rubble	0.579	not significant

Table:3.3 Summary of results of Mann Whitney test for differences in coral rock, sand and rubble between stations.

Transect	Substrate	Year	p	Significance ($p<0.05$)
1	Coral Rock	1984	<0.001	significant
		1989	0.024	significant
		1991	0.007	significant
	Sand	1984	0.011	significant
		1989	0.031	significant
		1991	0.052	not significant
	Rubble	1984	<0.001	significant
		1989	0.022	significant
		1991	<0.001	significant
2	Coral Rock	1984	0.679	not significant
		1989	0.002	significant
		1991	<0.001	significant
	Sand	1984	0.172	not significant
		1989	0.962	not significant
		1991	0.384	not significant
	Rubble	1984	0.079	not significant
		1989	0.086	not significant
		1991	0.620	not significant
3	Coral Rock	1984	<0.001	significant
		1989	<0.001	significant
		1991	<0.001	significant
	Sand	1984	0.759	not significant
		1989	0.212	not significant
		1991	0.350	not significant
	Rubble	1984	<0.001	significant
		1989	0.073	not significant
		1991	<0.001	significant
4	Coral Rock	1984	<0.001	significant
		1989	0.002	significant
		1991	<0.001	significant
	Sand	1984	<0.001	significant
		1989	0.021	significant
		1991	0.041	significant
	Rubble	1984	<0.001	significant
		1989	0.014	significant
		1991	0.003	significant
5	Coral Rock	1984	<0.001	significant
		1989	0.283	not significant
		1991	0.546	not significant
	Sand	1984	<0.001	significant
		1989	0.016	significant
		1991	0.916	not significant
	Rubble	1984	<0.001	significant
		1989	0.415	not significant
		1991	0.241	not significant
6	Coral Rock	1984	0.007	significant
		1989	<0.001	significant
		1991	0.840	not significant
	Sand	1984	<0.001	significant
		1989	<0.001	significant
		1991	0.213	not significant
	Rubble	1984	0.013	significant
		1989	<0.001	significant
		1991	0.035	significant

Table: 3.4 Summary of results of Kruskal Wallis Anova on Ranks testing for differences in zoanthids and corals between years.

Transect		P	Significance
1	Zoanthids	0.996	not significant
	Live Corals	0.746	not significant
	Dead Corals	0.999	not significant
2	Zoanthids	0.980	not significant
	Live Corals	0.001	significant
	Dead Corals	0.054	not significant
3	Zoanthids	0.926	not significant
	Live Corals	0.237	not significant
	Dead Corals	0.610	not significant
4	Zoanthids	0.983	not significant
	Live Corals	0.002	significant
	Dead Corals	0.009	significant
5	Zoanthids	0.842	not significant
	Live Corals	0.015	significant
	Dead Corals	0.999	not significant
6	Zoanthids	0.518	not significant
	Live Corals	0.918	not significant
	Dead Corals	-	-

Table: 3.5 Summary of results of Mann Whitney test for differences in zoanthids and corals between stations.

Transect		P	Significance	Years
1	Zoanthids	<0.001	significant	'84'89'91
	Live Coral			
	Dead Coral	0.999	not significant	'84 '91
2	Zoanthids	<0.001	significant	'84'89'91
	Live Coral	0.012	significant	'84
		0.378	not significant	'89
		0.005	significant	'91
	Dead Coral	0.06	not significant	'89'91
3	Zoanthids	<0.001	significant	'84'89'91
	Live Coral	<0.001	significant	'84'89'91
	Dead Coral	<0.001	significant	'84'89'91
4	Zoanthids	<0.001	significant	'84'89'91
	Live Coral	>0.05	not significant	'84
		<0.001	significant	'89'91
	Dead Coral	<0.001	significant	'84 '91
		0.009	not significant	'84 '91
5	Zoanthids	<0.001	significant	'89
	Live Coral	<0.001	significant	'84'89'91
	Dead Coral	<0.001	significant	'84 '91
		>0.999	not significant	'84 '91
6	Zoanthids	<0.001	significant	'84
	Live Coral	<0.001	significant	'84 '91
		0.918	not significant	'84 '91
	Dead Coral	<0.001	significant	'91

Table: 3.6 Summary of results of Kruskal Wallis Anova on Ranks testing for differences in algae and seagrass between years.

Transect		P	Significance
1	Coralline Algae	<0.001	significant
	Fleshy Algae	0.061	not significant
	Turf Algae	0.36*	not significant
	Seagrass	0.828*	not significant
2	Coralline Algae	0.019	significant
	Fleshy Algae	0.494	not significant
	Turf Algae	0.477	not significant
	Seagrass	**	**
3	Coralline Algae	0.093	not significant
	Fleshy Algae	0.027	significant
	Turf Algae	0.02	significant
	Seagrass	**	**
4	Coralline Algae	0.002	significant
	Fleshy Algae	0.113	not significant
	Turf Algae	0.034	significant
	Seagrass	**	**
5	Coralline Algae	<0.001	significant
	Fleshy Algae	0.849	not significant
	Turf Algae	0.006	significant
	Seagrass	0.981	not significant
6	Coralline Algae	<0.001	significant
	Fleshy Algae	0.384	not significant
	Turf Algae	0.01*	significant
	Seagrass	**	**

Table: 3.7 Summary of Mann Whitney test for differences in algae and seagrass between stations.

Transect		P	Significance (p<0.05)	Years
1	Coralline Algae	0.376	not significant	'84
		<0.001	significant	'89
		0.681	not significant	'91
	Fleshy Algae	<0.001	significant	'84'89'91
	Turf Algae	<0.001	significant	'89'91
	Seagrass	<0.001	significant	'89'91
2	Coralline Algae	<0.001	significant	'84'89'91
	Fleshy Algae	<0.001	significant	'84'89'91
	Turf Algae	<0.001	significant	'89'91
3	Coralline Algae	0.027	significant	'84
		0.006	significant	'89
		<0.05	significant	'91
	Fleshy Algae	<0.001	significant	'84'89'91
	Turf Algae	<0.001	significant	'89'91
4	Coralline Algae	0.052	not significant	'84
		0.032	significant	'89
		0.031	significant	'91
	Fleshy Algae	<0.001	significant	'84'89'91
	Turf Algae	<0.001	significant	'89
		0.110	not significant	'91
5	Coralline Algae	0.011	significant	'84
		<0.001	significant	'89
		0.249	not significant	'91
	Fleshy Algae	<0.001	significant	'84'89'91
	Turf Algae	<0.001	significant	'89'91
	Seagrass	<0.001	significant	'89'91
6	Coralline Algae	<0.001	significant	'84 '89
		0.162	not significant	'91
	Fleshy Algae	0.031	significant	'84
		<0.001	significant	'89'91
	Turf Algae	<0.001	significant	'89'91
	Seagrass	<0.001	significant	'91

Table: 3.8 Summary of results of Kruskal Wallis Anova on Ranks testing for differences in echinoderm groups between years.

Transect		P	Significance (P<0.05)
1	Echninoids	0.875	not significant
	Asteroids	0.587	not significant
	Holothurians	0.391	not significant
2	Echinoids	0.073	not significant
	Asteroids	0.534	not significant
	Holothurians	0.008	significant
3	Echinoids	<0.001	significant
	Asteroids	0.968	not significant
	Holothurians	0.075	not significant
4	Echinoids	<0.001	significant
	Asteroids	0.262	not significant
	Holothurians	0.276	not significant
5	Echinoids	0.016	significant
	Asteroids	0.812	not significant
6	Echinoids	0.095	not significant
	Asteroids	0.889	significant

Table: 3.9 Summary of results of Kruskal Wallis Anova on Ranks testing for differences in echinoderm species abundance between years.

Transect		P	Significance (p<0.05)
1	*E. mathaei*	0.881	not significant
	L. laevigata	0.587	not significant
	S.chloronotus	0.999	not significant
	H. atra	0.893	not significant
2	*E. mathaei*	<0.05	significant
	L.laevigata	0.534	not significant
	S.chloronotus	0.006	significant
	T.gratilla	0.823	not significant
	D. setosum	0.973	not significant
3	*E. mathaei*	<0.001	significant
	L. laevigata	0.823	not significant
	S.chloronotus	0.550	not significant
	H. atra	0.064	not significant
4	*E. mathaei*	<0.001	significant
	L. laevigata	0.262	not significant
	S.chloronotus	0.628	not significant
	H. atra	0.262	not significant
5	*E. mathaei*	0.004	significant
	L. laevigata	0.812	not significant
6	*E. mathaei*	0.095	not significant

Table: 3.10 Summary of results of Mann Whitney test for differences in echinoderm species abundance between stations.

Transect		P	Significance	Years
1	*E. mathaei*	<0.001	significant	'84'89'91
	L. laevigata	<0.001	significant	'84'89'91
	S. chloronotus	<0.001	significant	'84 '91
	T. gratilla	<0.001	significant	'84'89
	H. echinites	<0.001	significant	'84'89
2	*E. mathaei* *L. laevigata* *S. chloronotus* *H. atra* *T. gratilla*	<0.001 <0.001 <0.001 <0.001 <0.001	significant " " " "	'84'89'91 '89'91 '84'89'91 '84'89'91 '89'91
3	*E. mathaei*	<0.001	significant	'84'89'91
	L. laevigata	<0.001	significant	'89'91
	S. chloronotus	<0.001	significant	'84'89
	H. atra	<0.001	significant	'84'89'91
	C. granulatus	<0.001	significant	'84
4	*E. mathaei*	<0.001 0.036	significant significant	'84 '91 '89
	L. laevigata	<0.001	significant	'89'91
	S. chloronotus	<0.001	significant	'91
	H. atra	<0.001	significant	'91
	T. gratilla	<0.001	significant	'91
	D. setosum	<0.001	significant	'91
5	*E. mathaei*	<0.001	significant	'84'89'91
	L. laevigata	<0.001	significant	'84'89'91
	D. setosum	<0.001	significant	'89'91
6	*E.mathaei*	<0.001	significant	'84'89'91
	L. laevigata	<0.001	significant	'89
	D. setosum	<0.001	significant	'89
	A. planci	<0.001	significant	'89

Table: 3.11 Summary of results of Student Newmann Keuls test for differences in some echinoderms species between stations.

Transect		P	Significance	Years
2	*S. chloronotus*	0.006	significant	'84'89'91
3	*E. mathaei*	<0.001	significant	'84'89'91
4	*E. mathaei*	<0.05 <0.05 >0.05	significant significant not significant	'84'89 '84 '91 '89'91
5	*E. mathaei*	>0.05	not significant	'84'89'91

CHAPTER 4

AERIAL MONITORING OF CORAL REEF COMMUNITIES ON SUVA BARRIER REEF FROM 1945 TO 1990.

4.1 INTRODUCTION

Aerial photography was the first method of remote sensing and even in the present era of satellite and electronic scanners, aerial photographs still remain the most widely used remotely sensed data (Curran 1985). Aerial photographs are popular because they are readily available for much of the world at a variety of scales. They are also cheaper than field surveys and are often more accurate than maps.

Aerial photographs also enable the detection of small scale features and spatial relationships that would not be evident on the ground. An aerial photograph is a record of the Earth's surface at one point in time and can therefore be used as an historical record. There is also an advantage in using aerial photographs with a stereoscopic view because this can be used to measure features both horizontally and vertically. This is a characteristic which is lacking for the majority of remotely sensed data and was not available for the present work.

Black and white aerial photographs have been used for many applications in the Earth sciences, for geological mapping (Allum 1980, Press *et al.* 1980), hydrogeological investigations (La Riccia and Rauch 1977) and terrain analysis (Ball *et al.* 1971, Sauer 1981). In particular, they have been used for the mapping of desert dunes (Finkel 1961, Davis and Neal 1963) and coastal formations (Kidson and Manton 1973, Welsted 1979). They are also used in agriculture for the identification of crop types (Smit 1978, Philipson and Liang 1982) and soil erosion surveys (Stephens *et al.* 1982).

Black and white aerial photographs have also been used throughout the world for regional planning (Avery 1965), urban planning (Collins and El-Beck 1971), and for more specific studies such as the census of population (Hsu 1971, Lo and Chan 1980) and the monitoring of urban growth (Ellefsen and Davidson 1980). Surprisingly, black and white aerial photographs have not previously been considered as a tool by coral reef researchers in monitoring long term changes on coral reefs. The main reason is probably a lack of knowledge of what aerial photographs have to offer.

During the second world war there was widespread photography of many Pacific Islands and reefs for military purposes. Since then aerial photographs had been used for illustrative purposes in mapping (Maxwell 1968, Guilcher *et al.* 1969, Flood 1974, Orme *et al.* 1974). In Australia, vertical aerial photographs of the Great Barrier Reef were taken as early as 1925. In 1928, vertical coverage of the Low Isles on the Great Barrier Reef were taken at a scale of 1:2400m. These photographs were used extensively as a ground check by the first Great Barrier Reef Expedition led by Yonge (Stephenson *et al.* 1931).

The paucity of relevant information on hydrographic charts and the complexity of the coral reef environment have led to the utilization of aerial photographs in defining areas in scientific surveys (Hopley & Stevenick 1977). Aerial photographs have also been used in reef studies for purposes such as recognition and differentiation of photopatterns (Hopley 1978). Numerous papers have been published on the applications of aerial photography to geomorphology (eg. Fezer 1971), oceanography (eg. Ewing (ed.) 1965; Badgley *et al.* (eds.) 1969) and biological studies (Howard 1970) within the reef environment. Research on the interpretation of coral reef features from aerial photographs has been undertaken on the Great Barrier Reef (Hopley 1978, Hopley and Stevenick 1977). Aerial photographs were used in determining reef geomorphology (Steers 1945, Teichert and Fairbridge 1948) and the general ecology of coral reefs (Kumpf and

Randall 1961, Kelly 1969, Kelly & Conrad 1969).

The wartime coverage and special purpose photography undertaken for land, agricultural censuses and commercial surveys have provided a time series of aerial photographs for some reefs on the Great Barrier Reef Region and many small Pacific Islands. In spite of the widespread availability and use of aerial photographs of coral reefs, little research has been undertaken on the long term changes of the coral reef environment from aerial photographs.

Earlier work on low level infrared and true colour photography to map reef flats at low tide suggested that it was possible to distinguish between major substrate categories and in particular, between hard corals, soft corals and algae (Hopley 1978). Hopley and Stevenick (1977) also suggested that, when comparing four types of photography based on tone alone, normal black and white photography is mostly successful in defining reef zones. Therefore monitoring from aerial photographs should be capable of providing valuable information on the types of changes occurring on coral reefs.

However, the recognition and identification of areas is important when interpreting aerial photographs (Walker 1964, Stanley 1982). Tone, texture, pattern, place, shape, shadow and size were aerial photographic characteristics identified by Curran (1978) to be vital to an interpreter. Tone is most important because it represents a record of the radiation that has been reflected from the surface onto the photographic film. The light tones represent areas of a high radiance and dark tones represent areas with low radiance. Briefly, texture is the frequency of tonal changes within an aerial photograph and pattern is the spatial arrangement of features. The place where a feature is located in relation to others usually helps in its identification. The shape is an outline of a feature and size of a feature is a function of the photo scale.

The separation of specific coral reef features from aerial photographs and remotely sensed images has been largely a matter of subjective assessment (Hopley and Stevenick 1977). The recognition and mapping of coral reef photo patterns requires a systematic approach such as those provided by image processing techniques.

Reef flat changes on Suva Reef were assessed from aerial photographs from 1945 to 1990. The reef slope and the deeper part of the lagoon were inaccessible to airborne data because of the narrow width of this zone and the rapid change in depth. The reef flats were also more accessible on foot for *in situ* monitoring. In addition, they are exposed at low tide and are accessible for aerial photography.

The specific objective of this part of the study is to use aerial photographs for assessing long term reef changes. In particular, the long term spatial and temporal variability of different reef zones are investigated over a period of 45 years. In addition, the aim is also to develop a suitable methodology based on the Geographical Information Systems (GIS) and image processing techniques for an effective detection of long term habitat changes. The potential of remote sensing as a tool in monitoring long term ecological changes are evaluated. Both the magnitude and nature of detected changes between different time periods were also investigated.

4.2 STUDY AREAS AND MATERIALS AND METHODS

4.2.1 STUDY AREAS

The main study area is Suva Reef located off the coast of Suva. A map and detailed descriptions of Suva Reef is presented in Chapter 3. Suva Reef was chosen as a study site for aerial photographic analysis because it had aerial photographs available at different scales and different dates. In addition, community changes were monitored during field studies in 1984, 1989 and 1991 and it has also been studied extensively for crown of thorns (*Acanthaster planci*) predation (Zann *et al.* 1987, Zann *et al.* 1990). All these factors contribute to making Suva Reef a suitable study area for detailed aerial photographic analyses of community changes.

In this study, aerial photographs were subdivided into two major groups according to their scale. The first group of images were at a scale of 1:50,000 but were further subdivided into two sections, the western and the eastern sections of the reef. The main reason for the subdivision into two sections was the limitation in the processing facilities available. Only a 512 by 512 pixel image could be displayed completely for image processing. Both sections were analysed at a resolution of 10m.

The second group consisted of higher resolution images of Nasese shoal and were analysed at 3m resolution. The shoal was chosen because there were no *in situ* data collected from the area. From the knowledge of Suva Reef and information from aerial photographs it was assumed that Nasese shoal consisted of homogeneous stands of seagrass and sand. This was subsequently verified by an independent researcher. Therefore, Nasese shoal was used as a validation test site for using aerial photographs to determine the accuracy of classifying unknown areas from the knowledge of the reef environment and aerial photographic interpretations of the area.

4.2.2 DATA COLLECTION, PREPARATION AND GEOMETRIC CORRECTION

The Department of Lands and Mineral Resources archive in Suva, Fiji were searched extensively for aerial photographs of Suva Reef. Aerial photographs were available at different scales and at different times for the periods, 1951 to 1990. Aerial photographs were also obtained from the Suva City Council, Department of Public Works, University of the South Pacific and the Ports Authority of Fiji. The National and the Royal New Zealand Air Force Archives in Wellington were also searched extensively for aerial photographs obtained during World War II. Some aerial photographs were available from 1939 to 1970 at the National Archive but were not suitable for this research because of unavailability of the film negatives. Oblique aerial photographs of Suva in 1945 were available from the Royal New Zealand Air Force Archive.

All the aerial photographs used for image processing were taken vertically. Vertical aerial photographs have been the most widely used because they have properties that are similar to those of a map. They also have approximately constant scale over the whole photograph (Curran 1978). The scale of aerial photographs for this research ranged from 1:50,000 to 1:1,500. There were also high resolution photographs developed as large double scale prints from the original negatives.

All aerial photographs were scanned using a Cannon X-L Scanner. They were stored as digital images in TIFF (Tagged Image File Formats) format after scanning at a resolution of 300 dpi and were imported into the software package called IDRISI (Eastman 1992). In IDRISI, the images were stored as a byte integer 8 bit format.

It has been reported that there is little difference between SPOT satellite maps and existing ground survey maps (Barrett & Curtis 1992). In this study, a SPOT panchromatic image of Suva Reef taken in August of 1990 was used as a reference map base to geometrically correct a 1986 image of Suva. All aerial photographs were corrected to the rectified 1986 aerial photograph which became the effective base map for the airphoto analysis study. There were more similar points on the aerial photographs than the partly cloud covered SPOT panchromatic image. Therefore the accuracy was improved when correcting all aerial photographs to a rectified 1986 aerial photograph.

When correcting the 1986 aerial photograph to the SPOT panchromatic image the *RESAMPLE* routine in IDRISI was used. *RESAMPLE* has the ability to take information on the positions of a set of control points in an existing file and apply it to the whole image by using a cubic polynomial mapping. The image was geometrically corrected using nearest neighbour substitution. The residual mean error was automatically calculated for each control point and then using rubber sheeting the computer automatically aligns and corrects each point on the photograph and also removes various distortions. All the airborne images were corrected to the 1986 airborne image by this procedure.

The accuracy of the resulting rectified image was assessed visually by overlaying the two images digitally on top of each other on the display screen to determine any distortions. If distortions were detected the control points on the unrectified image were re-selected and the *RESAMPLE* routine repeated until there were no distortions detected. The root-mean-square (*RMS* error) was usually a good indicator of whether the *RESAMPLE* was satisfactory. The *RMS* error from the *RESAMPLE* procedure for each of the images used are presented in Table 4.1 The *RMS* error is a measure of the variability of the resampled position of control points about their true values.

The accuracy of rectified images is vital to the analysis and interpretation of the images. Any distortion would give false information on temporal change. Because of this, the rectified images that were found to have reasonable fit in the *OVERLAY* routine had to be assessed further by using the Statistical Analysis System in IDRISI. *CROSSTAB* was used to compare the rectified image to the 1986 base image. Before *CROSSTAB* was undertaken three sub-images (256 by 256 pixels) were each extracted from both the rectified image and the 1986 base map. The extracted sub-images were then compared using *CROSSTAB* to calculate the correlation coefficient (Cramer's V) and also the Kappa Index of Agreement (another measure of association) between the two images. For both tests, the value of 0 indicates no correlation of images and the value of 1.0 indicates perfect correlation. For the purpose of this study, the rectified image was accepted as satisfactory when the values of both Cramer's V and the Kappa Index of Agreement were between 0.9-1.0. The time series of airborne images were then ready for image processing and interpretation.

Table 4.1 Accuracies of geometric corrections of airborne images.

ORIGINAL	CORRECTED AGAINST	NO OF CONTROL POINTS	RESIDUAL MEAN ERROR (RMS)
1986(MASTER)	SPOT (PAN)	25	0.001
1951	1986(MASTER)	30	0.01
1967	"	25	0.01
1971	"	30	0.005
1978	"	30	0.0015
1979	"	30	0.0001
1982	"	27	0.004
1984	"	30	0.0008
1989	"	30	0.004
1990	"	30	0.0005
SHOAL			
1951	"	30	0.003
1967	"	30	0.064
1971	"	30	0.004
1978	"	30	0.02
1979	"	30	0.0015
1982	"	28	0.0016
1984	"	30	0.0008
1986	"	30	0.005
1989	"	30	0.001
1990	"	30	0.0016

Table 4.2 Summary of tones and texture patterns of major habitats.

Feature	Location where applicable	Tonal key	Texture pattern
Corals	Reef flat	Dark tones	Fine "micro-dot" pattern often with strong lineations determined by wave passage over the reef flat.
Sand	Backreef	Very light tones to brilliant white.	Smooth texture pattern and may follow wave refraction.
Seagrass beds	Backreef	Dark patches standing out sharply against lighter tones of the reef flat.	"Fluffy" cotton wool appearance especially around edges.
Algae	Reef flat	dark line	linear pattern
Coral pavement	Seaward reef edge	Uniform light grey tones	Even texture and broad bands
Consolidated Rubble	Middle Reef Flat	Medium tones	Strong but irregular lineations
corals	backreef	light to dark patches	irregular shapes
rubble	reef flat	light tones and especially if mixed with sand	irregular shapes

4.2.3 INTERPRETATION, IMAGE PROCESSING, CLASSIFICATION AND EXPERIMENTAL METHODOLOGY

4.2.3.1 INTERPRETATION AND CLASSIFICATION

In all the image analysis, black and white panchromatic images were used. Black and white aerial photographs provided the most information on Suva Reef. Colour infra-red (CIR) photographs were available for 1978 and 1982 and were found useful in further interpretations of black and white photographs and image analysis. CIR photographs were particularly useful in detecting live corals and algae because these reflected infra-red light very strongly.

All the original aerial photographs were first visually examined using a hand lens on the original prints to account for the different tones on the reef. To help differentiate between the habitats aerial photographic characteristics such as tones, texture, patterns, place, shape, shadow and size were important considerations. Using these characteristics the preliminary analyses of aerial photographs were carried out to help interpret the results of major changes taking place on Suva Reef.

Specific features on the aerial photographs were identified using the following systematic approach and using tone as an example:

1. For preliminary analysis the photographs were assessed to determine the tonal structure. The variations resulting from isolated cloud patches, and contrasts between individual photographs were noted. The variation resulting from the sun's angle, weather conditions and quality of processing were also noted.
2. The tonal structure was related to specific coral reef features of biological and geomorphological significance.
3. The tones were cross checked with field notes and transect data to confirm photopatterns. Some of the features had to be re-checked by an independent observer (Edward Lovell).

The establishment of the identities of patterns detected in the images and confirming what they represent is vital in photo interpretations. The major tones and texture patterns of some of the habitats are summarised in Table.4.2.

Some examples of tones and texture patterns are shown at different resolutions in Figs.4.1 & 4.2. *In situ* photographs of some of the areas are shown in Figs. 4.3, 4.4A & 4.4B.

However, the overall objective of any classification is to use a computer classification method to automatically categorize all pixels in an image into various cover classes. Computer classification generally involves the application of statistically based decisions for discriminating the different cover classes and whether the classes are "mixed or pure". The two major types of computer based classification methods are supervised and unsupervised. Unfortunately, these computer based classifications are usually based on the spectral characteristics of each pixel in an image.

A major drawback in not being able to use a computer based classification method is that it is tedious and slow to digitise manually the different habitats from an image. However, it was beyond the scope of this study to develop algorithms for classification using texture patterns and tones as the main delineating factors. Although the manual method of classification which was adopted has limitations it was found to be the most accurate method bearing in mind the author's extensive knowledge of the study area. It was also vital to integrate the diverse information required to interpret airborne images and to make the detailed, subtle distinctions necessary for accurate interpretations. It is, however, recognised that computer methods may be best for some tasks. In this study, the author's knowledge added to information from colour infra-red, a SPOT multispectral satellite image and subsequent *in situ* surveys were found to be sufficient for classifying black and white aerial photographs. From the information available, it was possible to define a number of categories into classes. A summary of a selected cover classes and their attributes are presented in

Table:4.2.

In general, areas of sand, dead coral and coral rubble produce lighter tones while the seagrass beds, algae and live corals exhibit darker tones (Figs. 4.1 & 4.2). Sandy areas and seagrass beds appear smooth with uniform texture. In contrast, areas with live or dead corals show a rough texture because of coral clumps or micro-atolls (Fig.4.2). Some of these corals may also show irregular shapes on the image. At the seaward reef edge, the texture becomes rougher and more organised. Areas of coral rubble at the reef edge would be sorted into rubble banks where they are aligned with the direction of the wave approach. Coral pavement coated with coralline algae at the seaward reef edge form a smooth texture and distinctive bands along the reef edge.

The main categories of classes were:

(i) live corals

(ii) seagrass

(iii) algae

(iv) consolidated rubble

(v) sand

(vi) rubble

(vii) mixture of sand and rubble

(viii) rubble bank

(ix) coral pavement

(x) boulder zone

(xi) tidal pool

When categorising the different classes there were some limitations in the ability to resolve the differences between turf algae and other substrata. As a consequence, turf algae were not classified into a category. Turf algae have very low canopy and it is difficult to distinguish them from any other substrata on aerial photographs. Turf algae were also intermixed between rubble, live corals and coral rocks (eg. see turf algae growing on rubble in Fig.4.3). A mixture of sand

and rubble were classified into one class because it was difficult to discriminate between mixed pixels of the two classes. But where there were homogeneous or relatively homogeneous stands of each class they were classified each as a class of their own. It is important to note here, that with the problem of mixed pixels some habitats may be either under-estimated or over-estimated.

One of the major problems with panchromatic data is that it is difficult to distinguish between dead corals and other substrata because of the low cover of dead corals scattered on the reef flat. In addition, dead corals are often found colonised by turf algae and therefore could be confused as live corals. There is a possibility that some of the dead coral covered by turf algae are classified as live corals. Therefore, the misclassification may result in the over-estimation of live corals and this must be taken into account when interpreting the results of the change. Because of the long term nature of this study and the results of *in situ* survey monitoring, it was assumed that most of the dead branching corals were turned to rubble by cyclones and increased water movement. But within a short time scale such as one year and without a major disturbance, the misclassification of dead corals as live corals would probably be greater.

Despite the simplicity of the classification method there are problems when the categories overlap. This was especially true for areas of tidal pools which also had live corals, algae, sand and rubble. The tidal pools therefore have varying covers of corals, algae, dead corals, sand and rubble intermixed with turf algae.

The airborne images were further manipulated on the visual display screen to differentiate between the different tones. Manual contrast stretch was carried out by using interactive adjustments on the look-up table. Hence, contrast stretching increased the range of image tones and enhancing the contrast between features. The digital approach, therefore, has major advantages in flexibility when compared to the photographic approach. Moreover, the visual display screen has the added ability of conveniently changing image scale, viewing specific areas and thus provide a capability to explore visually the varied dimensions of an image. Such capabilities are not available with the photographic approach, where considerable effort and time are required to study varied representations of photographs.

4.2.3.2 DRAWING HABITATS MANUALLY AND AREA CALCULATIONS OF EACH HABITAT

The classified areas differentiated from the airborne images were drawn manually using a mouse on the visual display screen. The interactive ability of the display screen was an advantage because of the ability to *ZOOM* into an area and thus enlarge the individual pixels. Each class was digitised as a unique identifier and stored as a separate vector file in IDRISI. Using the command *INITIAL*, a blank image of the airborne image of interest was created. Then using the command *POLYRAS* a new image was created by adding each vector file on the blank image.

The error from manual digitising was estimated by extracting a sub-image with only a few distinctive categories, for example sand and live corals where the contrast was large and thus the digital numbers (DN) were distinctive. By using the command *RECLASS* the DN values for each category was specified. The computer was then able to calculate the total area of each category and was compared to those digitised manually. The error estimated from manual digitising was <0.01 of a pixel. This automated method of classification could not be used for classification in this study because of the similarity in the DN values for most habitats. Therefore this can only be carried out if several habitats were masked while only a few remain for classification. This was still not possible because of the natural pattern of distribution of most habitats on the reef where they were not arranged in any particular shape, some were mixed while others were very close to each other in location.

Nevertheless, the areas of each of the habitats were calculated using the command *AREA* for the airborne image of interest and were compared with other images in the sequence. Therefore a time series of information was obtained defining the surface areas of each of the different zones; for example zone of seagrass, zone of rubble, zone of live corals and zone of sand. The percentage change for each habitat was calculated by using this example for seagrass

The *OVERLAY* module in IDRISI is an important ingredient of Geographical Information Systems (GIS) and it is an arithmetic operator where two input images were used to produce a single output. For each habitat, a time series of images from 1951 to 1990 were available for overlay. The first image is usually the previous year's image. For example when using the *OVERLAY* command to compare seagrass habitats at the eastern section of the reef, the first image was 1951 and the second image was 1967. By using the command *OVERLAY*, the corresponding pixels of the two images were added. As a result, a new image was created from the data on the two input images. These new images are those presented in this chapter and were used for determining changes in spatial patterns of each habitat types from 1951 to 1990. In order to interpret the images, a palette was created. Blue corresponding to a value of 2 showed the section of the habitat which was unique to the first image (losses) and red (a value of 1) showed the section which was unique to the second image (gain). However, yellow (a value of 3) showed areas of the habitat which were common to both images (no change).

4.2.3.3 **EXPERIMENTAL METHODOLOGY**

Several image processing techniques were used to determine whether they would be useful in this study. These image processing techniques are listed here although they proved not to be applicable.

(a) **Edge Enhancement**

This was used to sharpen images by restoring high-frequency components through the removal of scan-line noise. It was very useful in emphasizing edges between seagrass and coral rubble. Unfortunately, the computer cannot distinguish desired lineaments from others of similar greyscale change. For example when enhancing seagrass beds the shallow waters and corals were also enhanced. The shallow water could be masked but the problems with corals still remained especially when there were soft corals located amongst seagrass.

(b) **Density Slicing**

Since the aerial photographs were in digital form it was possible to simplify the information by reducing the number of classes through the selection of appropriate threshold levels. This method was found to be inadequate because of the similarity of grey levels for the different categories. This method would have been suitable if the grey levels were completely different. The procedure requires the development of suitable algorithms and computer programmes which is beyond the scope of this research.

4.4 RESULTS

4.4.1 TEMPORAL AND SPATIAL CHANGES OF SEAGRASS BEDS

Field surveys from 1984 to 1991 showed that *Syringodium isoetifolium* was the most dominant species of seagrass present on Suva Reef. It was restricted in its distribution to the backreef which separated the reef from the lagoon. The seagrass species *Halophila ovalis* was distributed sparsely at the backreef. It was very difficult to detect *Halophila ovalis* on aerial photographs because of its low canopy cover and height (see Fig.4.4). It is possible that *Halophila ovalis* was classified as sand because of the difficulty in identifying it from aerial photographs.

However, a large bed of *Syringodium isoetifolium* has existed continuously on Suva backreef between 1945 and 1991 according to aerial photographs and *in situ* surveys. From 1945 to 1991, *Syringodium isoetifolium* was clearly the dominant seagrass on Suva Reef. Fig.4.0 shows the general location of seagrass beds in relation to the location of other habitats on the reef.

4.4.1.1 **Eastern Suva Reef**

The distribution of seagrasses at the eastern Suva backreef indicated that large fluctuations have occurred between 1951 and 1990 (Fig.4.5). Appendix 4.3 summarises the amount of change and the rate of change in seagrass beds from 1951 to 1990. However, Fig.4.6 showed that there was relatively little change occurring between 1951 and 1971 when compared to changes occurring between 1978 and 1990. One of the main limitations of this study is the lack of aerial photographs between 1951 and 1971 available for analysis. It is possible that fluctuations could have been recorded if there were more data available during this period. Alternatively, the frequency of fluctuations of seagrass between 1978 and 1990 may be a result of increased human activity such as high siltation from sand dredging, and also from natural disasters.

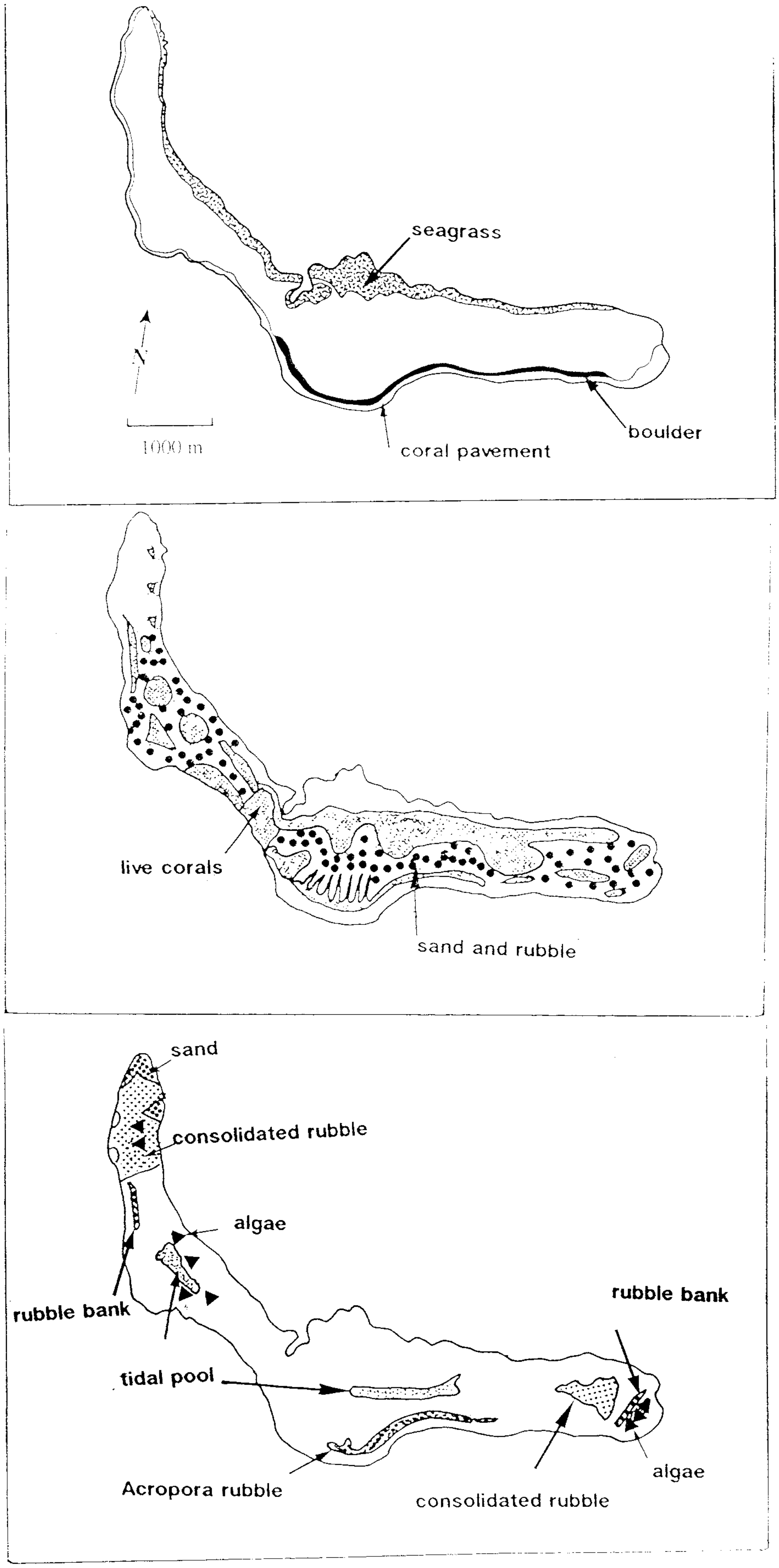


Fig.4.0 Diagrams of Suva Reef showing the general location of different substratum on the reef flat.

The decline in seagrasses between 1951 and 1971 may have been caused by the effects of tsunami and cyclone damage. There were, however, no available aerial photographs after the tsunami in 1953 to substantiate the effects of the tsunami damage. Severe cyclones occurred in 1955, 1958 and 1967 (see Appendix 4.4) and were usually associated with heavy flooding. The effects of flood are increasing siltation, turbidity and lowered salinity which could have retarded the recovery of seagrasses after tsunami damage. In addition, there is also physical damage to seagrass beds caused by cyclones. Field observations show considerable quantities of seagrass floating on the reef during high tide and in the lagoon after a major cyclone. The cyclones could also cause physical damage by removing suitable substratum for seagrasses from the backreef. Further decline in seagrass beds in 1986 was the result of severe flooding.

There were increases in seagrass between 1971 and 1979 even though three cyclones were recorded during this period. The effects of cyclones on the seagrass beds may not have been as severe as those in previous years. It is also possible that seagrass had recovered from the damage caused by the tsunami and were able to withstand the disturbance caused by cyclones. Further increases in seagrass were recorded between 1986 to 1990. The increases in seagrass were the result of regrowth (Fig.4.7) probably assisted by the absence of major cyclones or flooding during this period.

The spatial changes in seagrass beds at the eastern Suva backreef over a period of 39 years are shown on Fig.4.7. The major spatial changes occurred between 1971 and 1978 and between 1979 and 1982. Between 1971 and 1978, there was significant regrowth in seagrass which resulted in seagrass beds being extended towards the lagoon. In contrast, the significant losses of seagrass between 1979 and 1982 resulted in the seagrass regressing towards the reef flat. It must be noted that the losses between 1979 and 1982 were from the same areas of seagrass where significant regrowth had occurred between 1971 and 1978. It is possible that nutrient enrichment from terrestrial run-off into the lagoon could enhance algal epiphytes. As a result these epiphytes could be the cause of seagrass decline.

Although there was a slight increase in the seagrass present between 1978 and 1979, the regrowth and the losses of seagrass were not significant(Fig.4.7). They occurred mostly at the fringes of the seagrass bed.

The losses caused by severe flooding in 1986 were re-established by significant regrowth of seagrass in 1989 in areas where losses had occurred. The loss by flooding is shown clearly by losses of seagrass at the eastern section of the reef which is closest to the Rewa River (Fig.4.7) and therefore would be influenced by lower salinity, high turbidity and siltation. There were, however, some losses at the middle section of Suva reef in 1986 (see arrows in Fig.4.7), that may have resulted from lower salinity as a consequence of small creeks emptying into the lagoon. This could have contributed to the loss of seagrass in this area, although one would expect the losses to be occurring at the landward section of the seagrass bed. A detailed study on the retention of flood waters within the reef and lagoon and their circulation would be required to ascertain which sections of the seagrass beds are affected most by flood waters. It is likely that this section of seagrass beds declined because of the damage by cyclones in 1985. It is also possible that some of the decline could be the result of disturbances by sand dredging but the exact location of dredged areas were not available.

A major section of seagrass bed that had fragmented in 1978 was re-established in 1989 as a result of regrowth. Moreover, a section of seagrass bed which had disappeared in 1978 reappeared in 1989. The regrowth of seagrass between 1989 and 1990 had re-established some of those beds lost between 1982 and 1984. Between 1989 and 1990, two sections of the seagrass bed had formed a continuous bed. This was the first appearance of this continuous section of the seagrass bed since 1951. These results indicate that although losses of seagrass occurred in some years because of major disturbances they are able to recover if there is an absence of disturbance.

In general, the long term spatial changes of seagrass bed show clearly that there is oscillation in the regrowth and losses of seagrass on eastern Suva Reef. Seagrass beds extend toward the lagoon in some years and they regressed in other years. In addition, seagrass is seen to have great resilience to recover the losses. The observations show that losses occurring at the seaward section could be a result of hydrodynamic influence during storms whereas losses occurring at the landward section are more likely to be a result of either increased siltation, sand dredging or flood.

4.4.1.2. WESTERN SUVA REEF

Figs.4.5 and 4.8 show the distribution of seagrass from 1951 to 1990 at the western Suva reef. There were no significant temporal changes in the total seagrass occurring between 1951 and 1990, although there were spatial changes. The summary of temporal changes and the rate of changes in total seagrass is presented in Appendix 4.1.

The spatial distribution of seagrass at the western Suva Reef is shown in Fig.4.9. It shows significant losses in seagrass between 1951 and 1967 and this may have been the result of the tsunami and cyclone damages as described in section 4.4.1.1. The most prominent spatial change at the western Suva reef is the shift in seagrass beds to the seaward section of the backreef and losses at the landward section between 1967 and 1978 (see arrows in Fig.4.9). Four cyclones had occurred between 1967 and 1978 which could have contributed to the loss. In addition, major land reclamations occurred at Suva wharf and at the Grand Pacific Hotel from 1959 to 1977 and may have contributed to the decline in seagrass. The areas of seagrass lost were located opposite the areas where reclamation activities had taken place. It is possible that the shift in growth towards the lagoon could be a reaction towards oceanic water flowing over the top of the reef. The oceanic water reduces the level of turbidity in the area and thus provides suitable conditions for seagrass growth.

Between 1982 and 1984, there was a continuous seagrass bed at the western Suva backreef as a result of regrowth. It extended the seagrass bed towards the lagoon where it had occurred between 1951 to 1967. Moreover, the regrowth had helped establish a continuous band of seagrass which persisted on western Suva Reef from 1982 to 1990.

There were significant losses of seagrass between 1984 and 1989. These losses were found to be located in sections of the reef where they would be prone to increased water movement during cyclones or storms damage. The losses of seagrass in 1986 were caused by severe flooding. These were also found at the eastern Suva Reef and Nasese Shoal.

There were, however, no significant spatial changes in seagrass between 1978 and 1982 and between 1989 and 1990. But there was minor regrowth and losses during these periods.

4.4.1.3 NASESE SHOAL

The dominant habitat on the Nasese shoal is the seagrass *Syringodium isoetifolium*. The temporal changes of total seagrass from 1951 to 1990 at Nasese shoal are shown in Figs. 4.5 and 4.8. There was relatively very little change in seagrass between 1951 and 1984. There was a dramatic decline in seagrass in 1986 which was caused by flood. This was also found to be a major cause of seagrass decline at the eastern and western Suva Reef in 1986 (see Fig.4.5).

In spite of the decline, there was a rapid re-establishment of seagrass between 1986 and 1989. These increases in seagrass resulted from the regrowth of those areas previously lost during the flood of 1986.

The spatial changes of seagrass at Nasese shoal from 1951 to 1990 are shown in Fig.4.10. There were minor regrowth and losses at the fringes of the seagrass beds from 1951 to 1984. A small strip of seagrass bed which appeared in 1967 had disappeared by 1978 (see arrows in Fig.4.10). Field observations in 1992 showed that seagrass was beginning to re-appear and was covered with algal epiphytes (Lovell pers. comm.). It is possible that this section of the seagrass bed was dominated by seasonal growth of algae.

The most conspicuous change occurring at Nasese Shoal was the decline of seagrass in 1986 as a result of flood. The flood waters from Nabukalou creeks and other smaller creeks caused the decline in seagrass because of increasing turbidity, low salinity and high siltation. The aerial photographs show that these areas were left with bare sand containing persistent seagrass rhizomes a month after the flood. The seagrass bed had recovered to its usual status by 1989.

4.4.2 TEMPORAL AND SPATIAL CHANGES OF LIVE CORALS AND ALGAE

4.4.2.1 Eastern Suva Reef

(a) Live Corals

Live corals were the dominant living community in 1951. The most pronounced decline in live corals occurred between 1951 and 1967. The decline was probably caused by the tsunami damage in 1953. There was relatively very little temporal change in the total live coral cover from 1971 to 1990 on the eastern Suva Reef (Fig.4.6 & Fig.4.12).

However, detailed analyses of aerial photographs enables better understanding of the spatial patterns of decline and expansion of live corals at the eastern Suva Reef (Fig.4.11). Most of the live corals disappeared from the seaward edge and at the inner reef flat (see arrows Fig.4.11). This belt of live corals were replaced by coral blocks and boulders by 1967. Since the tsunami damage of 1953, resulting areas of coral blocks and boulders were never recolonised by corals to the 1951 status. Recent field observations show that these areas are still occupied by boulders with very minor coral recruitment occurring.

There was significant coral recovery between 1967 and 1971 at the inner reef flat. Most live corals that existed in 1951 at the inner reef flat re-appeared by 1971 except for those that were at the seaward edge (Fig.4.11). Further coral recovery was found at the middle reef flat between 1971 and 1978.

Between 1979 and 1982, there were significant losses of live corals at different sections of the reef. This decline in live corals was attributed to *Acanthaster planci* predation which were found to be abundant on eastern Suva Reef (Zann *et al.* 1990). The largest patch of live corals which disappeared between 1979 and 1982 occurred in the vicinity where large aggregations of *A.planci* and high coral mortality were observed in 1979 (see arrows in Fig.4.11). This clearly shows the impact of *A.planci* predation on the removal of large patches of corals from Suva Reef.

A further decline in live corals occurred between 1982 and 1984 (Fig.4.11) The decline was attributed to more *A.planci* predation and this was supported by evidence of large aggregations of *A.planci* at the eastern Suva Reef between 1982 and 1984 (see Table 1.2).

Between 1984 and 1986 there was some loss of corals and this may have been caused by a combination of factors. The flood that occurred in 1986 caused coral mortality (Seeto pers. comm.) at the landward section of the patch of live corals and also at the section closest to the Rewa River. Predation on corals by *A.planci* was also one of the causes of coral decline between 1984 and 1986 at the middle of the reef flat (Zann *et al.* 1990).

Between 1978 and 1979, and between 1986 and 1989, there was no significant decline or growth in live corals at the eastern Suva Reef. The decline and accretion in corals were at the fringes of the existing coral colonies. Some losses that occurred by 1989 may have been caused by *A.planci.* In contrast, there was significant coral growth between 1989 and 1990 which extended the coral patch further into the backreef. The increase in coral growth could have been the result of luxuriant growth of existing colonies or because of the recolonisation of this area by fast growing *Acropora* spp.

(b) Fleshy Algae

Fleshy algae were found, from aerial photographs, to be restricted to a section of the eastern Suva Reef. Field observations showed that these fleshy algae were *Turbinaria ornata* and *Sargassum* spp. Field observations also showed that most of the fleshy algae were more prominent during warmer months (December and January). Since the aerial photographs examined were obtained during the cooler months, the seasonal aspects of the growth of these fleshy algae were not taken into account.

There were no significant changes in fleshy algae from 1951 to 1990 (Figs.4.12 & 4.13B). The spatial changes occurred between 1951 and 1967 where there was regrowth. These areas of regrowth disappeared between 1971 and 1978. There was also a strip of fleshy algae which first appeared between 1971 and 1978 but later disappeared between 1978 and 1979. The regrowth of fleshy algae may be a response to major disturbances occurring on the reef. However, the seasonal aspect of the growth of algae cannot be ruled out and it is possible that some species such as *Colpomenia sinuosa* may appear during cooler months. The photographs examined covered several months ranging from May to August.

4.4.2.2 Western Suva Reef

(a) Live Corals

There were fluctuations in the temporal changes occurring at the western Suva Reef (Fig.4.8). There was a marked decline in live coral cover between 1951 and 1967. This coral decline also occurred at the eastern Suva Reef and the damage was probably caused by tsunami. There was coral recovery but no significant change in total coral cover between 1978 and 1984. There was a coral decline in 1986 and slight coral recoveries between 1986 and 1990. The coral decline in 1986 may have been the result of low salinity and siltation during the flood. The absence of any major disturbance such as cyclones or *A.planci* predation between 1986 and 1990 enabled limited coral recoveries during this period.

The spatial pattern of changes in coral cover between 1951 and 1990 are shown in Fig.4.14. There were major losses between 1951 and 1967 and these occurred at different sections of the reef. Between 1967 and 1978, there were coral recoveries but a patch of coral disappeared (see arrows in Fig.4.14). This patch of coral was *Acropora* spp. where very little regrowth were found by 1982. *A.planci* outbreaks were observed to cause extensive damage to the adjacent Namuka Reef (Zann *et al.* 1990), and this outbreak could have been the cause of coral mortality between 1967 and 1978.

Between 1978 and 1982, the loss of corals at the middle of the western Suva reef may have been caused by *A.planci* (see arrows in Fig. 4.14). Between 1972 and 1982 there were some *A.planci* observed on the western Suva Reef as reported by Zann *et al.* 1990. Since the patch of coral that disappeared was an isolated one it is highly likely that its disappearance was caused by *A.planci* predation.

Further losses located near the Taiwanese wreck between 1986 and 1989 were also a result of *A.planci* predation (see arrows Fig.4.14). Between 1989 and 1990, *Acropora* spp. colonies near the wreck had disappeared almost completely.

In general minor losses at the seaward fringes of coral patches may be the result of increased water movement and physical damage by cyclones and storms. The devastation of isolated patches of live corals observed from airborne images is related to *A.planci* predation. Field surveys showed that they would kill large patches of corals and especially the preferred *Acropora* spp.

(b) **Fleshy Algae**

The temporal and spatial distribution of fleshy algae was relatively consistent from 1951 to 1990 and were not significantly different (Figs.4.11 & 4.15). There was a decline of algae between 1951 and 1967 and this was a result of losses from the tsunami damage. These algae were again found on the reef by 1978. Between 1978 and 1982 there was no obvious temporal changes in algae although the spatial patterns show losses and regrowth at the fringes of existing algae.

There was an increase in algae between 1984 and 1986 and this was a result of regrowth in 1986 (Fig.4.15). These regrowths disappeared by 1989. It is possible that the increase in algae by 1986 was a result of disturbance caused by flood because they were replacing the substratum removed by the flood.

4.4.3 TEMPORAL AND SPATIAL CHANGES OF CORAL RUBBLE AND SAND

4.4.3.1 EASTERN SUVA REEF

(a) ***Acropora* Rubble**

There were significant increases in *Acropora* rubble between 1951 and 1978 (Fig.4.16). The spatial patterns of distribution showed that by 1978 these increases had formed a continuous belt of rubble at the inner reef flat (Fig.4.17). The tsunami and cyclone damage may have contributed to the increases in rubble during this period.

There were no significant temporal or spatial changes from 1978 to 1990 (Figs.4.16 & 4.17), only additions and losses occurred at the fringes of the rubble belt. The spatial patterns showed that the long term distribution of *Acropora* rubble was relatively stable bearing in mind that this material can be easily transported by water movement across the reef. It is possible that *Acropora* rubble was being replenished from the reef slope during storms and cyclones.

(b) **Consolidated Rubble**

There were no significant temporal changes in the total consolidated rubble between 1951 and 1990 (Fig.4.16). This indicates a long term stability of this substratum on the eastern Suva Reef. The spatial distribution showed additions and losses at the fringes (Fig.4.18). The losses between 1951 and 1967 may have been the results of the damage caused by the 1953 tsunami.

The losses at the landward section of the consolidated rubble may have been caused by the rock-boring echinoid *Echinometra mathaei*. The losses in consolidated rubble at the seaward section may have been the result of hydrodynamic influence or wave damage during cyclones.

(c) **Rubble Bank**

There were no significant temporal and spatial changes in the rubble bank between 1951 and 1990 (Fig.4.19 & Fig.4.13A). However, there were slight increases and decreases in some years. The damage caused by the 1953 tsunami could have explained the slightly higher cover and additions in spatial patterns by 1967. Minor losses and accumulations occurred at the fringes of the rubble bank in most years. Between 1984 and 1986, the accumulation may have been supplemented by damages caused by the three cyclones which occurred in 1985.

(d) **Mixture of Sand and Rubble**

The substratum classified as sand and rubble consisted of variable proportions of sand and rubble. The temporal changes in the mixture of sand and rubble show significant decline between 1967 and 1971, then a steady increase in sand and rubble between 1971 and 1984 but relatively little change between 1984 and 1990 (Fig.4.19).

The spatial distribution of sand and rubble between 1951 and 1990 are shown in Fig.4.20. It shows that there were losses at the landward and seaward sections. It is likely that the losses at the seaward section were caused by increased water movement. Sand and rubble are highly mobile material and can easily be transported by increased water movement during cyclones or major storms. It is likely that rubble lost from the seaward section may be that added to the landward sections, although there is also the possibility that rubble at the seaward section is replenished from the reef slope. Additional rubble could also result from dead corals on the reef flat disintegrating because of increased water movement during cyclones and severe storms.

There were significant losses in the mixture of sand and rubble between 1951 and 1971 and these may have been the result of removal by the 1953 tsunami and cyclones.

The breaking down of dead and live corals during storms and cyclones may also have contributed to significant extensions and accumulations of sand and rubble between 1951 and 1967 and as well as between 1982 and 1984. The accumulations between 1951 and 1967 occurred at the seaward sections and indicated that these may have been replenished from the reef slope. These areas had almost disappeared by 1971.

(e) **Sand**

There were fluctuations in the quantity of sand at the eastern Suva Reef from 1951 to 1990 (Fig.4.21). There were major increases in the sand deposited on the eastern reef in 1967, 1982, 1986 and 1990. The increase in sand in 1967 would have been contributed by the 1953 tsunami and cyclone damages. In 1982 and 1986, cyclones and terrestrial run-off may have been the major contributor of sediments to the reef.

The general spatial pattern of sand deposits was not significantly different from 1951 to 1990 when considering the high mobility of this material (Fig.4.22). Therefore, sand should show a more rapid variation than most of the other substratum. The results clearly show that in some years losses occur and in other years there were accumulations of sand. If new deposits of sand emerge on the reef it is because of a major disturbance. Because sand is a mobile deposit and can easily be transported by water movement it can disperse in the following year. As a result, it may be scattered amongst other substratum on the reef. It is difficult to predict from these results whether sand deposits have increased over the long term at the eastern Suva Reef.

4.4.3.2 WESTERN SUVA REEF

(a) *Acropora* Rubble

At the western Suva Reef, the *Acropora* rubble were either intermixed with sand, and classified here as sand and rubble, or accumulated as a rubble bank, or became consolidated rubble. This is in contrast to the eastern Suva Reef where the reef is more exposed to south-easterlies and thus more *Acropora* rubble accumulated as a result of increased water movement at the slope or on the reef flat. On the other hand, the western reef flat is more sheltered and less exposed to increased water movement caused by the south-easterlies.

In general, there were no significant temporal changes in overall levels of *Acropora* rubble at the western Suva Reef between 1951 and 1990 (Figs.4.16). There were, however, some minor spatial changes with losses and additions (Fig.4.23A).

(b) Consolidated Rubble

There was a steady decline in consolidated rubble between 1951 and 1978 (Fig.4.16). Between 1978 and 1990 there was no significant change in the coverage of consolidated rubble present on western Suva Reef. The decline in consolidated rubble between 1951 and 1967 was probably caused by the tsunami and the further decline between 1967 and 1978 may have been caused by cyclones.

The spatial distribution patterns of consolidated rubble at the western Suva Reef is shown in Fig.4.24. In general, the distribution patterns from 1951 to 1990 are very similar with expansion and reduction in areas of consolidated rubble in some years. The major losses in consolidated rubble occurred between 1951 and 1967. This could have resulted from the effect of tsunamis during the earthquake of 1953. Fig.4.24 showed that two major sections of the consolidated rubble were destroyed. A smaller section was almost totally re-established by 1986 (see arrows

Fig.4.24). There was an absence of major disturbance during this period which could have prevented damage to this section of the reef flat. There were losses and extensions of consolidated rubble between 1986 and 1990. Some of the losses may have been caused by rock boring echinoids which were present in large numbers at the western reef flat during this period.

(c) Rubble Bank

There were no significant temporal changes in rubble bank at the western Suva Reef from 1951 to 1990 (Fig.4.19). There were, however, some spatial changes between 1951 and 1990 (Fig.4.23B). In spite of the limited change, minor losses and expansions of the rubble bank occurred at the fringes and were recorded from 1951 to 1990. These may have been caused by increased water movement during storms and cyclones. There were, however, two main depositions of rubble banks at the western Suva Reef which persisted from 1951 to 1990.

(d) Mixture of Sand and Rubble

There was a marked decrease in the mixture of sand and rubble at the western Suva Reef from 1951 to 1967 (Fig.4.19). This was probably caused by tsunami damage. The spatial distribution of sand and rubble are shown in Fig.4.25. There were major losses between 1951 and 1967. Losses between 1951 and 1967 were caused by the formation of a large tidal pool. This tidal pool was first observed from airborne images on the western reef flat in 1967 and existed from 1967 to 1990. Field observations from 1984 to 1990 showed that a mixture of sand and rubble, coral blocks, and stands of corals and algae exist in the tidal pool. However, there were losses in sand and rubble in 1986 and these may have been caused by the three cyclones in 1985.

(e) Sand

Sand deposits changed very little on western Suva Reef between 1951 and 1967 (Fig.4.21). A notable increase in sand occurred in 1986. The flood in 1986 may have contributed to these accumulations and also the three cyclones in 1985 may have contributed to the removal of substratum such as seagrass and loose rubble and as a result the exposure of sand. Alternatively, sand may have been replenished from the reef slope. There was a steady decline in sand between 1986 and 1990. These may have been the result of seagrass regrowth and expansion which took over bare areas of sand.

The spatial patterns of sand distribution from 1951 to 1990 are shown on Fig.4.26. The major additions in 1986 largely disappeared in 1989 but some had remained on the reef flat until 1990. It is possible that some additions of sand between 1986 and 1990 were the result of excavations by the echinoid *Echinometra mathaei*. There were large numbers present at the western reef which contributed to the changes in substrata from coral rock to sand or rubble during this period (see Chapter 3). These echinoids created patches that were filled with sand. In addition, the decline in seagrass beds caused by the 1986 flood exposed areas of sand at the backreef.

4.4.3.3 NASESE SHOAL

There was relatively little change in the total area of sand deposits at Nasese Shoal from 1951 to 1984 and between 1989 and 1990 (Fig.4.21), but there was a marked increase in sand deposited at the shoal in 1986 because of the loss of seagrass as a result of flood. After the flood, sand was contained with seagrass rhizomes.

The spatial pattern of sand distribution is shown in Fig.4.27. Similar spatial distributions were found between 1951 and 1984 and between 1989 and 1990. Most of the sand deposits were distributed at the edges of seagrass beds. The losses and depositions of sand were not restricted to any particular area and the disappearance of small patches in some years and their appearance in other years indicate the relatively high mobility of sand in this area. It is also clear from Fig.4.10 that seagrass had extended to sand covered areas but later disappeared when there was a disturbance such as flood.

However, the most striking temporal and spatial changes occurred in 1986 and 1989 (Fig.4.27). This was mainly caused by the disappearance of seagrass in 1986 during the flood. After the disappearance of seagrass, sand was left with seagrass rhizomes. As a result, there was exposure of sand deposits by 1986 where seagrass beds had occurred. The sand deposits were overgrown by seagrass by 1989 and this explained the decline of sand recorded from aerial photographs (Fig. 4.27).

4.4.4 TEMPORAL AND SPATIAL CHANGES OF OTHER COVER TYPES (CORAL PAVEMENT, BOULDER ZONE AND TIDAL POOLS).

4.4.4.1 EASTERN SUVA REEF

(a) Coral Pavement

The coral pavement was encrusted with coralline algae and zoanthids. At the eastern Suva Reef, the coral pavement declined from 1951 to 1978 (Fig.4.28). There was a slight increase in coral pavement between 1978 and 1979 and a further decline between 1979 and 1984. Between 1984 and 1990, there was a steady increase in coral pavement on the eastern Suva Reef.

The spatial distribution of coral pavement showed similar patterns from 1951 to 1990 (Fig.4.29). There were minor losses and additions at the fringes of the coral pavements. Losses of coral pavement at the seaward sections may have been the result of wave activity during cyclones. Losses at the landward sections may be the result of rock-boring echinoids. In general, there is a long term stability in the spatial patterns of distribution of coral pavement on the eastern Suva Reef from 1951 to 1990, although the temporal changes showed some decline and recovery in some years.

(b) Boulder Zone

The most striking change occurring at the eastern Suva Reef from 1951 to 1990 was the formation of a boulder zone between 1951 and 1967 (Fig.4.28). There were no boulder zone in 1951. The most plausible explanation for the establishment of the boulder zone is the effects of tsunami. This explanation was also supported by Zann *et al.* (1987) and Zann *et al.* (1990).

However, a further increase in boulder zone in 1986 may have been the result of boulder accumulation by the three cyclones that struck in 1985. This was followed by a decline in boulder zone by 1989 which may have been caused by the removal of boulders and coral rocks because of increased water movement during storms.

The spatial distribution of the boulder zone is shown in Fig.4.30. Between 1967 and 1990 there was no significant change in the spatial pattern of the boulder zone. However, there were losses and additions at the fringes. It is possible that the losses at the seaward sections may have resulted in the accumulation at the landward sections, although additions at the seaward sections may have been the result of those being replenished from the reef slope by cyclones. Field observations show that after a cyclone boulders were replenished from the slope.

(c) Tidal Pools

There were noticeable increases in the area covered by tidal pools between 1951 and 1967 (Fig.4.28). The increases may have been the result of the tsunami which extended the area covered by tidal pools (Fig.4.31).

There was a further increase in tidal pool area between 1967 and 1971 (Fig.4.31) and this may have been caused by cyclones filling the tidal pools with sand and rubble. It is also possible that there was coral growth in this area. There were, however, minor losses between 1971 and 1978.

A slight increase in the total area covered by the tidal pools between 1984 and 1986 may have been the result of the three cyclones in 1985 (Fig.4.28). These cyclones were within a few weeks of each other and may have resulted in further damage.

The basic structure of the spatial pattern of tidal pools were similar from 1951 to 1990 (Fig.4.31). There were, however, major extensions of the tidal pools at all sections by 1967 and minor additions and losses at the fringes in other years.

4.4.4.2 WESTERN SUVA REEF

(a) Coral Pavement

There was a decline in coral pavement between 1951 and 1982 at the western Suva Reef (Fig.4.28), perhaps caused by the tsunami. There were no significant changes in coral pavement between 1967 and 1986 but there were slight increases in 1989.

The spatial distribution patterns of coral pavement were similar from 1951 to 1990 with losses in some years and additions in other years (Fig.4.32). The losses occurred in sections of the western Suva Reef where they would mostly be affected by hydrodynamic effects (see arrows on Fig.4.32). The extensions of the coral pavement were not particularly restricted to any section.

(b) Tidal Pools

There were fluctuations in the area covered by tidal pools at the western Suva Reef with a major increase in 1967 (Fig.4.28). The area covered by tidal pools increased from 1951 to 1967 and the effects of tsunami could have been the cause of such a noticeable change. In addition, the increase in area coverage in 1986 may be explained by the three cyclones that struck Suva in 1985. However, there were relatively little changes in tidal pools between 1978 and 1984 and also between 1989 and 1990.

The spatial structure of the pool area was significantly different between 1951 and 1967 (Fig.4.33). There were major additions to the tidal pool area by 1967 and may have been the result of the combined effects of the tsunami in 1953 and several cyclones that occurred between 1951 and 1967. The losses between 1967 and 1978 were significant in terms of the structural pattern of the pool. This pattern was a different shape from those that existed from 1978 to 1990.

4.5 DISCUSSION

The results of the airborne analysis indicate that long term changes on Suva Reef can be determined by classifying major cover types using remote sensing methods. The results have important implications for the analysis of coral reef ecology.

This study also highlight the importance of scale in determining long term stability of coral reef communities. There is little doubt that patterns that emerge advance our knowledge of long term stability when contrasted to those derived from conventional, small scale ecological studies. Small scale monitoring, sometimes, misses important patterns that are obscured by the "noise" of short term variation (Green et al 1987). The "noise" may be important in answering specific local and immediate questions but may be potentially misleading. However, it is recognised that to understand some specific effects and mechanisms of processes such as predation and behaviour, small scale approaches are generally more important.

In any consideration of long term changes to natural plant communities care has to be taken not to confuse man-induced effects with natural events. Unfortunately, there have been no long term studies of seagrasses of coral reefs where they are unaffected by human influences. Studies undertaken in southern Australia indicate that long term changes in seagrass beds do occur and that some appear to be cyclic in nature (Shepherd & Womersley, 1981). It is therefore important to scrutinise the nature of the changes that have been documented for Suva Reef and to determine if they are also natural long term cycles.

Some decline or losses of seagrass may be attributed to induce loss by storms, flood and cyclones. The decline caused by such events may cause severe loss of seagrass beds. Other areas that have been left bare may also be recolonised by other reef species such as soft corals.

For Suva Reef, there is clear evidence from historical airborne images and field observations that several processes have occurred. Seagrass beds occur at the backreef. The major decline in seagrass at all sites studied was during the 1986 flood. There were cyclic changes in the area of seagrass along both the eastern and western backreef with an overall increase in coverage in some years and an overall decrease in coverage in other years.

Between 1951 and 1971, large losses of seagrass occurred on the backreef of eastern Suva Reef. This may have been a result of large waves caused by the tsunami which resulted in substratum erosion and as a consequence seagrass losses. In addition, three cyclones occurred between 1951 and 1971 and these were associated with flooding. The effects of lowered salinity, high turbidity and siltation would have contributed to the decline of seagrass on Suva Reef.

However, one man-induced factor contributing to the decline of seagrass in some years was widespread dredging for sand by the Fiji Cement Industries (Penn 1983). This is supposed to have triggered the depletion of seagrass beds in the 1970's and 1980's. This offers a possible explanation for the effect of bottom dredges in depleting *Syringodium* beds on eastern Suva Reef from 1979 to 1984. The release of sewage and industrial effluent into Laucala Bay could also be a major factor responsible for losses of seagrass beds during this period.

It seems likely that seagrass beds were the most prone substratum affected by the flood in 1986. Areas of seagrasses were lost in the western and eastern parts of the reef. Further seagrasses were also lost from the Nasese Shoal. The eastern section of Suva Reef may have been affected by run-off from the Rewa River and other small river catchments in the area where residential development and reclamation expanded greatly during this period. Coincident with increased residential development, the installation of sewage treatment works and associated outfalls to rivers, extensive seagrass losses have been noted.

Water from the Rewa River has been noted (Seeto pers. comm.) to have had higher turbidity and the effects of this turbidity extended to eastern Suva Reef during heavy rainfall and flooding (Fig.4.1). There was evidence from airborne images that there was a loss of seagrass on sections of the eastern Suva Reef near the Rewa River during the 1986 flood.

Sediments around the Suva area are also reported to have had a higher silt content in recent years (Dickie *et al.* 1991). The western section of Suva Reef and the Nasese Shoal may have been affected by run-off from Nabukalou Creek and other smaller river catchments. The dramatic depletion in seagrass in 1986 was most evident at the Nasese Shoal because of its proximity to turbid inshore waters. The oceanic waters entering the lagoon may have prevented further damage to the seagrass beds on the backreef because of its frequent flushing during high tide.

Therefore, the analysis of airborne images shows that a combination of man-induced and natural events are considered responsible for the decline in distribution of *Syringodium* on Suva Reef.

Mayer (1924) noted that reefs in the Suva area had deteriorated by the 1920s as a result of siltation following the deforestation of the Rewa watershed. By 1967, the coral-dominated eastern and western sections of Suva Reef were altered by the tsunami induced by the 1953 earthquake. The changes caused by the tsunami modified the habitats on the reef flat with the death of coral colonies. As a result, the largest decline in corals recorded from airborne images occurred between 1951 and 1967. In addition to the coral damage, considerable damage by tsunami caused one end of the reef to collapse into deep water (Zann 1992). Although, this was not substantiated from the airborne images, it is possible that this was a section of the reef slope.

Cyclones appear to have played a significant role in determining the structure of the reef flat. Cyclone damage to coral reefs is caused through several mechanisms, including wave damage, scouring, sedimentation and reduced salinity

(Endean 1976, Woodley *et al.* 1981, Macintyre *et al.* 1987). The extent of the damage to reef habitats depends upon the frequency and intensity of storms and upon the resultant accumulation or removal of mobile rubble at a particular site (eg. Randall & Eldredge 1977). The different reef habitats seem to be differently affected by cyclones depending on its severity, the time of recovery and also the intensity of previous disturbance. It is possible that the post-tsunami recovery of corals was delayed further by three cyclones between 1953 and 1967. Rough seas from cyclones were responsible for damage to corals before they recovered from the effect of the tsunami.

Previous studies of the impact of cyclones upon corals and other sessile reef organisms have contributed substantially to the understanding of the dynamics of reef communities (Knowlton *et al.* 1981, Porter *et al.* 1981, Wulff 1985, Yoshioka & Yoshioka 1987). However, most studies document only short, rather than long term, effects. The long term changes in the abundance of reef habitats have important implications for the structure and function of coral reef communities.

However, there were also large reclamations for urban development in the Suva City area in 1959 (Dickie *et al.* 1991). This may have caused localised damage to corals on the reef flat as a result of heavy sediment load during heavy rainfall. In 1965, there was coral death on Suva Reef by siltation after a major flood (Robinson 1971).

Between 1967 and 1990, there were varied fluctuations and structure of reef habitats. The dominance and the types of community structure reflects the type of substratum present and also the amount of time which had elapsed since the previous disturbance. Substratum stability ensued if there was absence of further major disturbance. Cyclones, tsunami, flood and *A.planci* seem to be major influences in shaping the structure of reef habitats from 1951 to 1990.

It has been suggested that rubble can be carried landward by breaking waves (Banner 1968, Glynn *et al.* 1965, Ball *et al.* 1967, Perkins and Enos 1968). The damage to coral colonies on the reef flat may have contributed to increased coral rubble in some years. This rubble may also be carried seaward by hurricane generated currents (Stoddart 1963). From the results of the analysis of airborne images, it is seen that rubble may either extend landwards or seawards depending on the presence of storm generated breaking waves in some years or cyclone generated currents in other years.

Other reef habitats underwent temporary decreases, increases or dislocations from 1951 to 1990. These habitats were tidal pools, sand, coralline pavement, boulder zone and algae. In general, there were major changes to the habitats when there was a cyclone or other disturbance such as flood. There was, however, habitat stability if there was absence of further disturbance.

According to oral histories of Fijian fisherfolk, outbreaks of the coral predator crown of thorns starfish (*A.planci*) have become more frequent and serious since the 1960s (Zann *et al.* 1990). The first documented crown of thorns outbreak on Suva Reef was between 1967 and 1970 (Owen 1971) when there was severe damage to coral colonies. A second outbreak occurred between 1986 and 1988 on Suva Reef (Zann *et al.* 1987, Zann *et al.* 1990) when again severe damage occurred to corals. In particular, the disappearance of patches of *Acropora* spp. on the western Suva Reef was mainly the result of starfish predation. The causes of crown of thorns starfish outbreaks are not known. Some scientists consider them as natural and others consider them to be a result of increased human activities (Zann 1992).

However, the results of *in situ* survey and published data (Zann *et al.* 1990) showed that echinoids were abundant on Suva Reef from 1988 to 1991. They are major bio-eroders of dead coral skeletons. Most coral colonies that were killed by *Acanthaster planci* were then largely eroded by a numerous population of the sea urchin *Echinometra mathaei* (see Fig.4.3).

Finally, the differences in recovery between the two sections of the reef appear to be related to the overall environmental degradation of the reef prior to cyclones. The differences in the two sections of the reef may also be a localised effect. The eastern reef is more exposed and is influenced by wave action and south-easterlies. It is also influenced by the Rewa River while the western reef is a more sheltered reef. Differences in recovery between the two sections of the reef between years were probably linked to differences in their previous degradation levels and habitat complexity. The biotic diversity and the topographic relief of the eastern reef was greater than the western Suva Reef.

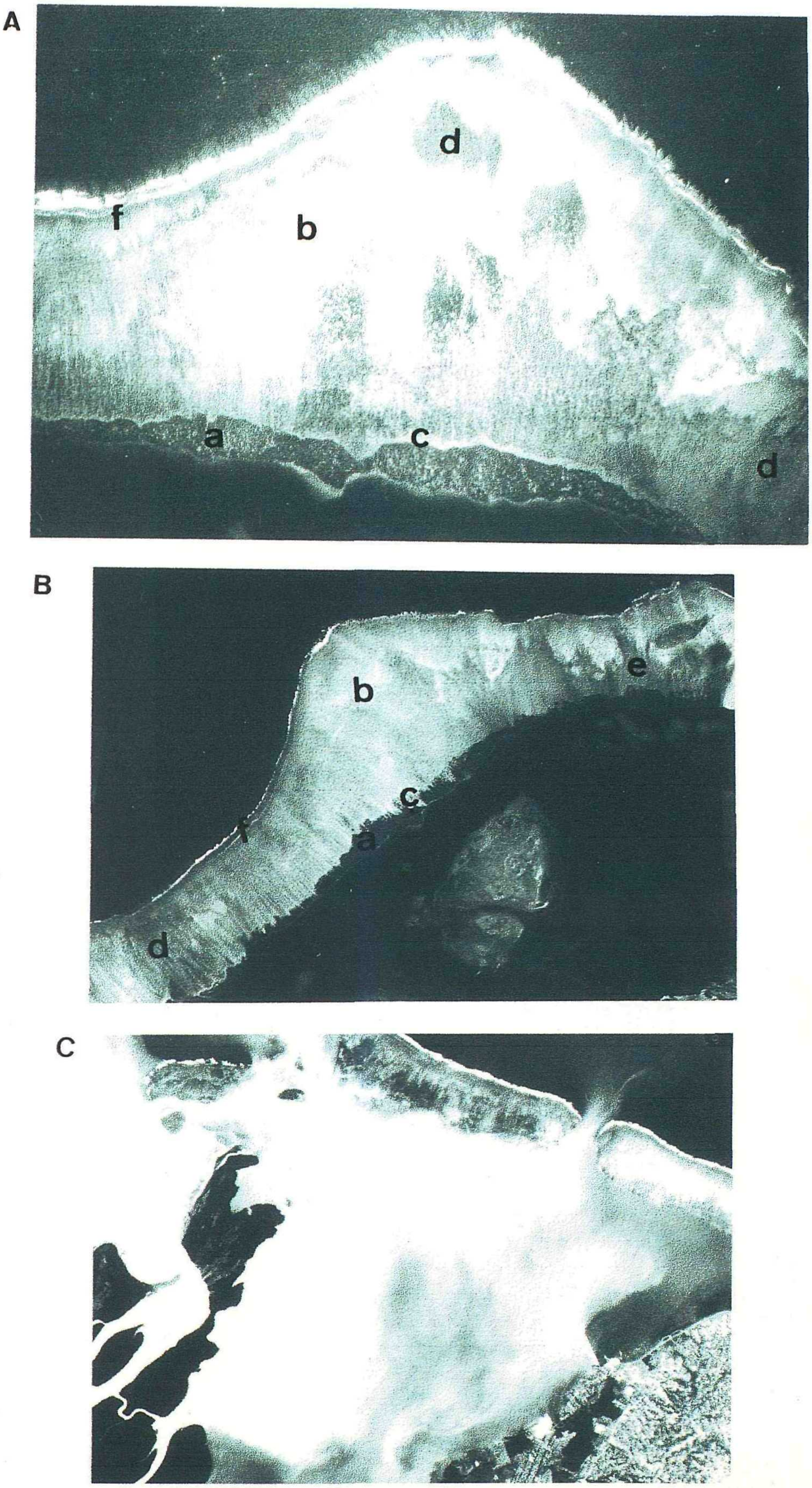
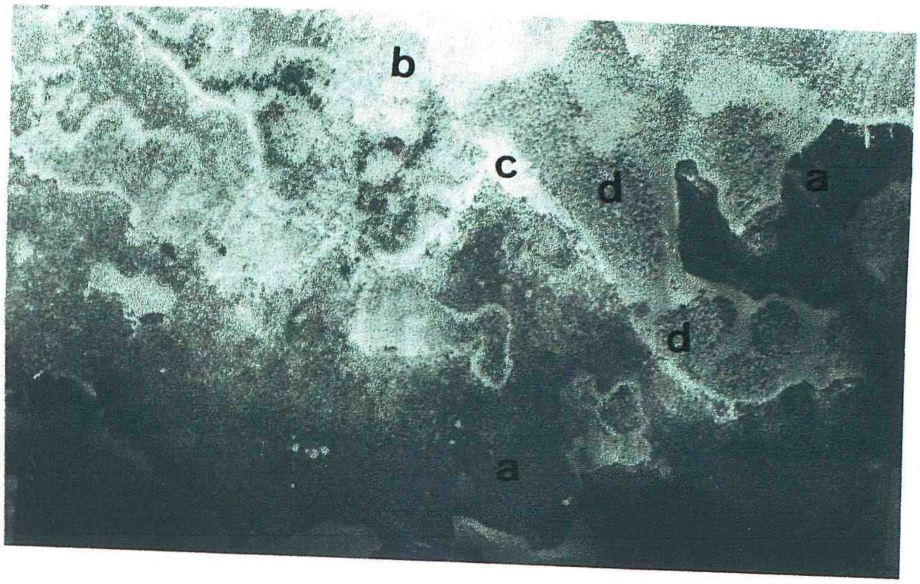


Fig.41 Tones and texture patterns at western section of Suva Reef and flood waters flowing from the Rewa River into Laucala Bay.

A. western section (1951)
B. western section (1990)
C. flood (1986)

a. seagrass
b. sand & rubble
c. sand
d. live corals
e. consolidated rubble
f. coral pavement

A



B

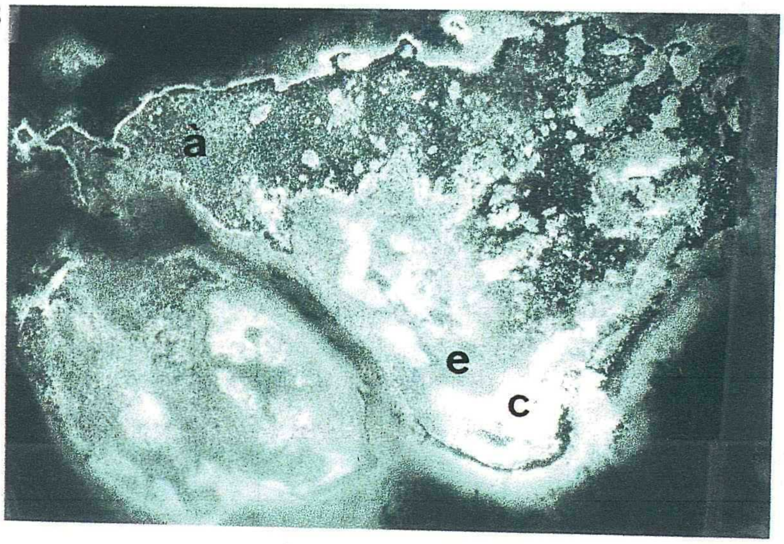


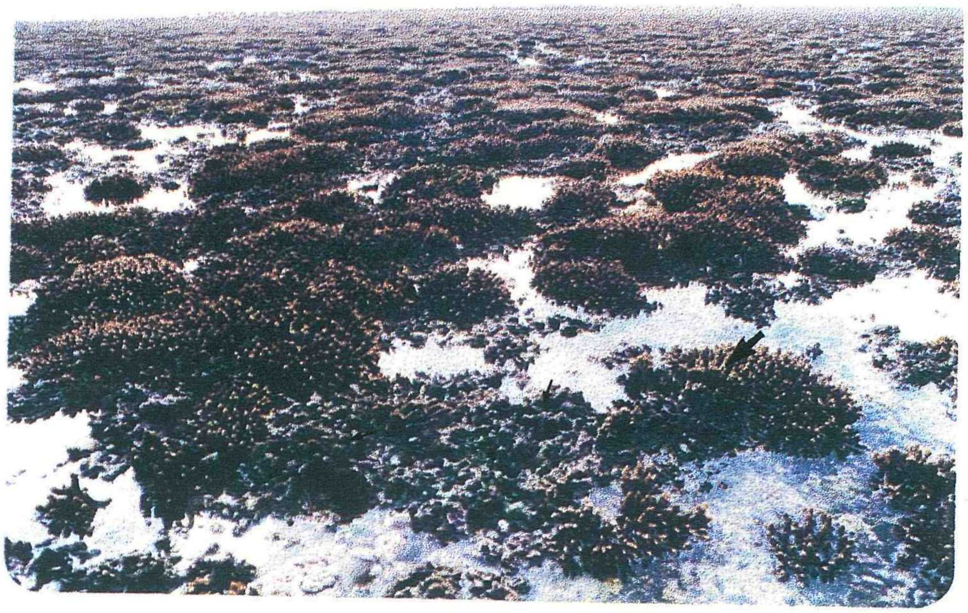
Fig.4.2 High resolution airborne images showing tones and texture patterns at eastern section and Nasese shoal.

A. eastern section

B. Nasese shoal

a. seagrass (*Syringodium*)
b. sand & rubble
c. sand
d. live corals (*Porites* spp. and *Xenia* spp.)
e. sparse stands of seagrass *Halophila ovalis* and sand.

A



B

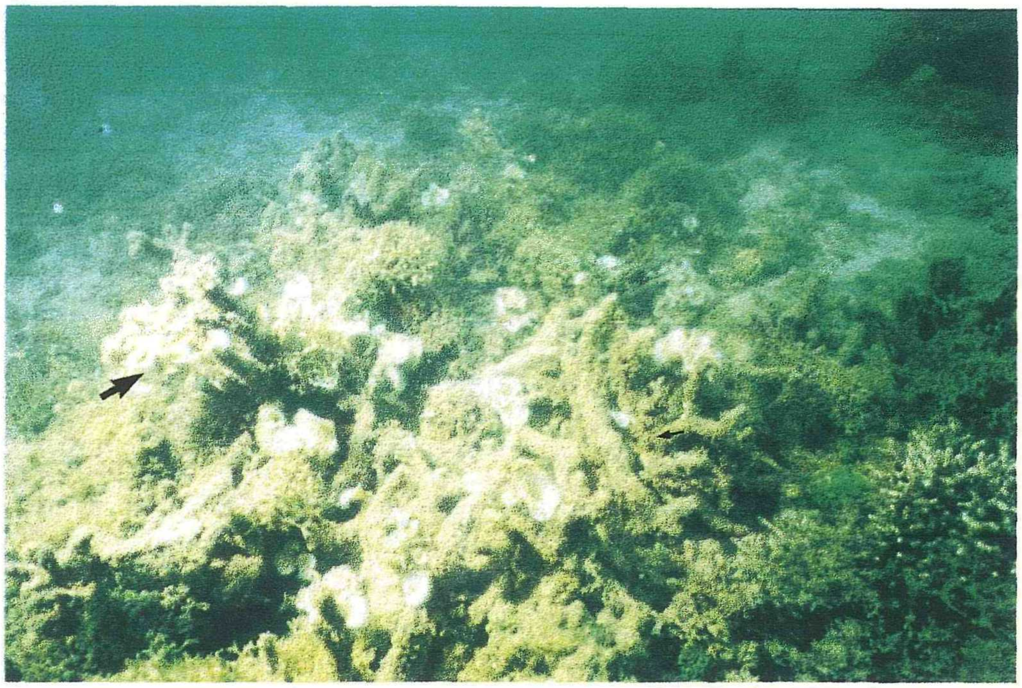
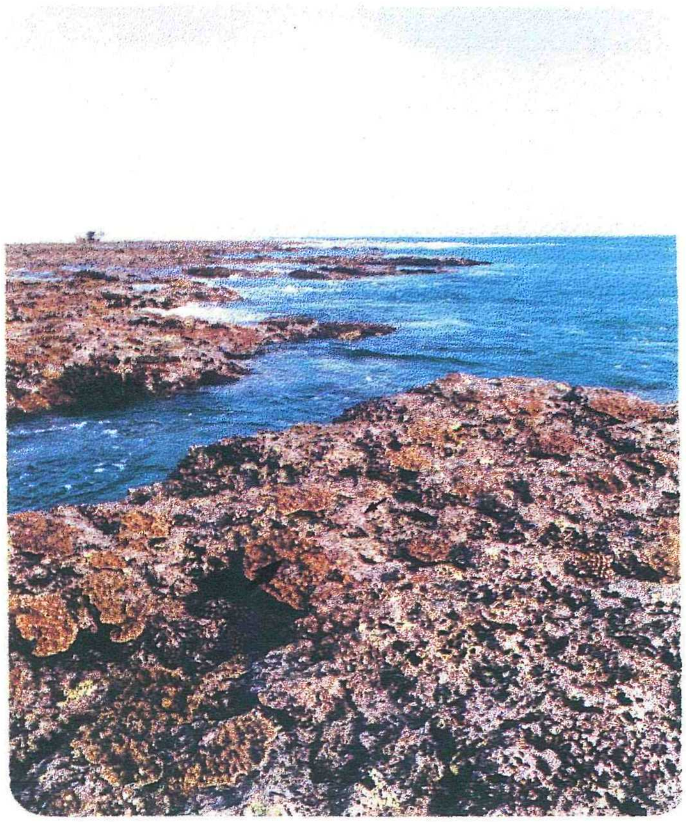


Fig.4.3 Live corals and coral rubble

A. *Acropora* spp. at the vicinity of transect 3 and effects of excavations by *E.mathaei*.

B. Coral rubble covered with turf algae and *Padina tenuis* at the eastern section

A



B

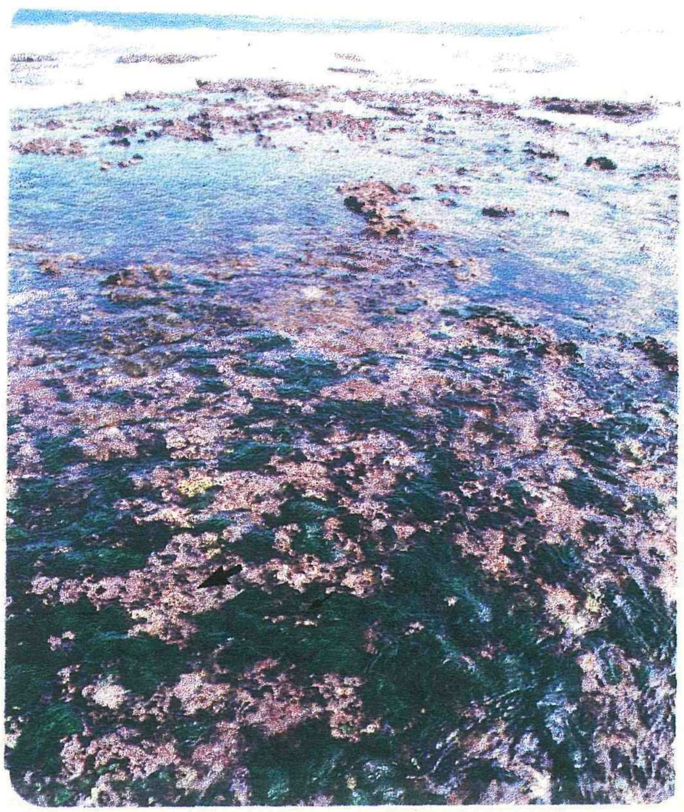


Fig.4.4A *In situ* photographs of seaward reef edge.

A. coral pavement coated with coralline algae and patches of encrusting live corals.

B. coral pavement coated with coralline algae and with patches of algae *Chlorodesmis* sp.

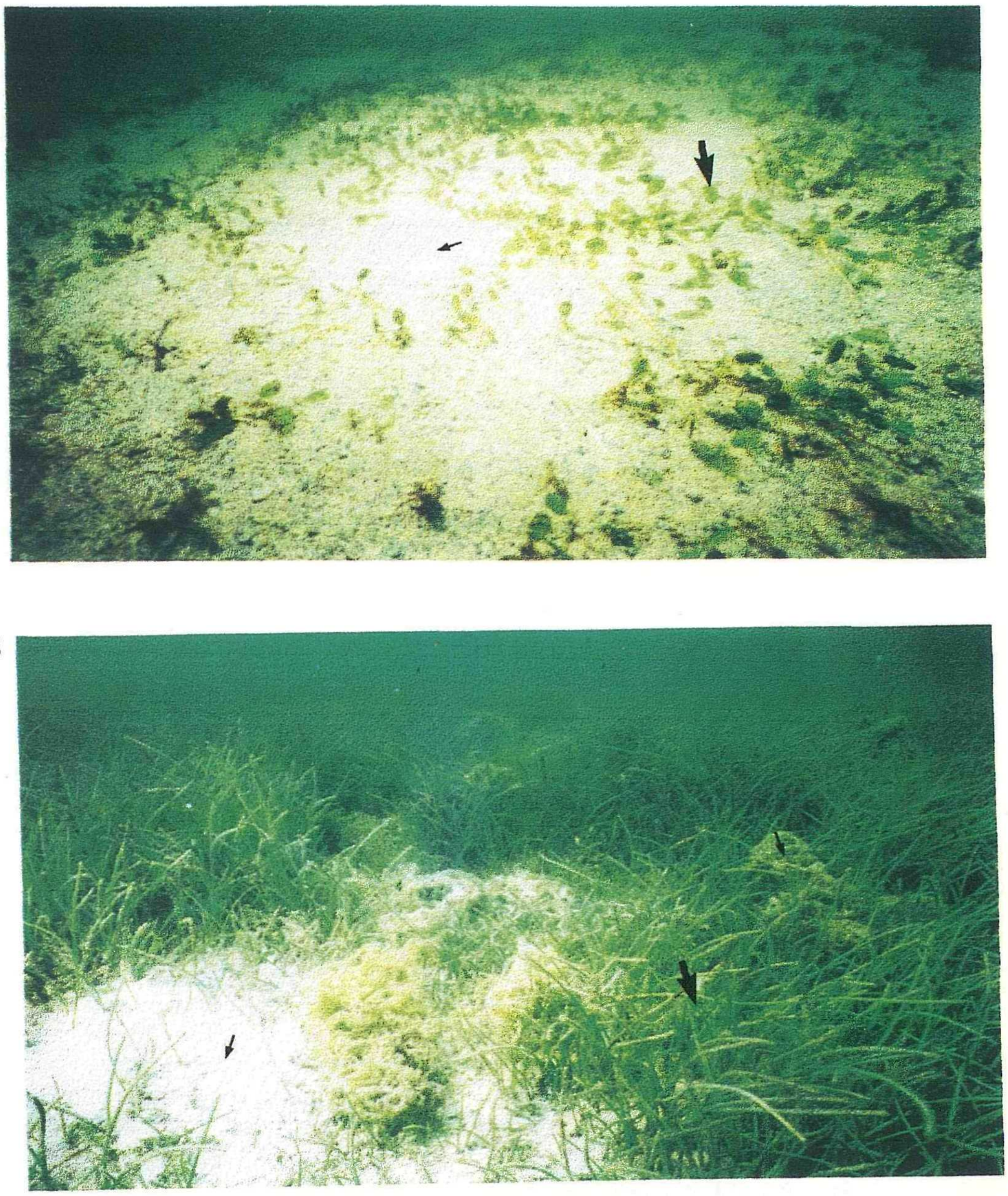


Fig.4.4B Seagrass at Nasese Shoal

(A) *Halophila ovalis* and sand

(B) *Syringodium isoetifolium* and *Hydroclathrus* sp. and sand.

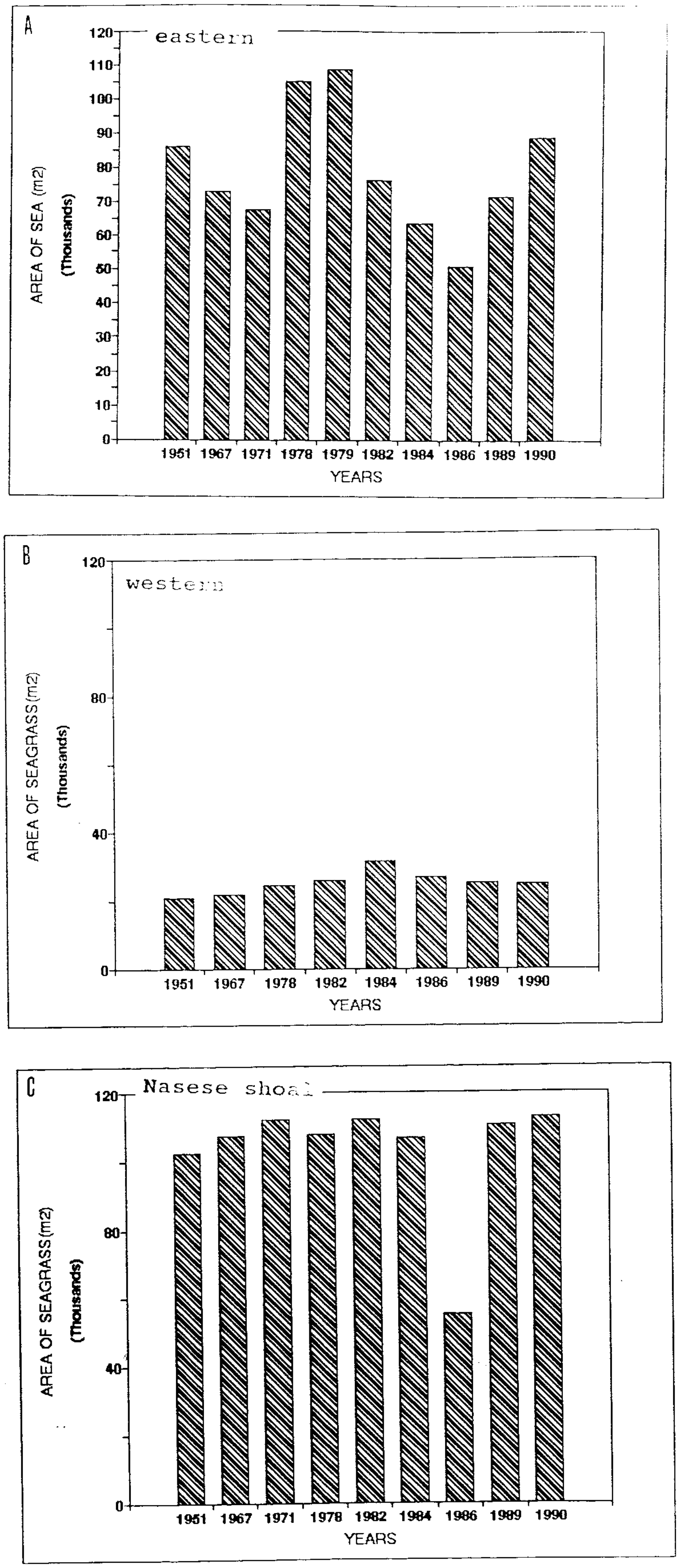


Fig.4.5 Distribution of seagrass

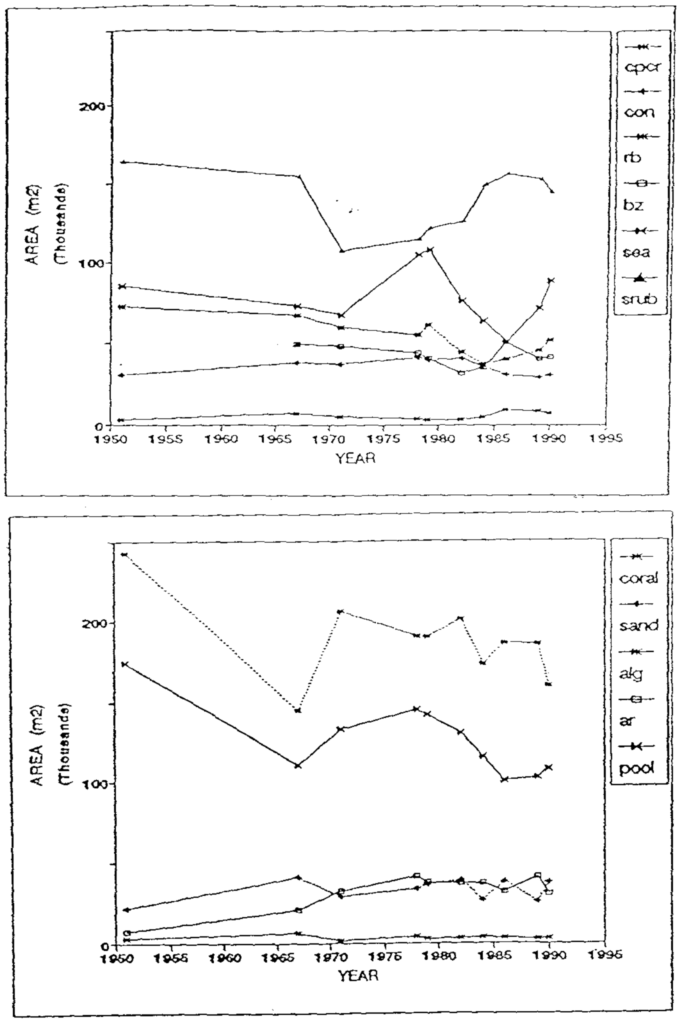


Fig.4.6 Distribution of all substrata at eastern section.

CPCR. coral pavement
CON. consolidated rubble
RB. rubble bank
BZ. boulder zone
ALG. algae
POOL. tidal pool
AR. *Acropora* rubble
SEA seagrass

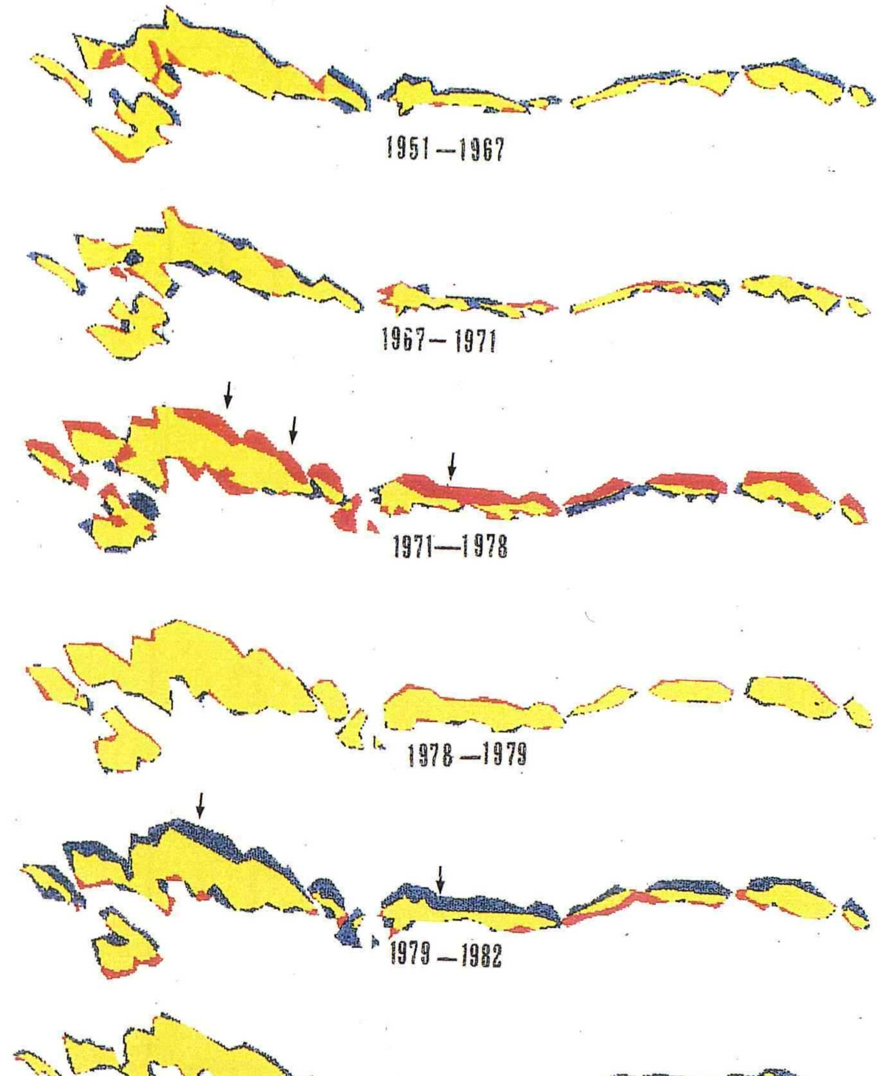


Fig.4.7 Distribution of seagrass at eastern section from 1951 to 1990
blue=loss, red=gain and yellow=no change

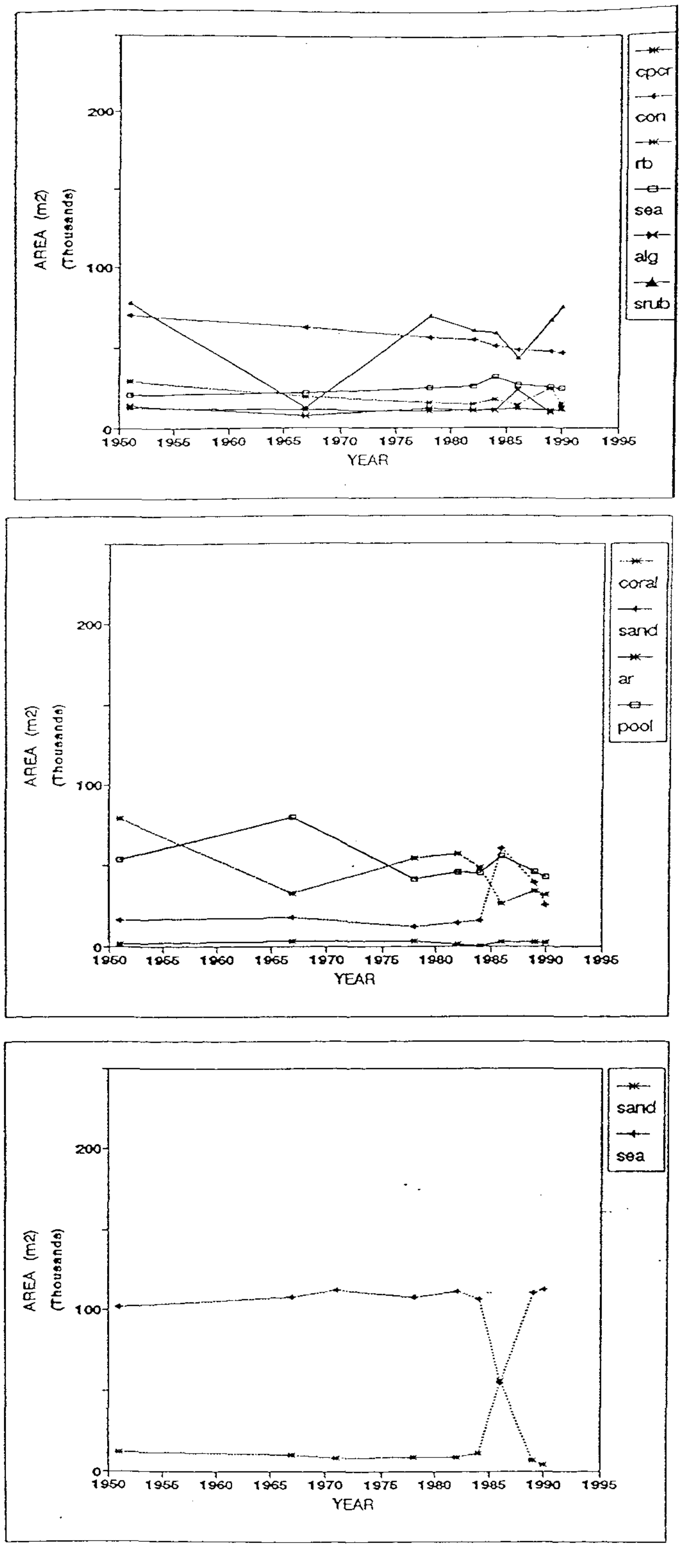


Fig.4.8 Distribution of all substrata at western section and Nasese shoal.

CPCR. coral pavement
CON. consolidated rubble
RB. rubble bank
BZ. boulder zone
ALG. algae
POOL. tidal pool
AR. *Acropora* rubble

SEA seagrass

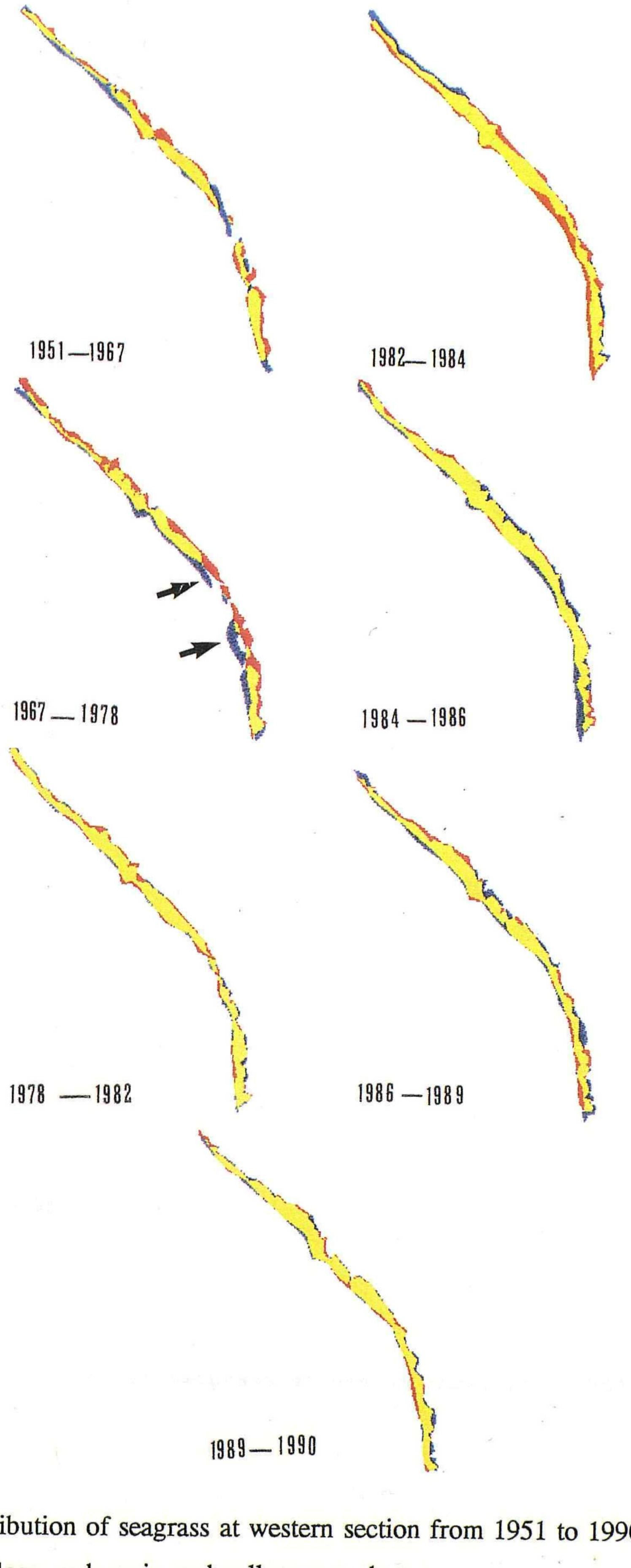


Fig.4.9 Distribution of seagrass at western section from 1951 to 1990
blue=loss, red=gain and yellow=no change

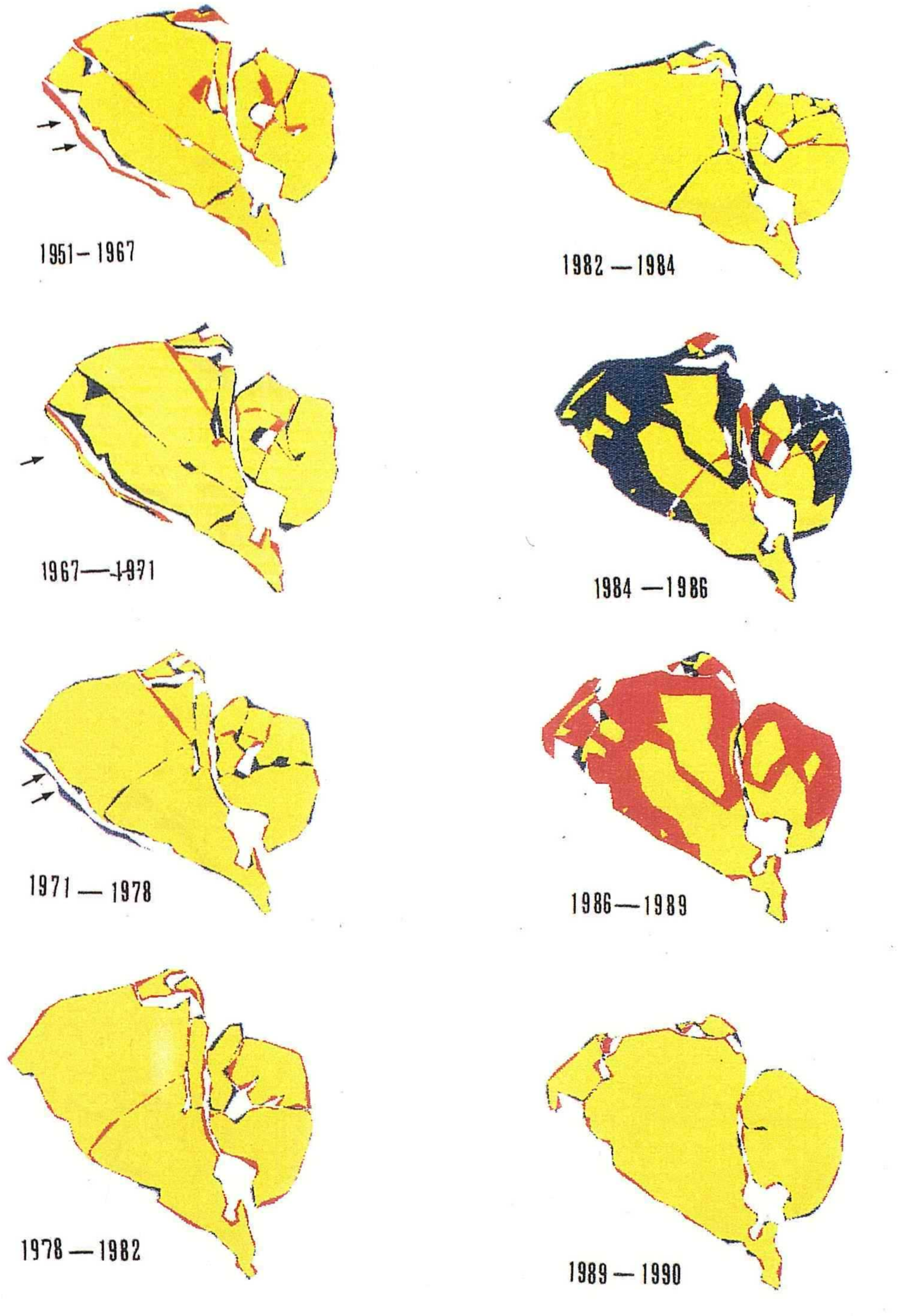


Fig.4.10 Distribution of seagrass at Nasese Shoal from 1951 to 1990

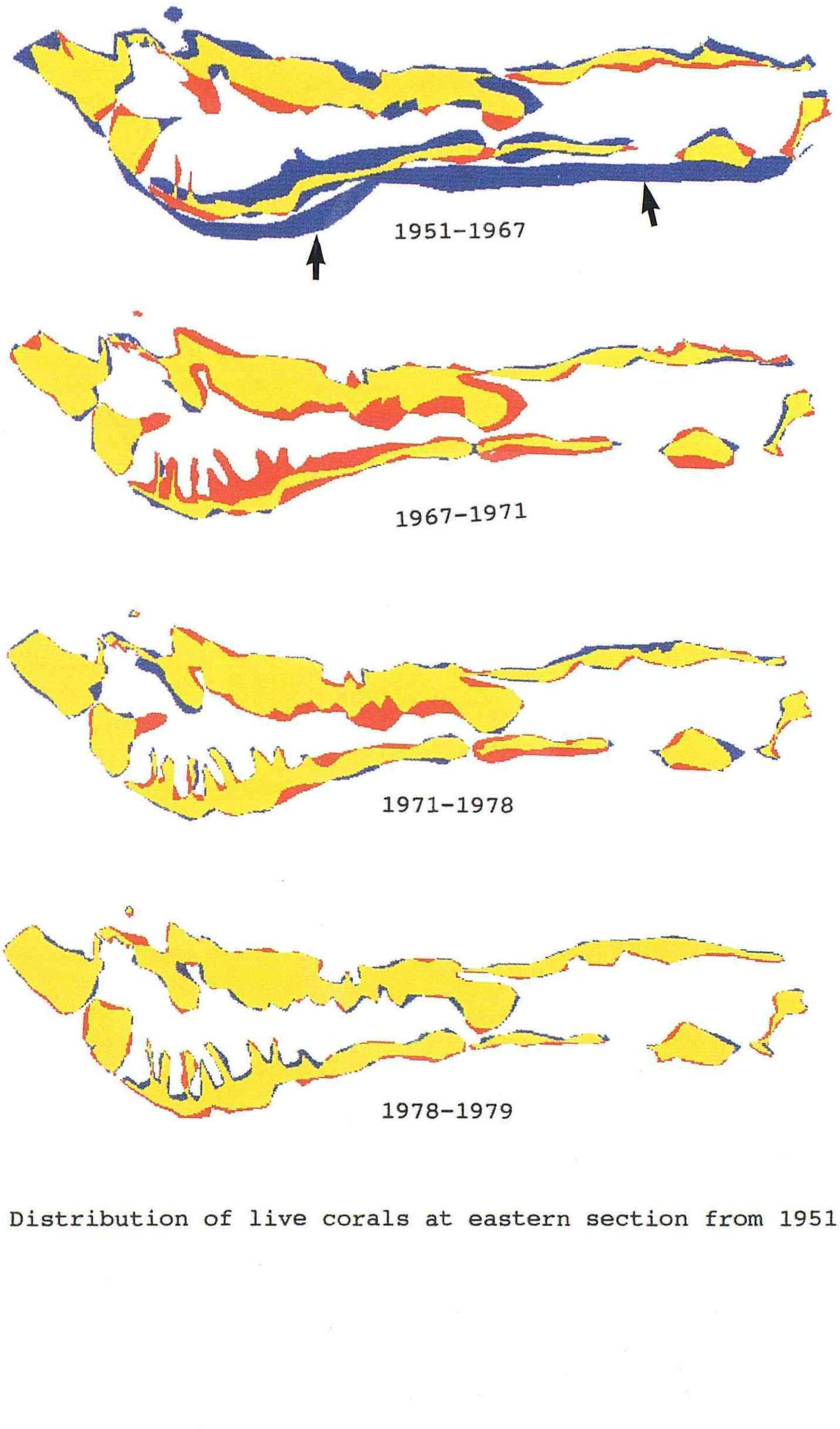
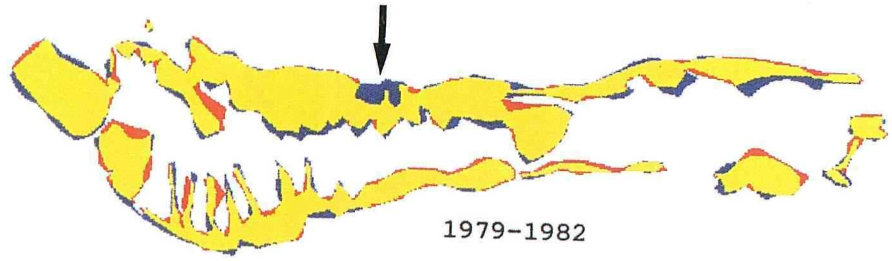
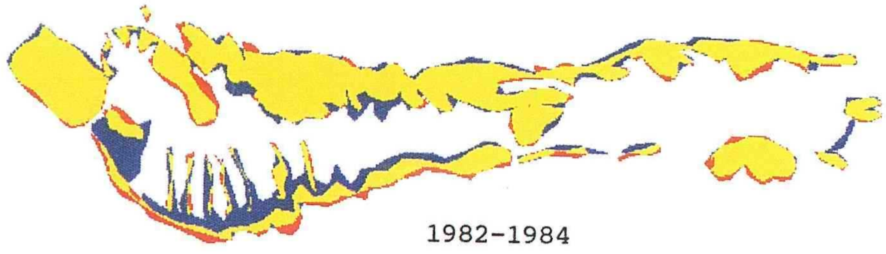


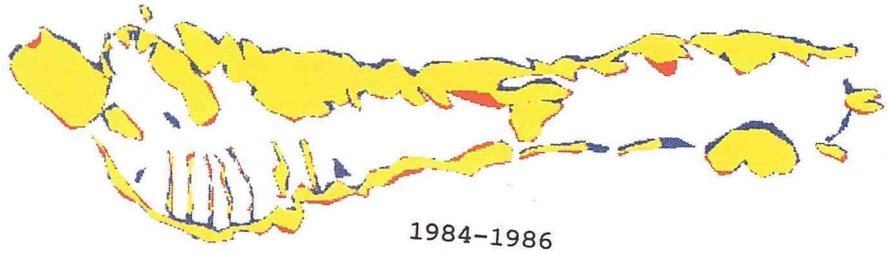
Fig.4·11 Distribution of live corals at eastern section from 1951 to 1990.



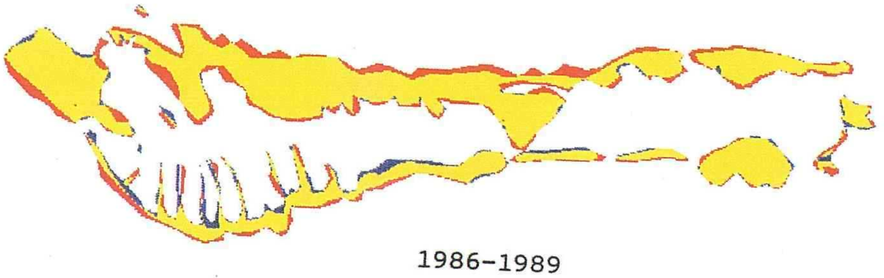
1979-1982



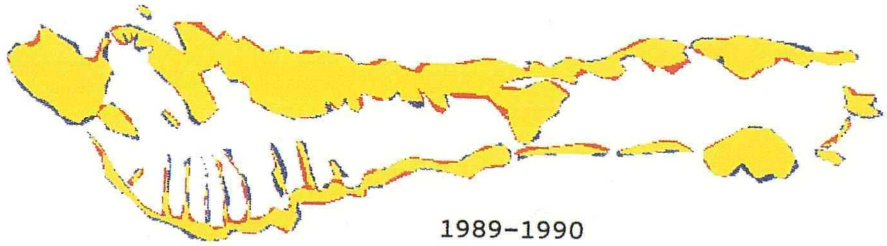
1982-1984



1984-1986

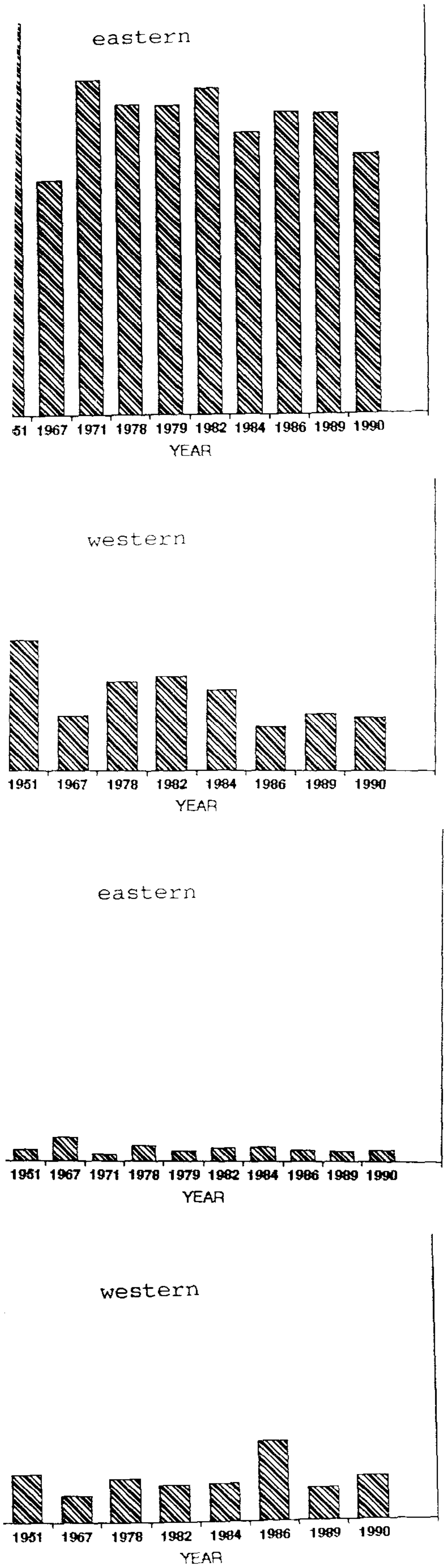


1986-1989



1989-1990

Fig.4.11 cont'd. Distribution of live corals at eastern section from 1951 to 199o



.12 Distribution of corals and algae

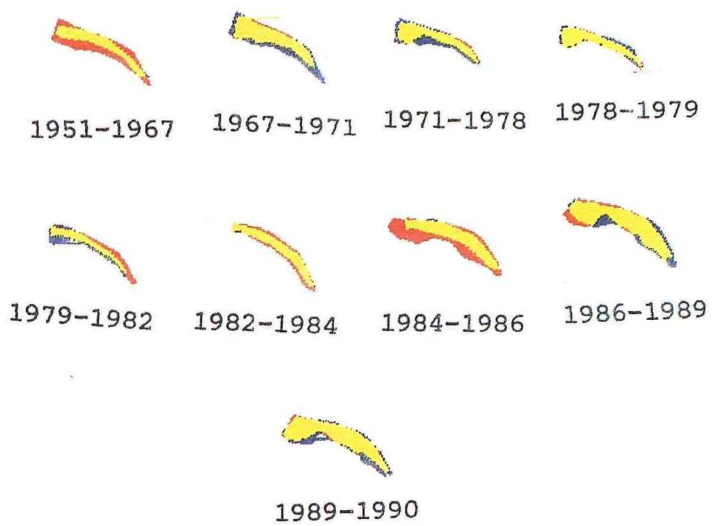


Fig.4.13A Distribution of rubble bank at eastern section from 1951 to 1990.

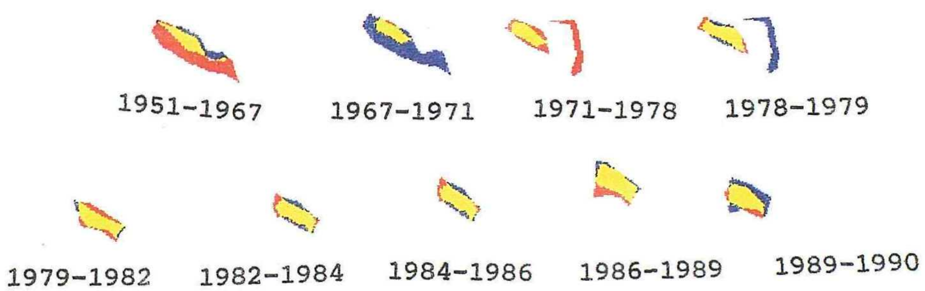


Fig.4.13B Distribution of fleshy algae at eastern section from 1951 to 1990.

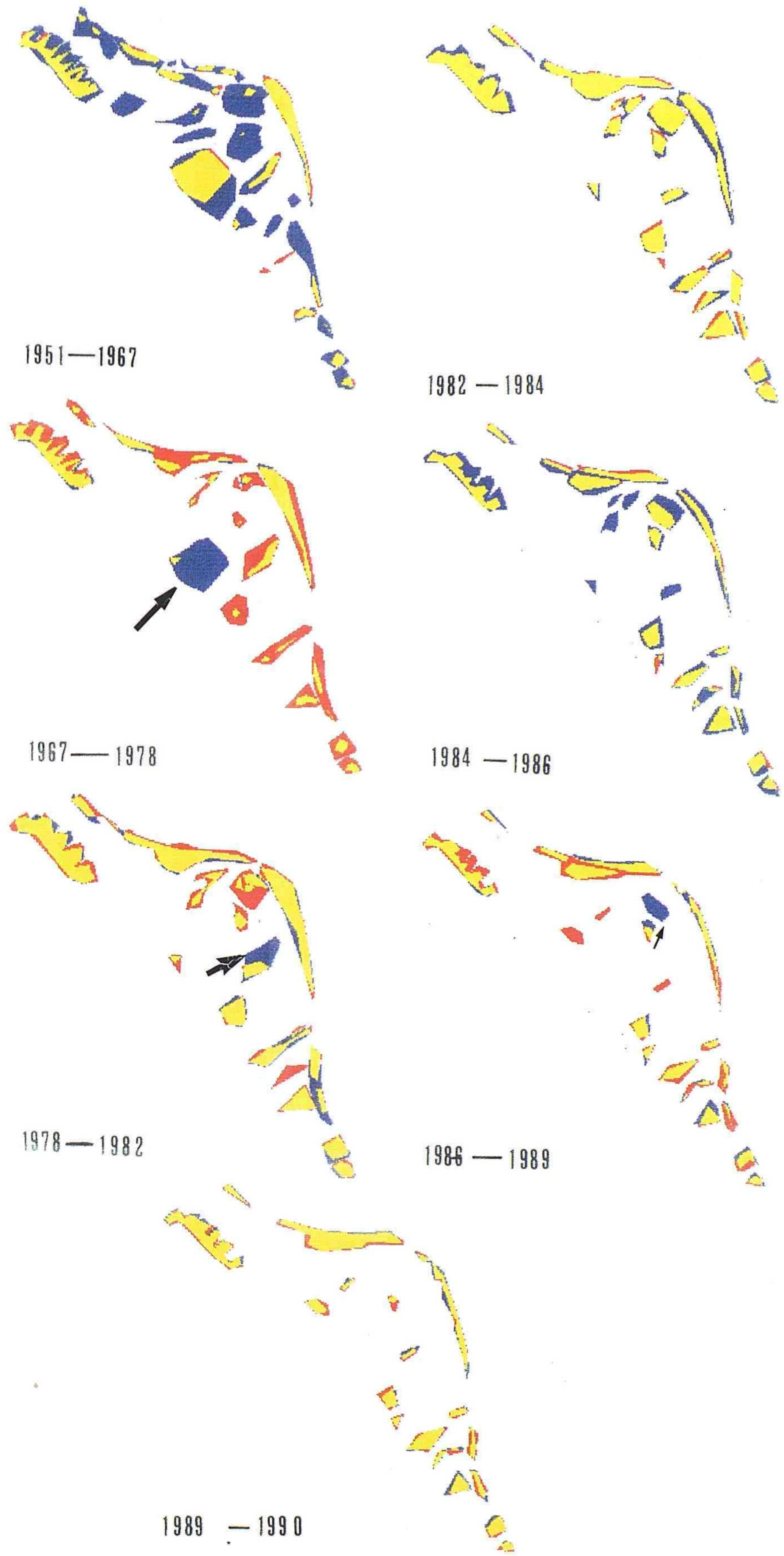


Fig. 4.14 Distribution of live corals at western section from 1951 to 1990

Fig.4.15 Distribution of fleshy algae at western section from 1951 to 1990

Fig.4.15 cont'd. Distribution of fleshy algae at western section from 1951 to 1990.

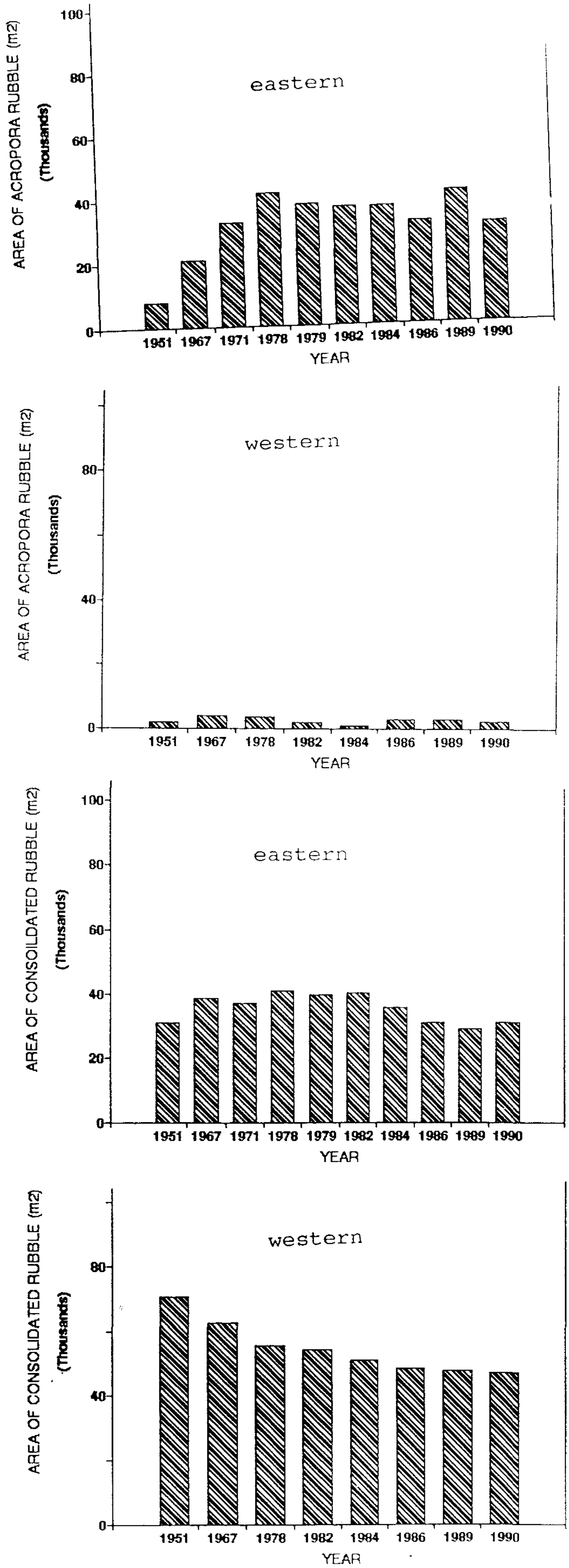


Fig.4.16 Distribution of *Acropora* rubble and consolidated rubble

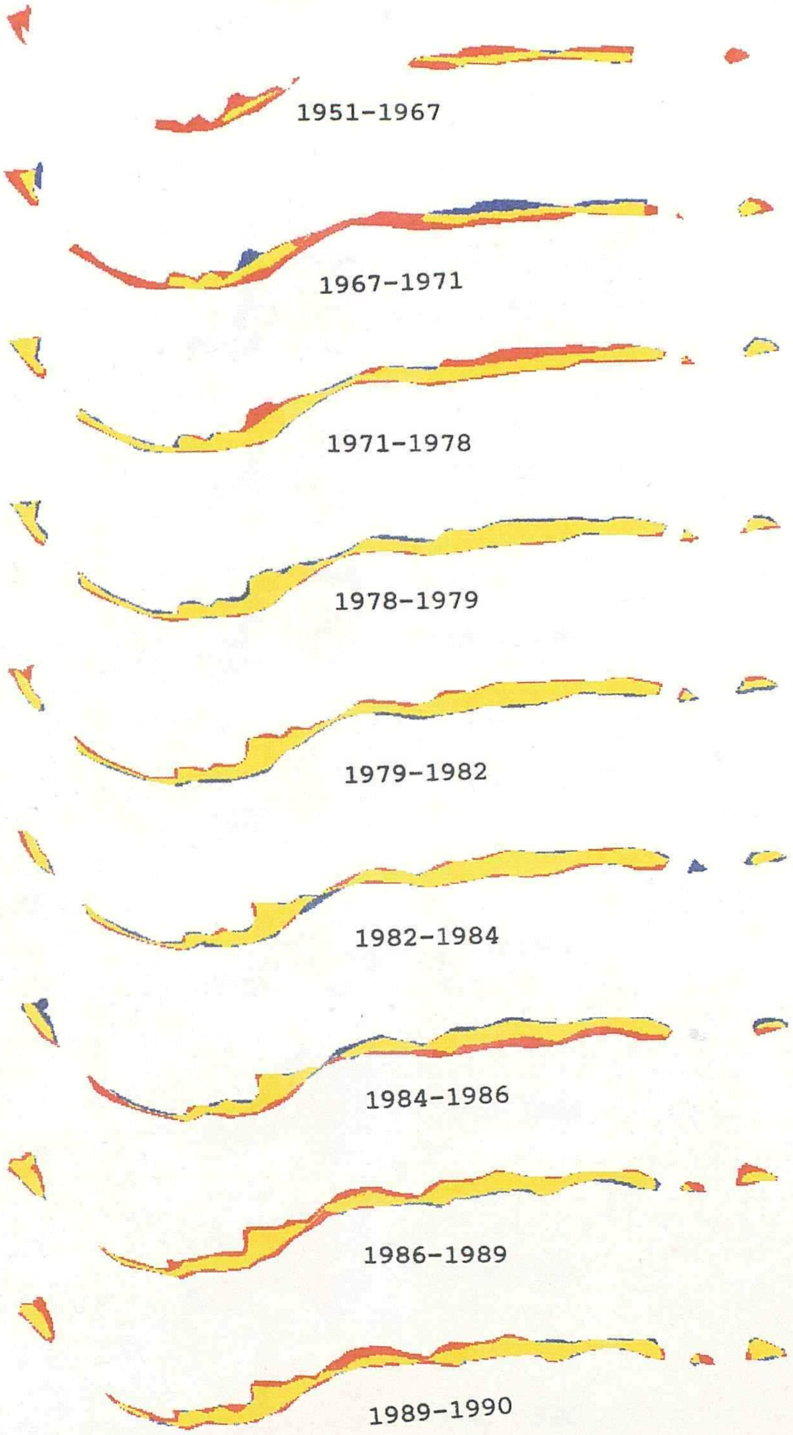


Fig.4.17 Distribution of *Acropora* rubble at eastern section from 1951 to 1990.

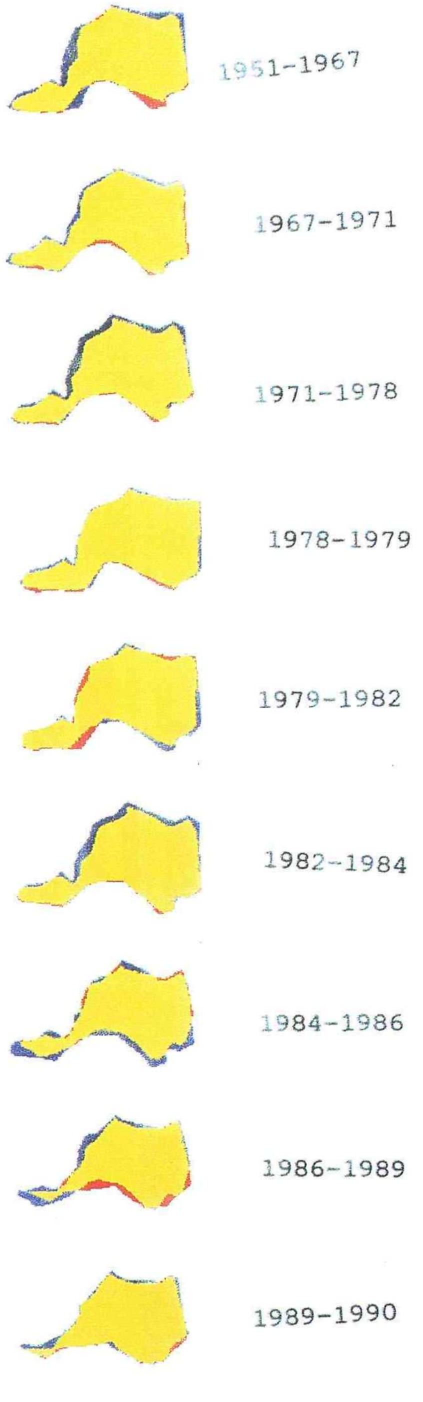


Fig.4-18 Distribution of consolidated rubble at eastern section from 1951 to 1990

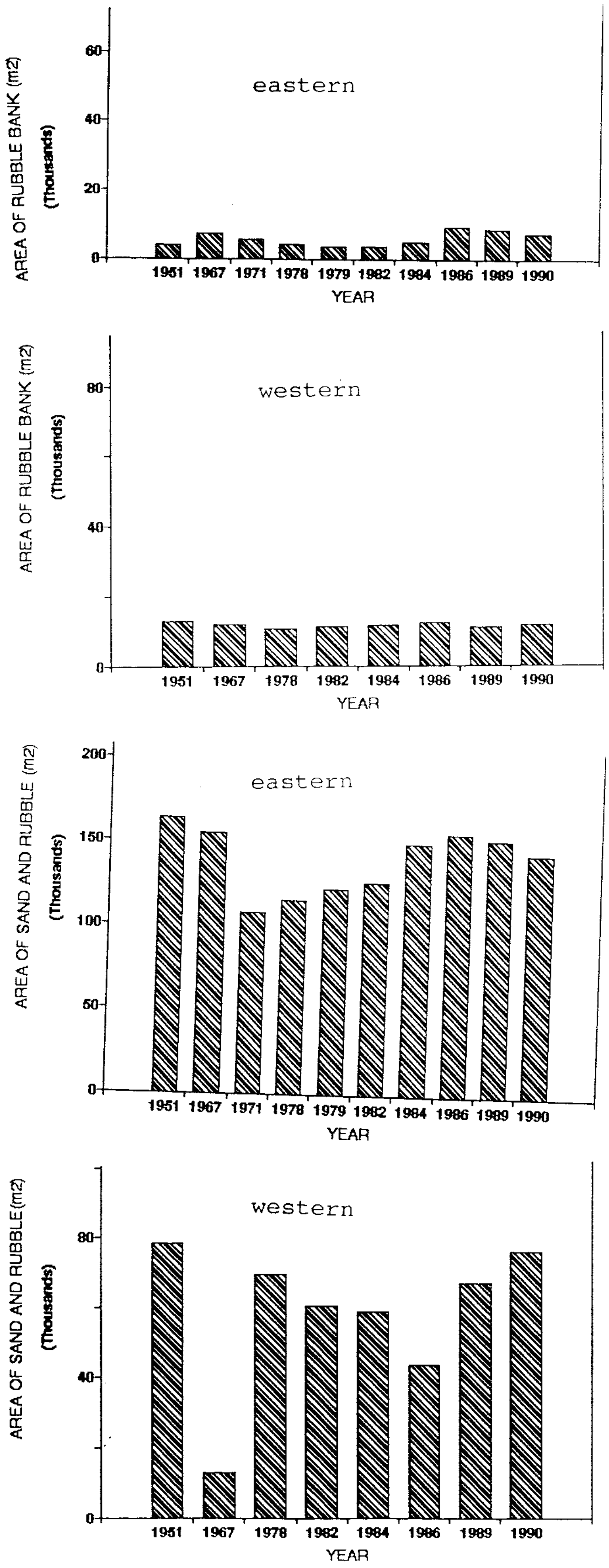


Fig.4.19 Distribution of rubble bank and sand and rubble

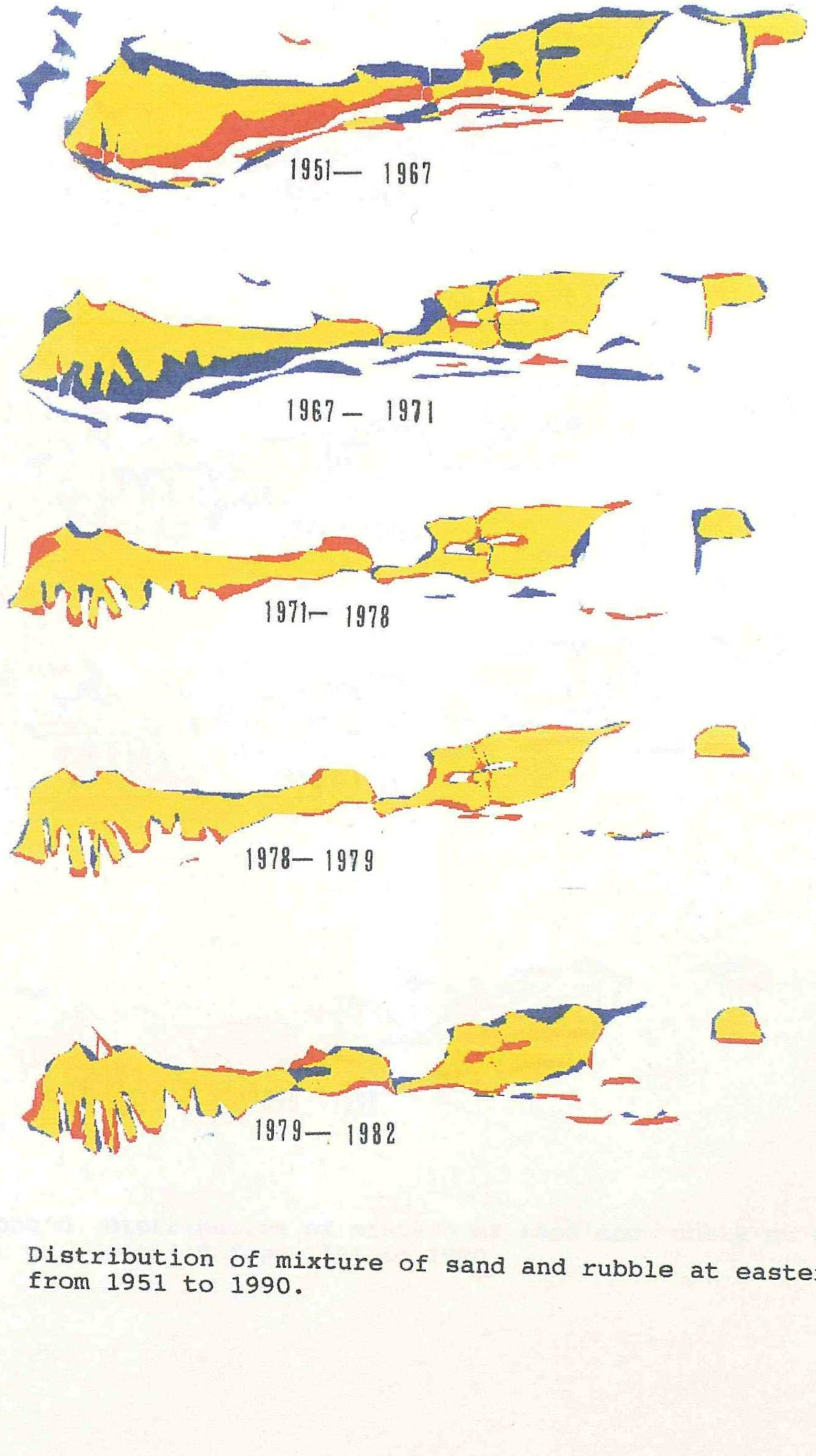


Fig.4.20 Distribution of mixture of sand and rubble at eastern section from 1951 to 1990.

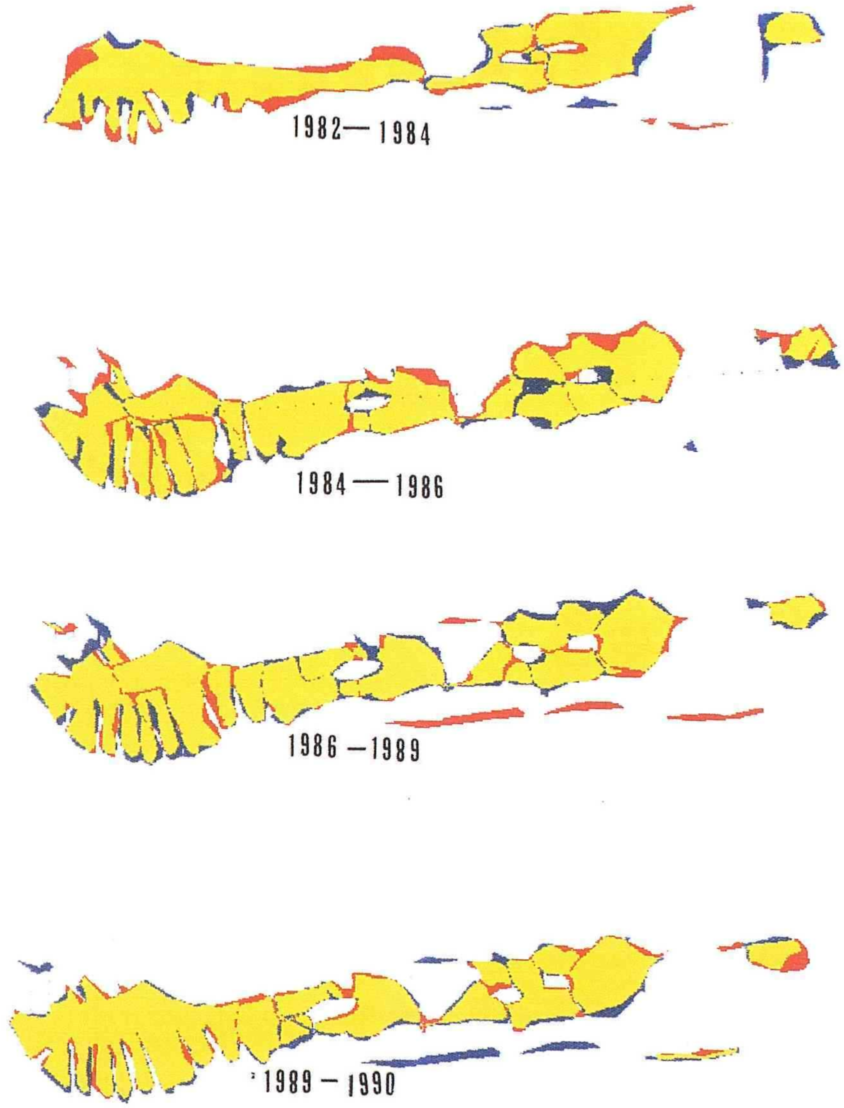


Fig.4.20 cont'd. Distribution of mixture of sand and rubble at eastern section from 1951 to 1990.

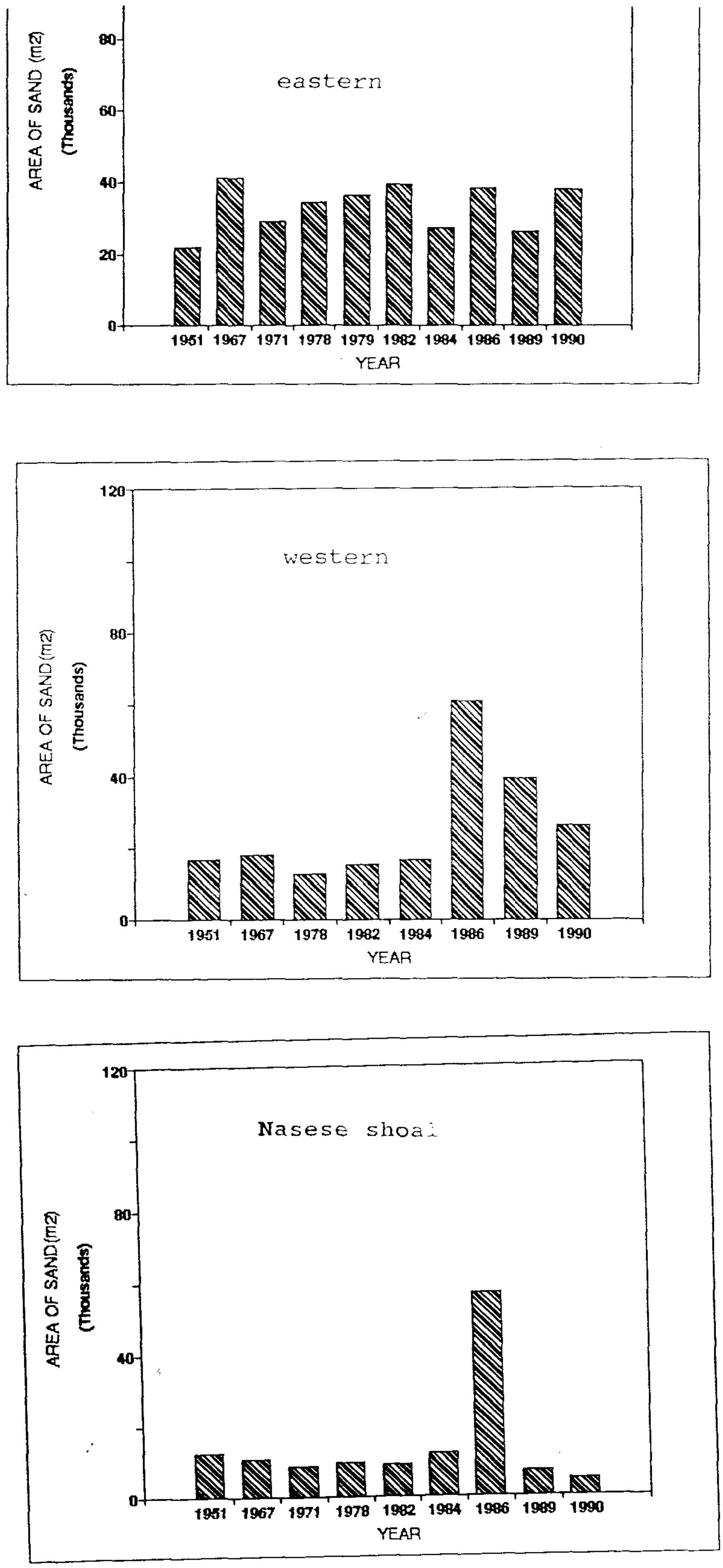


Fig.4.21 Distribution of sand

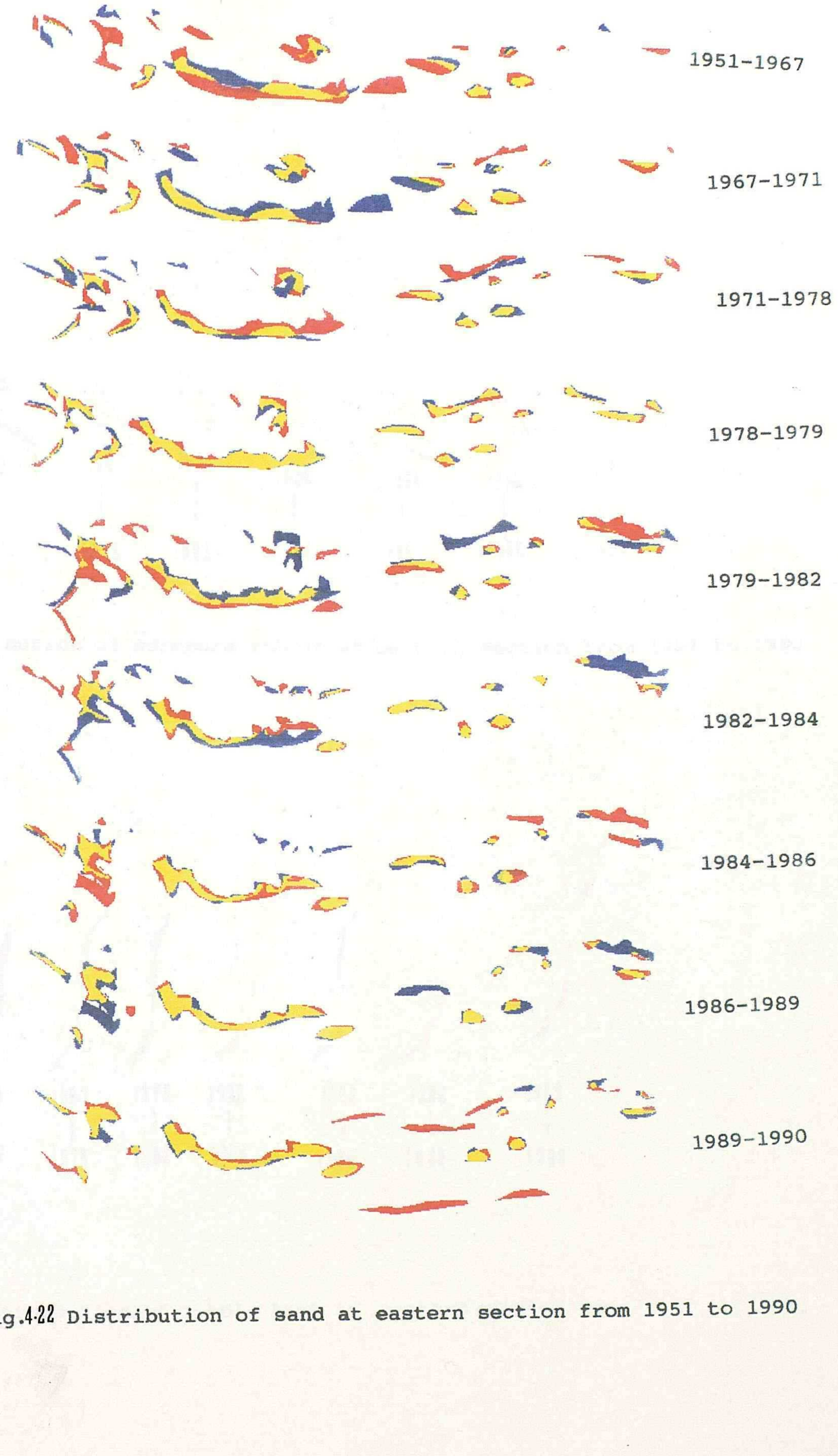


Fig.4-22 Distribution of sand at eastern section from 1951 to 1990

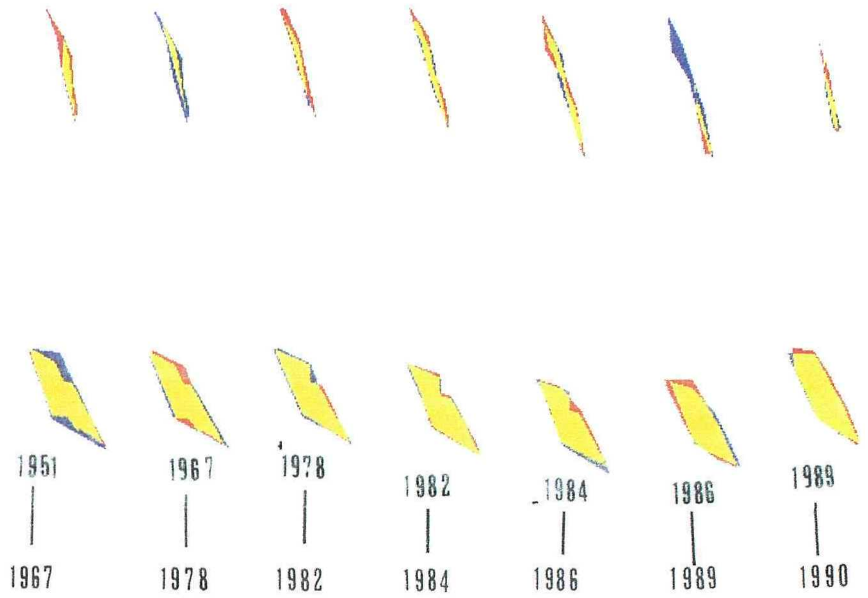


Fig.4.23A Distribution of *Acropora* rubble at western section from 1951 to 1990

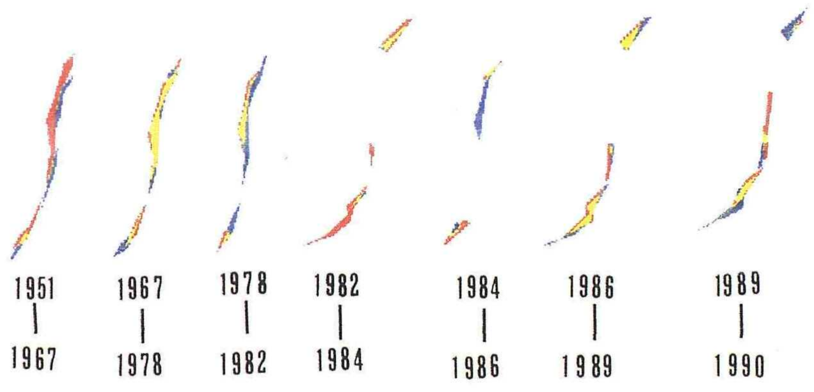


Fig.4.23B Distribution of rubble bank at western section from 1951 to 1990.

Fig.4.24 Distribution of consolidated rubble at western section from 1951 to 1990

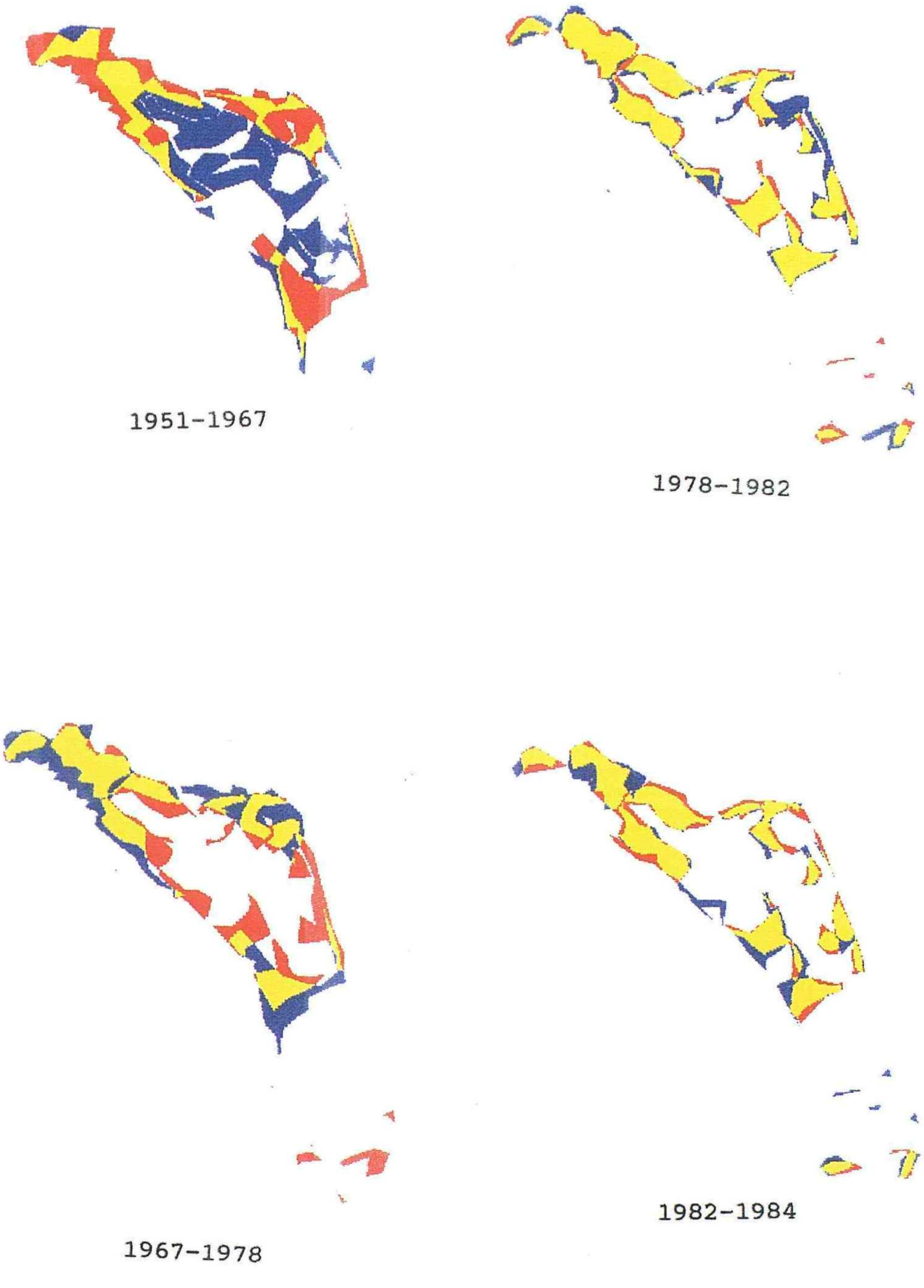


Fig.4.25 Distribution of mixture of sand and rubble from western section from 1951 to 1990

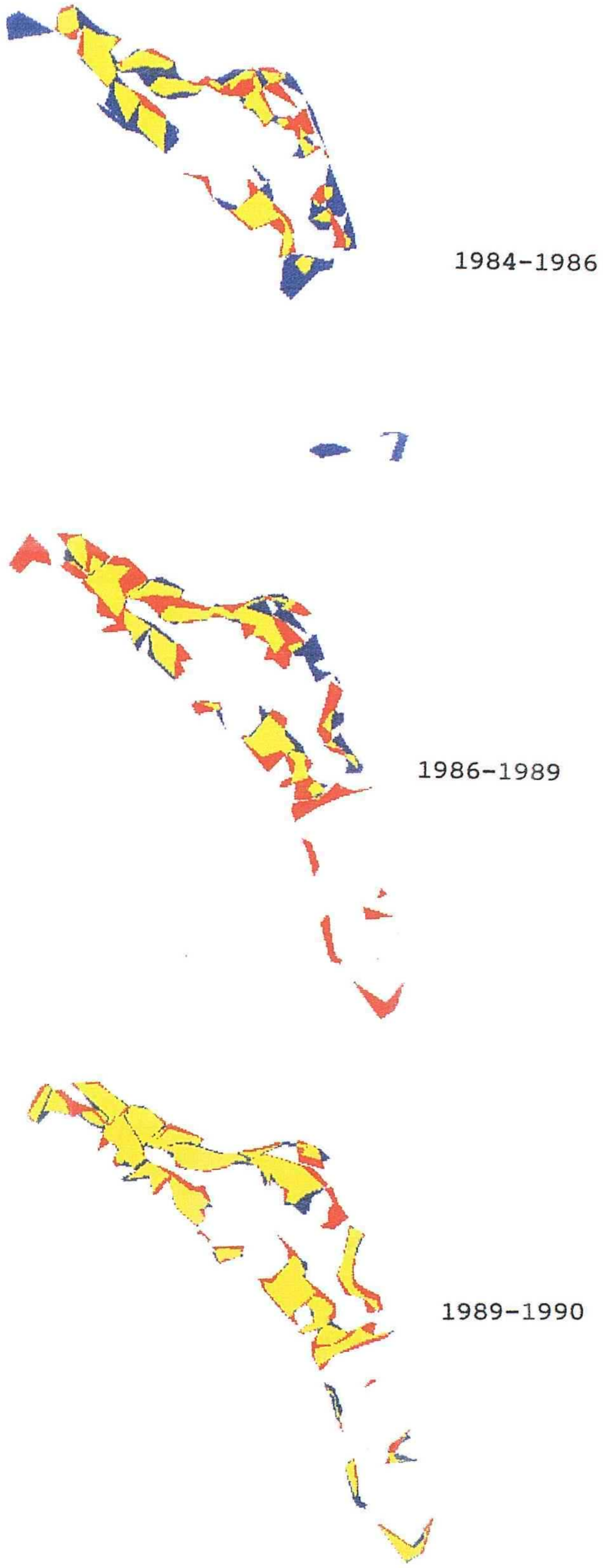


Fig.4.25 cont'd. Distribution of mixture of sand and rubble at western section from 1951 to 1990.

Fig.4.26 Distribution of sand at western section from 1951 to 1990

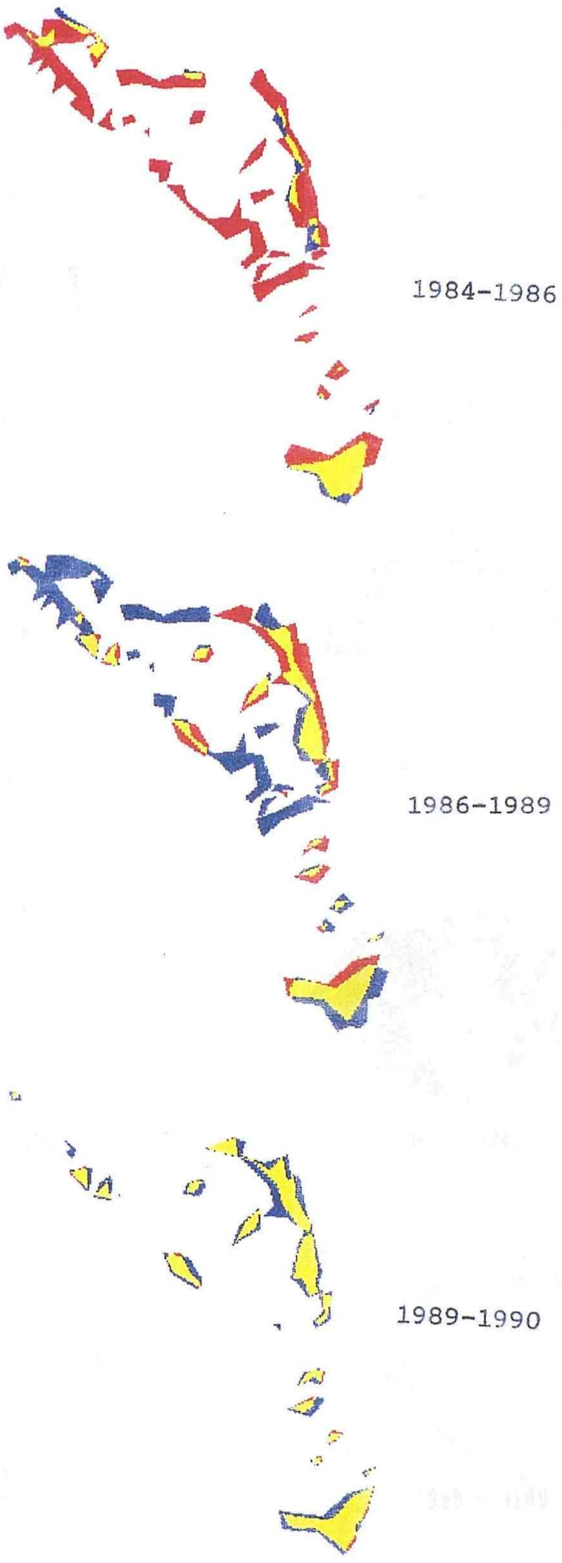


Fig.4.26 cont'd. Distribution of sand at western section from 1951 to 1990

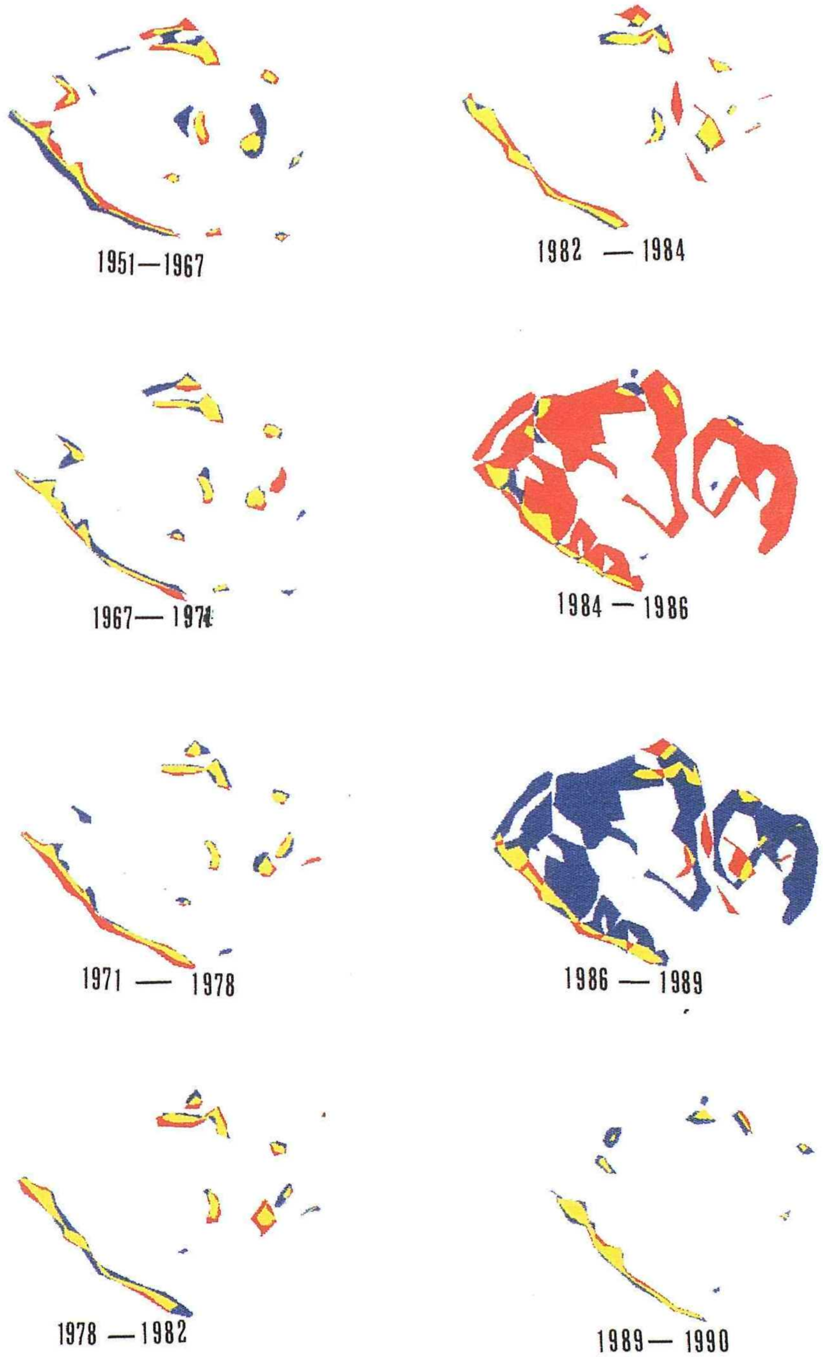


Fig.4.27 Distribution of sand at Nasese Shoal from 1951 to 1990

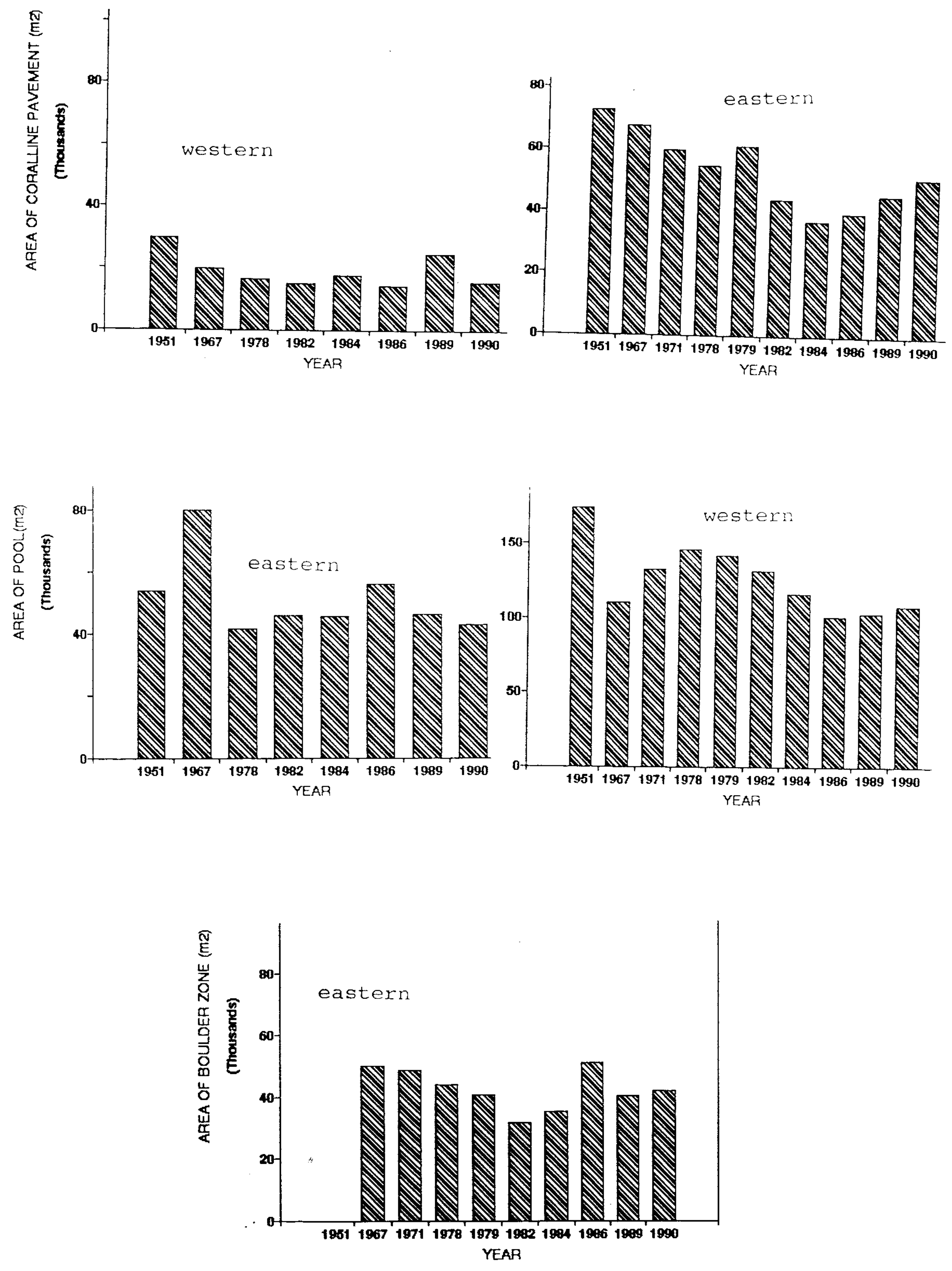


Fig.4.28 Distribution of coral pavement, tidal pool and boulder zone

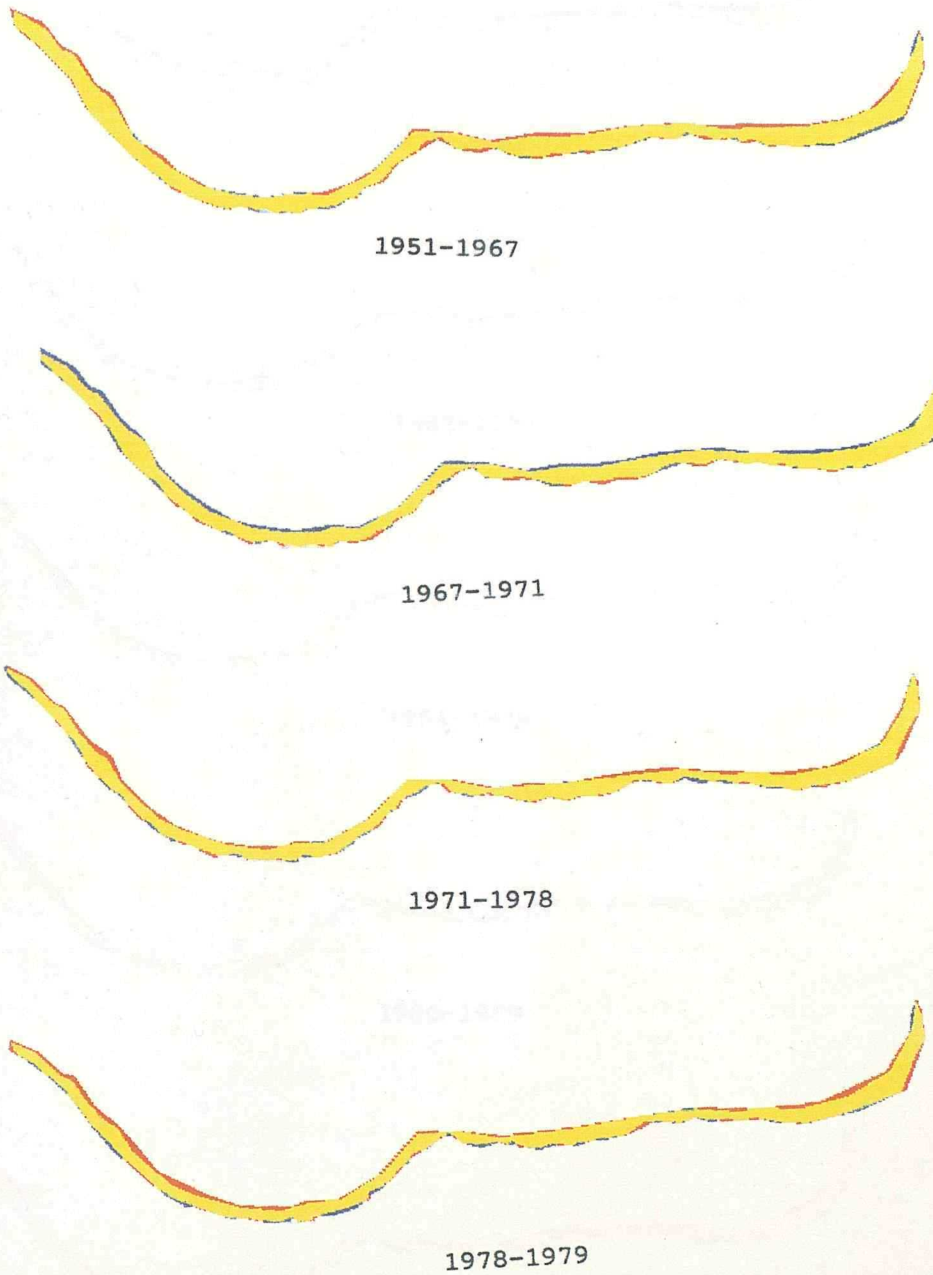


Fig.4.29 Distribution of coral pavement at eastern section from 1951 to 1990

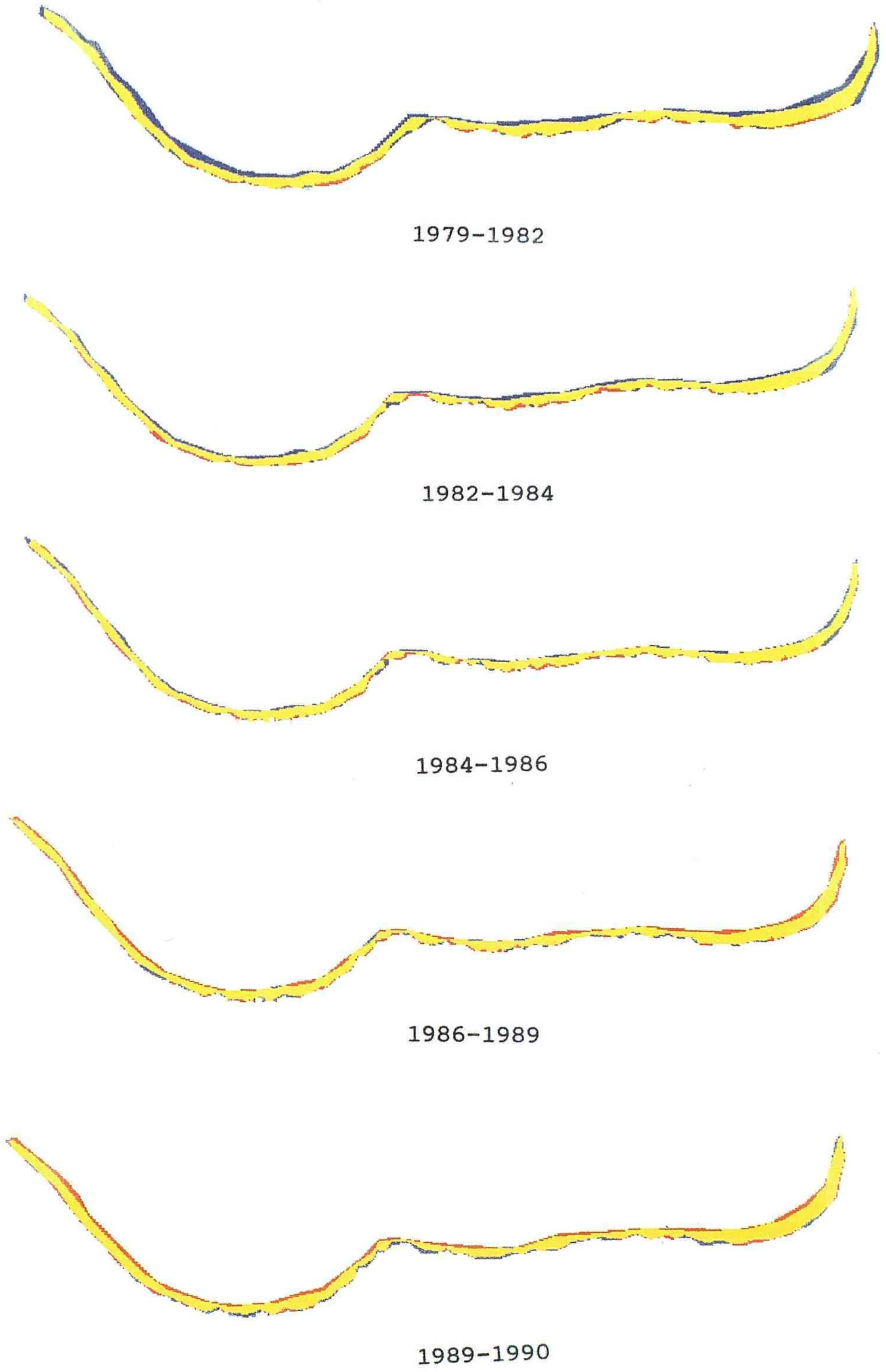


Fig.4.29 cont'd. Distribution of coral pavement at eastern section from 1951 to 1990.

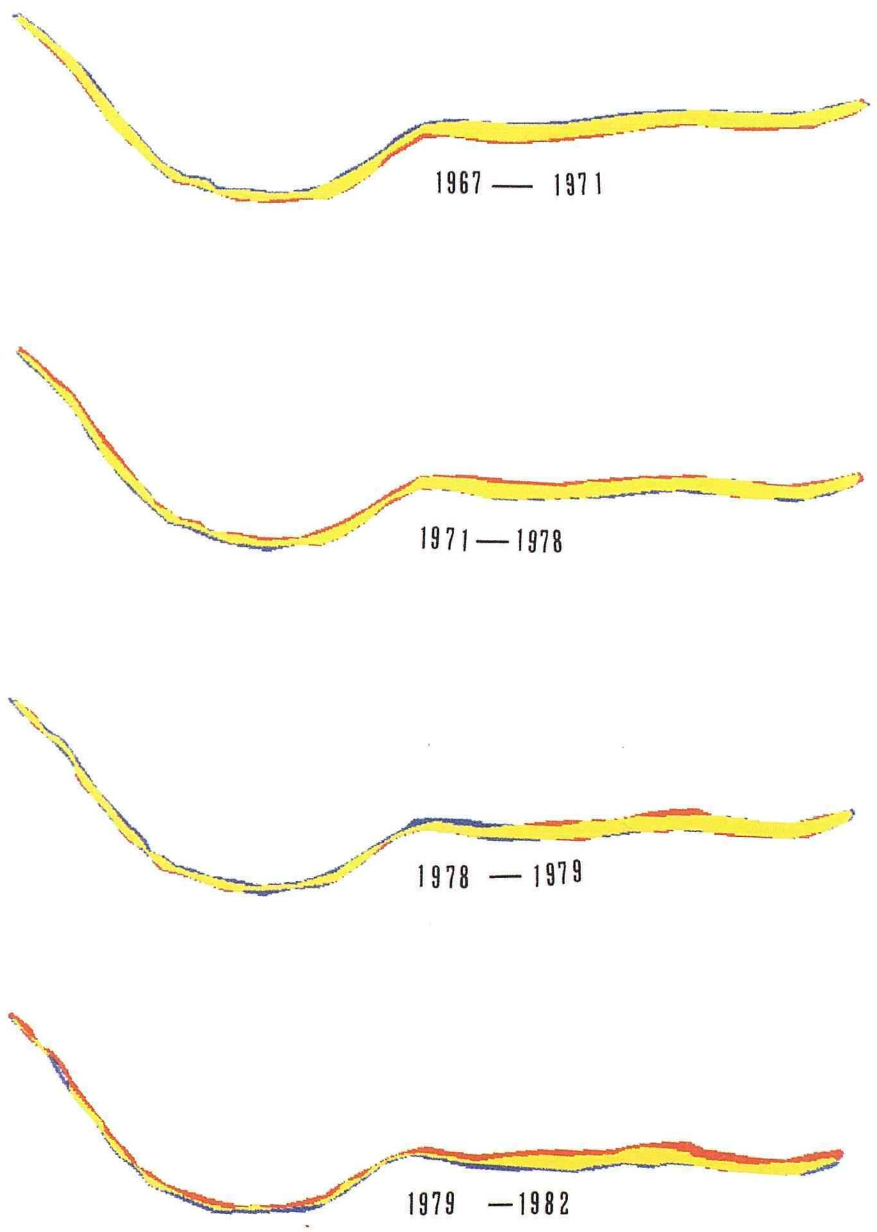


Fig.4.30 Distribution of boulder zone at eastern section from 1967 to 1990.

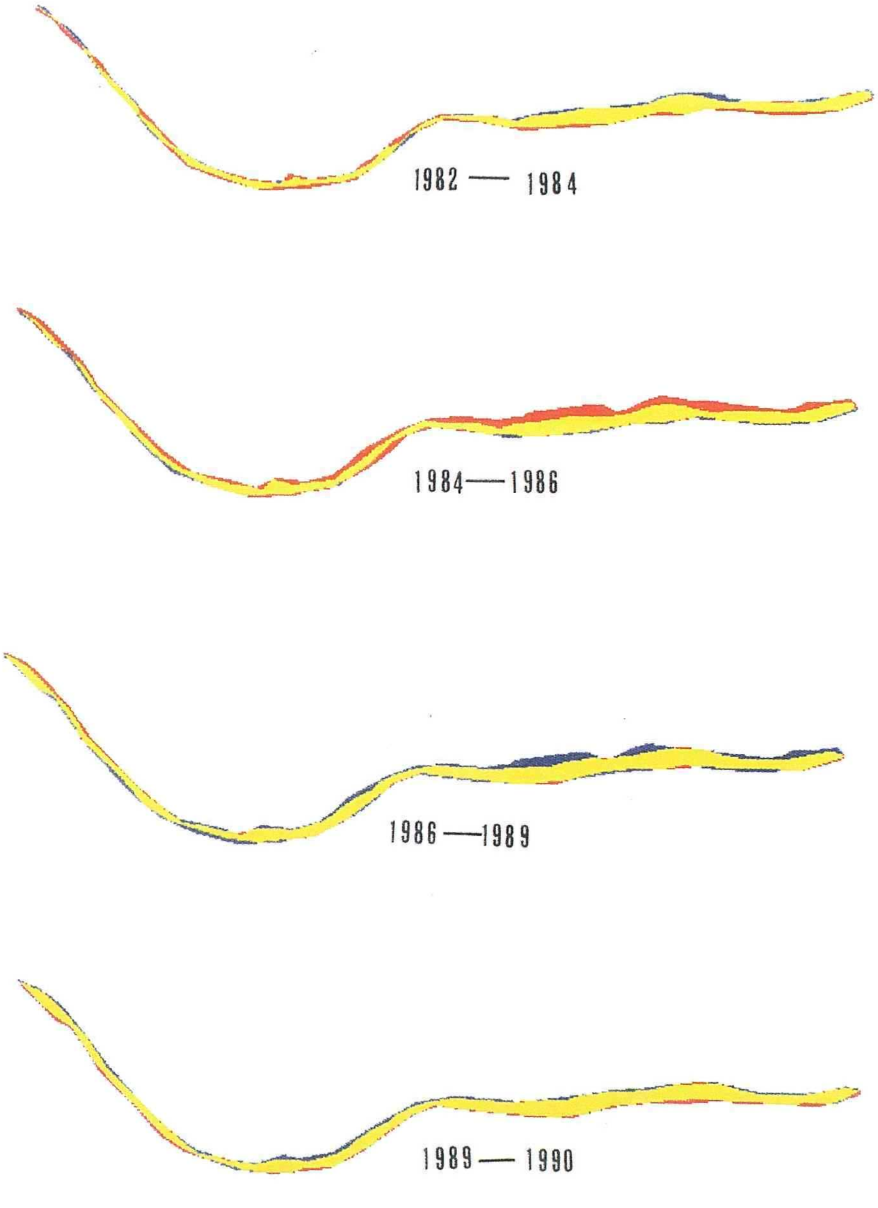


Fig.4.30 cont'd. Distribution of boulder zone at eastern section from 1967 to 1990.

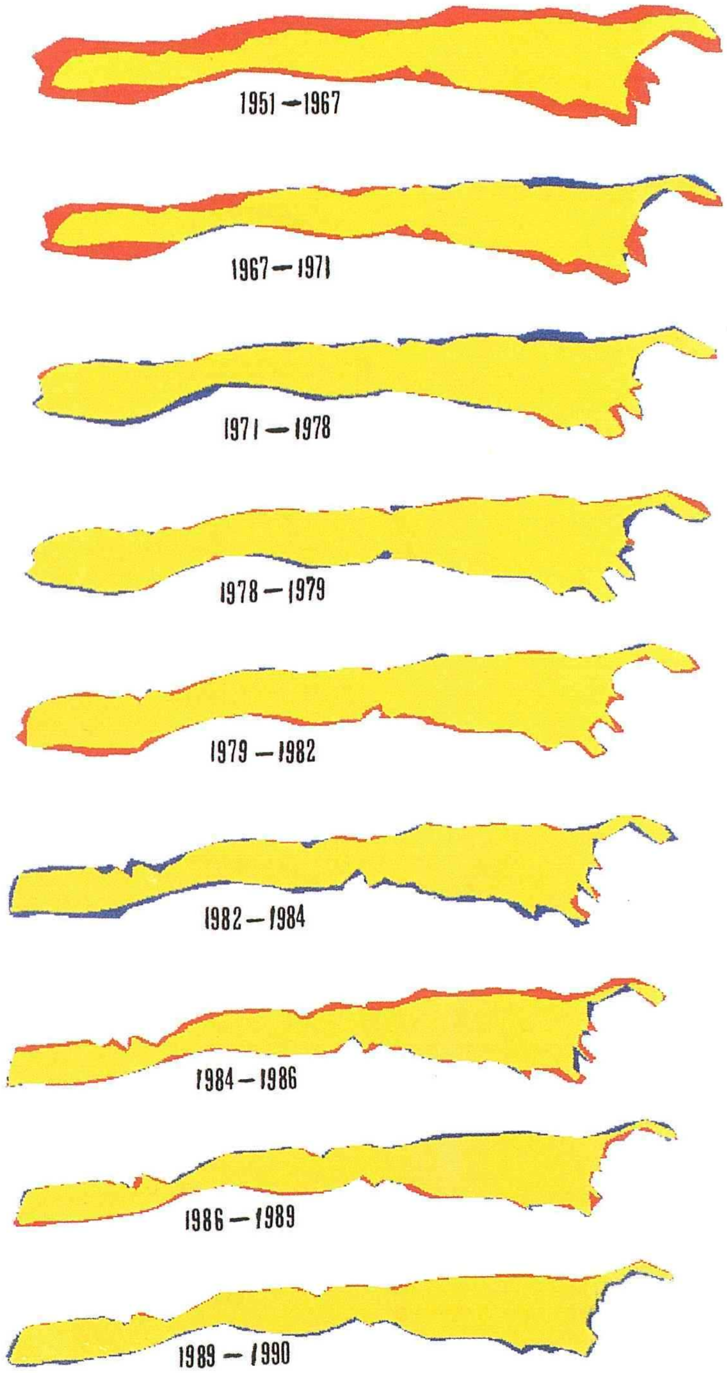


Fig.4-31 Distribution of tidal pool at eastern section from 1951 to 1990

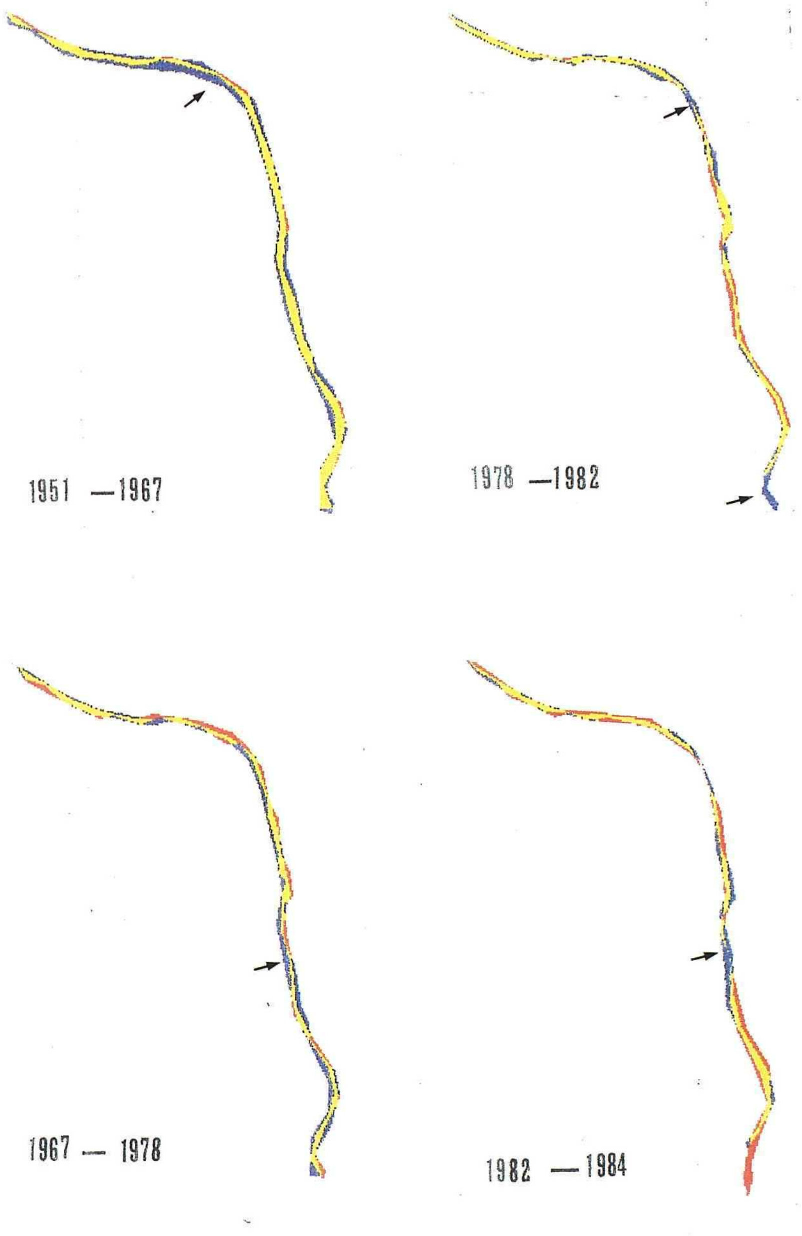


Fig.4.32 Distribution of coral pavement at western section from 1951 to 1990

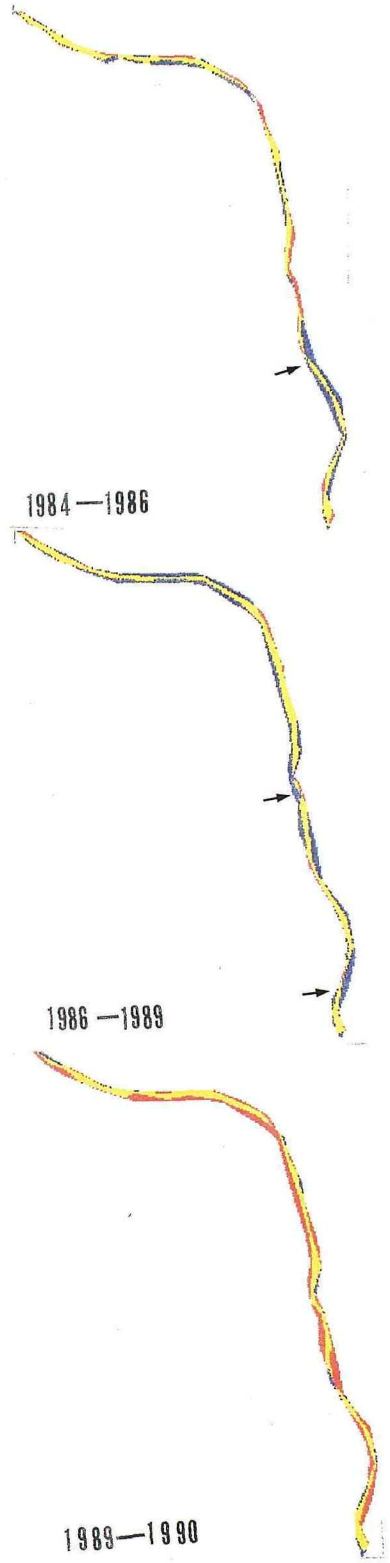


Fig.4.32 cont'd. Distribution of coral pavement at western section from 1951 to 1990.

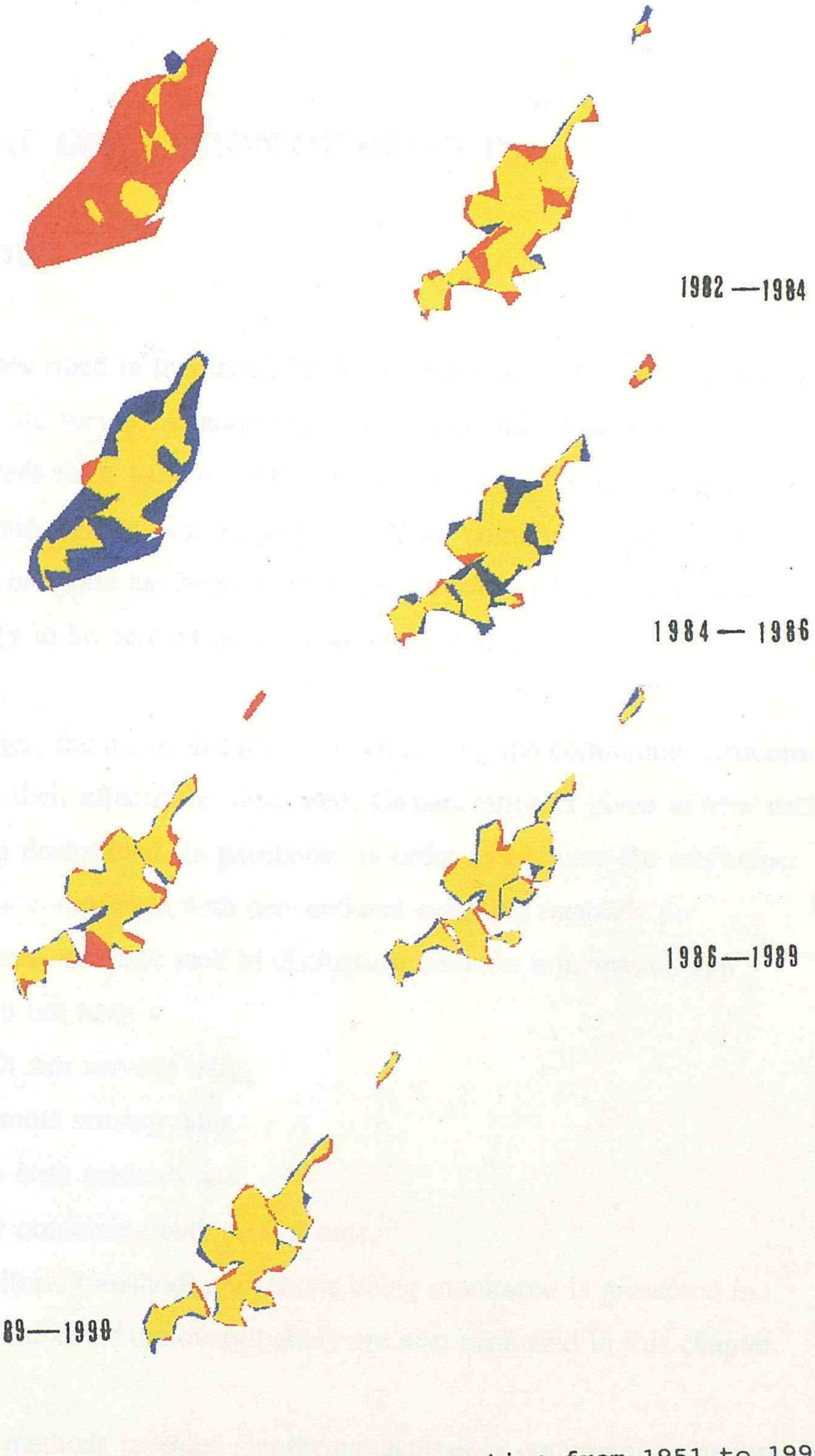


Fig.4.33 Distribution of tidal pool at western section from 1951 to 1990

CHAPTER 5

GENERAL DISCUSSION OF RESULTS

5.1 INTRODUCTION

The work described in this thesis has two main aspect. The first is the use of conventional *in situ* survey methods to determine community structure and changes on Suva Reef from 1984 to 1991. The second aspect is the use of aerial photography and image processing techniques to study community changes from 1945 to 1990. The intention has been to integrate the two types of results and to consider the synergy to be derived from combining them.

In this chapter, the major disturbances influencing the community structure on the reef flat and their effects are discussed. Consideration is given to how each conclusion has been determined. In particular, in order to evaluate the usefulness of remote sensing in comparison with conventional sampling methods for monitoring coral reefs, we shall seek to distinguish between information and understanding which has been :

(a) observed from *in situ* surveys only,

(b) derived from remote sensing only,

(c) made evident by both methods and

(d) deduced only by combining both sets of data.

A summary of monitoring methods and events being monitored is presented in Table 5.1. The limitations of the overall study are also evaluated in this chapter.

Both survey methods revealed significant changes in community structure. However, it is not enough simply to document the changes in community structure but each change needs to be interpreted in relation to its nature and causes. Whether the changes show evidences of human-induced degradations or whether these are natural temporal and spatial variations are important considerations.

Table 5.1 Summary of monitoring methods and events being monitored. Where both methods were used to monitor events, the most effective of the two methods is marked with an asterisk (*).

Events	Remote Sensing	*In situ*	Both Methods	Deduced by both methods
Tsunami	+			
A.planci predation				+
Flood	+			
Cyclone	*	*	+	
Sand dredging	+			
E.mathaei excavations		*	+	
Fishing pressure		+		
Coastal reclamation effects	*		+	
Effects of agriculture, deforestation and related activities	*		+	

Clearly, the importance of understanding the ecological history of Suva Reef is critical to the interpretation of the specific impacts of a particular physical, biological or anthropogenic disturbance. Major aspects of the physical disturbance regimes such as magnitude, intensity and aerial extent of disturbance as well as the elapsed time since the last disturbance are important in determining impacts to reef community structure. Aerial photographic analysis therefore presented an opportunity to document four decades of habitat changes on Suva Reef and to relate these changes to likely causes. The magnitude and spatial extent of these changes were also documented. The aerial photographs were able to substantiate changes that were dramatic in nature such as accretion of coral on the reef flat and seagrass expansion into the lagoon. Results from airborne image analysis were complemented by available *in situ* survey results for specific years. The *in situ* surveys provided detailed information on reef community dynamics at a small scale while the aerial photography was able to detect more long term general patterns.

However, it should be recalled from Chapters 3 and 4 that the major disturbances affecting Suva Reef were tsunami, cyclones and flood, *A.planci* and *E.mathaei* and human activities. It is possible that *A.planci* and *E.mathaei* population increases may be human induced (Zann *et. al.* 1990, Done 1992a, Broadie 1992), although it is debatable whether the outbreaks are natural elements of the current ecology of Suva Reef. There is little doubt that similar communities and general zonation patterns to those observed from aerial photographs and *in situ* surveys have prevailed for hundreds of years on Suva Reef. It is also recognised that, although there are major disturbances affecting the reef, the structure of the reef has not changed dramatically apart from the tsunami damage.

5.2 MAJOR DISTURBANCES AND THEIR EFFECTS

The major disturbances and their influence on communities on Suva Reef are summarised in Fig.5.1 and discussed in detail here. In addition, how each major disturbance was determined from the two methods utilised in this study are examined.

5.2.1 TSUNAMI

The effects of tsunami probably caused considerably more damage to the structure of the reef than any other disturbance occurring between 1945 and 1991. These effects were documented from airborne images between 1951 and 1967. There were no available *in situ* observations for this period except for the assumption that the boulder zone was a result of tsunami (Zann *et al*, 1987). Therefore, the importance of remote sensing methods in documenting the effects of tsunami is vital in the understanding of long term patterns and the persistence of spatial patterns over time on the reef.

The most remarkable change caused by the tsunami was the formation of the boulder zone at the eastern section. The boulder zone replaced live corals at the inner reef flat. The remote sensing method revealed clearly that coral cover was displaced by boulders and this was probably caused by the effects of tsunami. The decline in coral cover caused by tsunami was probably the most significant change in coral communities on the reef.

There were major extensions in the tidal pools at the eastern and western sections which were caused by tsunami. There were also additions in *Acropora* rubble at both sections of the reef as a result of large waves generated by the tsunami which caused physical damage to live corals and dead standing corals.

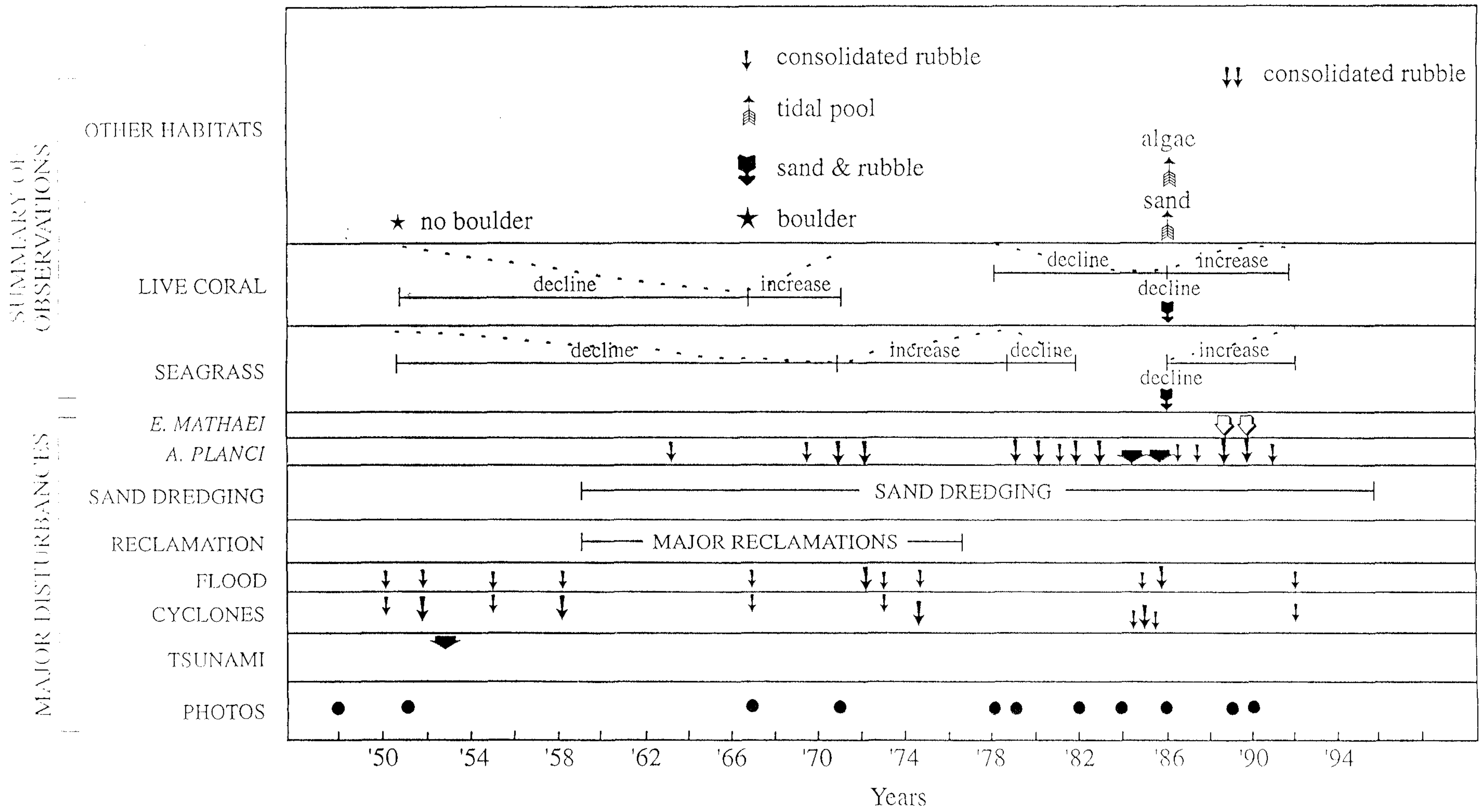


Fig.5.1 Diagram showing a summay of available photographs, major disturbances and observations.

5.2.2 TROPICAL CYCLONES AND FLOOD

Cyclones caused periodic damage to Suva Reef (see Appendix 4.4). There was not only physical damage but also associated flooding, which increased sedimentation on Suva Reef. The combination of several disturbances such as physical damage from cyclones, increased turbidity and sedimentation and lower salinity from associated floods may reduce the ability of the reef communities to recover from a major disturbance such as a cyclone.

Although, the major causes of habitat decline between 1951 and 1967 were tsunami damage, it is also possible that there was damage on the reef caused by the three cyclones occurring during this period. The cyclone damage may have resulted in further decline in habitats which may have prolonged the recovery from the tsunami damage.

However, almost all the cyclones occurring on south-east Viti Levu were associated with flooding. Two hurricanes (Eric and Nigel) hit Suva within 48 hours of each other in January 1985 and a further one (Hina) in March 1985. Their effects were documented on the aerial photographs in 1986 and also from the *in situ* surveys in 1989. The physical damage caused by cyclone-generated waves were mostly located at the seaward section of the reefs and these spatial patterns were observed from airborne image analysis.

There was also large scale flooding following exceptional rainfall in early 1986 which caused massive damage to corals and seagrasses (Wells 1988, this study). The damage to coral reef communities was caused by extensive siltation, lowered salinity and high turbidity. In particular, seagrass was affected mostly by flooding and a dramatic decline occurred at inshore sites (Nasese shoal) and at the eastern section closer to the Rewa River. This information was obtained from airborne image analysis.

5.2.3 **CROWN OF THORNS STARFISH** ***(Acanthaster planci)***

In the 1960's *A.planci* infestation was considered a serious problem in the Suva area (Owen, 1971, Robinson 1971). A detailed account of the status of *A.planci* on Suva reef is presented in Appendix 4.5. In general, crown of thorns starfish caused progressive coral decline. These starfish caused loss of large patches of live corals as documented from airborne images between 1967 and 1978 at the western section.

According to oral histories of Fijian fisherfolk, outbreaks of *A.planci* have become more frequent and serious since the 1960's (Zann *et al.* 1990). These may have been caused by a number of factors such as increase in eutrophication, which provided abundant food source for *A.planci* larvae (Birkeland 1989). In addition, the removal of the crown of thorns predator (*Charonia* sp.) from the reef may also have been a factor in the increase of crown of thorns (Endean 1969).

The long term temporal and spatial patterns of coral decline from airborne images were related to published historical records of *A.planci* predation (Zann *et. al.* 1990). The explanation for loss of large patches of corals observed from airborne images were by *A.planci* predation. Large patches of corals disappeared at both the eastern and western sections and their disappearance coincided with records of large numbers of *A.planci* on the reef. Moreover, some of the patches of corals which disappeared from airborne images were in the vicinity of the areas where there were published records of corals being preyed on by *A.planci*. This further shows the importance of using airborne images in conjunction with *in situ* observations to detect the likely causes of coral decline.

It must be borne in mind that the airborne images show evidence that the effects of *A.planci* on Suva Reef may be a more recent phenomenon occurring between the late 1960's and 1980's. The disappearance of patches of *Acropora* spp. from the western section were a result of *A.planci* predation. These were further validated by *in situ* observations published by Zann *et. al.* 1990.

5.2.4 **SEA URCHINS** (*Echinometra mathaei*)

The *E.mathaei* was observed in large numbers during *in situ* surveys at the western section of Suva Reef from 1989 and 1991. These are major bio-eroders on the reef flat and are major contributors in changing the structure of the reef framework from hard coral rock substratum to rubble and sand.

The changes in the substratum caused by *E.mathaei* was also supported by results of airborne image analysis in 1989 and 1990 at the western section. This highlights the importance of the two methods of survey utilised in complementing each other to explain the changes and causes of disturbance on the reef.

The results from both survey methods indicate that it is possible that the occurrence of large numbers of *E.mathaei* on the reef may be a recent phenomenon and associated with *A.planci* predation and high fishing pressure on the reef. It has been suggested that *E.mathaei* increases in Southern Japan were second order effects of *A.planci* outbreaks (Birkeland 1989). However, *E.mathaei* increased on Kenyan reefs as a result of removal of predators and high fishing activities (McClanahan & Muthiga 1989).

5.2.5 **HUMAN ACTIVITIES AND USES**

Coral reefs have provided dietary protein for Fijians for thousands of years and this continues to be an essential ingredient of their dietary requirements (Vuki 1991, Zann 1992). Fijians are therefore dependent on reefs as they rank amongst one of the highest seafood consumers in the world (ca 40kg per capita per year) (Zann 1992).

However, Suva Harbour and Laucala Bay have been classified as the most disturbed areas in Fiji with general pollution problems, moderate eutrophication, overfishing and crown of thorns starfish outbreaks (Wells 1988). Human activities and uses of Suva reef are subdivided into three major sections. These are fishing pressure, sand dredging and effects of agriculture. These are the three most important human activities that may have long term effects on the reef. Other human activities such as recreation and tourism, sewage outfall and reclamation activities also have some localised effects on Suva Reef. These human activities are likely to be very important in determining reef changes on the western coast of Viti Levu where tourism resorts are located.

5.2.5.1 **FISHING PRESSURE AND EXPLOITATION OF RESOURCES**

The use of traditional fish poisons such as *Derris* is prevalent in Fiji. Unpublished data of fishing activities on Suva Reef from 1984 to 1990 showed large numbers of gleaners on the reef flats gleaning for shellfish and other edible marine invertebrates. The most common fishing techniques used were gleaning and handline fishing but the use of netting and spear diving are also common.

The physical damage caused by reef gleaners may be important on the reef flats where they are exposed at low tides. Unpublished data showed that gleaners visit the reefs during low tides that occur in the afternoon. Most of these gleaners are women who overturn rocks in search of trochus, octopus, sea urchins and other edible marine invertebrates.

There are, however, detrimental effects in the removal of fished species by handline and nets. The removal of large predatory fish may result in less pressure on species lower in the food chain. For example, the removal of triggerfish and some snappers may have encouraged the *A.planci* outbreaks (Zann 1992).

5.2.5.2 **SAND DREDGING**

Coral sand is an essential raw material for cement manufacturing in Fiji. Sand extraction between 1960 and 1979 was estimated to be 123 million tons (dry weight) from seven different sites in Laucala Bay (Bajpai 1979). Sand extracted from the backreef was causing destruction of seagrass beds within the dredge pit areas (Penn 1983). These sand extractions caused extensive damage to *Syringodium isoetifolium* (Baines 1977, Penn 1983). In this study the exact location of the dredge pits were not available so that the full impact of sand extraction on seagrass beds could be related to documented changes from airborne analysis results.

5.2.5.3 **EFFECTS OF AGRICULTURE AND RELATED ACTIVITIES**

Poor agricultural land use practises such as logging on native forests and slope cultivation of ginger have resulted in serious soil erosion. This is transported to sea by rivers during flooding and as a result there is an overall increase in sedimentation on the reef.

The effects of nutrients and sediments from land is less well known. In this study, airborne images were able to reveal the combined effects of increased sedimentation and lower salinity on the decline of seagrass beds. The spatial patterns showed that areas of seagrass which are prone to sedimentation are those located close to the river and the landward sections. The effects on seagrass are short term effects and they are able to recover to their original 1951 status. The effect of sedimentation on corals was not clearly shown from aerial photographs because of the combination of several factors such as sand dredging, increased water movement etc., affecting the accretion and decline of live corals. It is possible to conduct sedimentation experiments to ascertain their effects on live corals.

5.3 THE VALUE OF REMOTE SENSING AS A TOOL

Remote sensing provides a synoptic view of Suva Reef that has never been appreciated before. The historical record of changes documented from airborne images demonstrated the usefulness of remote sensing as a tool in determining long term changes in reef habitats. The lack of local technical expertise to conduct *in situ* surveys in the past has hindered any accumulation of long term data for any Fijian reef. Therefore the only way to answer questions on the long term status of Suva Reef is to consider information from airborne images.

Information on the spatial patterns of habitats on the reef flat provided the most valuable contribution of airborne images to the understanding of long term community dynamics on Suva Reef. Moreover, as a result of information obtained on spatial patterns the likely causes of changes in habitats were able to be related to the environmental history prevalent at any particular period. Furthermore, remote sensing has greater benefits when used in conjunction with *in situ* survey data to examine the possible causes of change.

Remote sensing as a tool has a lot to offer in terms of understanding Suva Reef as an entity as well as in remote reef areas. Although the loss of information at species level is recognised, the information on the direction of change and the exact location of change is vital in the overall understanding of significant habitat changes and their likely causes.

The experience gained from remote sensing analysis should enable reef ecologists to re-evaluate the current methodology of monitoring long term coral reef changes. There should, however, be a balanced approach to the question of scale in which the monitoring is taking place. An appropriate scale should be able to help distinguish between significant changes and "noise" from any conventional *in situ* survey. For example homogeneous stands and mixed stands of habitats that are recognised from airborne images should be identified and used as permanent sites for long term monitoring in addition to the transects already established. This will enable the documentation of important habitat changes using the *in situ* survey method at a more appropriate spatial scale than the conventional scales and the results could be compared without compromising the information obtained. Therefore it may have been useful if several spots on Suva Reef had been established as large permanent quadrats for detail analysis of reef communities through time. Such detailed study would have a resolution similar to the data from satellite or aerial photographs and with which it could be compared.

5.4 LIMITATIONS OF THE OVERALL STUDY

It is instructive to evaluate the characteristics and limitations of survey techniques used. The study area was restricted to the reef flats which are regularly subjected to considerable fluctuations in the physical environment (Pearson 1981). Hence, the study area did not take into account the changes that are taking place on the reef slope and also at the lagoon. It must be noted, however, that a study such as this which incorporates *in situ* survey methods and aerial photography will not be able to appreciate the changes occurring in the lagoon and the slope because of depth-related problems where significant habitat changes may not be supported from aerial photographs.

However, the transect methods provided a snapshot of the reef and were also restricted to the section of the reef where the transects were located. Despite the limitations of information obtained, the results from airborne image analysis were useful in complementing *in situ* survey results.

A major concern with regards to problems of mixed pixels was the contribution of dead corals covered with turf algae. Dead corals are often colonised by turf algae after a major disturbance such as cyclones or *A.planci* predation (Done 1992a, Zainal 1993). As a result, dead standing corals recorded from airborne images had texture patterns similar to live corals. Because of turf algae covering dead corals the tones will be darker in contrast to lighter tones for dead corals. Dead corals are shown as lighter tones because of the removal of zooxanthellae when the corals are dead. Therefore, the possibility exists that some of the pixels classified as corals may be dead corals covered with turf algae. This problem may be alleviated by the use of multispectral data.

However, it was not possible to provide an estimate of the error involved because of the close proximity of dead corals with live corals and their small area coverage. The error would probably be larger if the aerial photographs were acquired within a shorter term of one year when compared with a longer term of five years.

Nevertheless, as there may be disturbances such as cyclone damage, rock boring echinoderms and increased wave activity during storms, the error may be reduced. Between longer time periods and more frequent disturbances dead corals would be more likely to be converted to rubble because of physical damage. It is possible to assess the significance of this problem by examining the results of winter and summer photograph acquisitions in the same year. In addition, *in situ* surveys could be conducted during summer and winter within a year. There were, however, no acquisitions available for both summer and winter within the same year on Suva Reef and since the airborne images were restricted to the winter images the problems should be minimised. *In situ* surveys, however, showed that the turf algal populations still existed during winter. It is therefore possible that some contribution of turf algae still remains and should be borne in mind when detecting change of coral cover between years.

It must be noted that although algae were classified from airborne images as a separate class, they may be grossly under-estimated because of the absence of spectral data. In addition, most species of algae grow in small patches and are usually intermixed with other substrata as found from *in situ* surveys. This problem may be solved with improved multispectral satellite sensors, although Zainal (1993) suggested that the current Landsat Thematic Mapper's 30m multispectral spatial resolution was not able to separate the mixed stands of algae.

Both survey methods employed may not offer the resolution at the species level for some organisms. The *in situ* survey method can be easily modified for more detailed studies. It must be borne in mind, that the potential of studying coral reef community changes by remote sensing method despite their different species has warranted merit in itself.

However, the remote sensing method was intended to be a prototype for change detection of coral reef habitats and as a result most of the techniques developed for this research are open to further improvement. It has a major drawback because of unavailability of spectral data. Although, it is a major limitation, the information obtained on the long term pattern and direction of change of habitats were significant contributions to our understanding of long term ecological patterns. It must be emphasised, however, that spectral knowledge of reefs are important in detecting change in addition to extensive knowledge of the reef (Zainal 1993).

Despite the limitations of remote sensing method, the results of airborne image analysis will be useful for interpreting the long term response for more sophisticated technology such as multispectral satellite data as well as an aid in understanding future *in situ* observations. However, the long term patterns of processes occurring on reefs will only be completely understood through an integrated approach between remote sensing methods and *in situ* measurements.

CHAPTER 6

CONCLUSIONS, SUMMARY AND FUTURE DIRECTIONS

6.1 PRELIMINARY REMARKS

In this chapter, the work undertaken in this thesis is summarised, major results obtained are reviewed and the interpretations and significance of this work are discussed. Some recommendations are also presented on how the work may be extended to long term monitoring of other coral reefs in Fiji which are less influenced by human activities.

6.2 SUMMARY OF INVESTIGATIONS AND MAJOR RESULTS

The main line of enquiry of this thesis has been the effects of major disturbances on long term reef patterns and has focused on ways of recording and understanding these effects. The results have highlighted the importance of integrating *in situ* methods and remote sensing methods to understand these patterns. There are some questions that are still yet to be answered and thus require further work before a definite answer can be obtained.

In the light of chapter 3, one of the major results to emerge was the distinctive zonation patterns distinguished from *in situ* surveys. These general zonation patterns were relatively stable from 1984 to 1991. Despite the relative stability of the general zonation patterns, there were some significant changes to the substrata. In particular, there were changes at the western section from coral rock to a mixture of sand and rubble from 1984 to 1989 and 1991 respectively. These changes were attributed to excavations by large aggregations of rock boring

E.mathaei. At the eastern section, marked changes were found from 1984 to 1989 and 1991. There were changes from rubble and sand to coral rock because of coral growth.

Other important results from chapter 3 were the location of dead corals on the reef flat since these were not detected from airborne images. In some years there were no dead corals at some sites while in other years there was loss of corals. Information on fleshy algae and turf algae were also obtained. There was generally high cover of fleshy algae in 1984. Turf algae were widely distributed across the reef and large increases were associated with *E.mathaei* disturbance.

The work presented in chapter 4 has shown the value of remote sensing method in studying coral reefs. However, the results of airborne analysis showed that the effects of tsunami probably caused more damage to the structure of the reef than any other disturbance occurring between 1945 and 1990. As a result of tsunami damage and cyclones between 1951 and 1967 there were dramatic declines in major habitats such as seagrass and live corals. However, some habitats demonstrated high resilience in the long term. These were coral pavement, consolidated rubble, boulder zone and rubble bank.

Further results presented in chapter 4, were those of seagrass changes. The losses of seagrass occurred in some years because of major disturbances such as tsunami, cyclones and flood. However, seagrass showed great resilience to recover after damage. The long term spatial patterns of seagrass beds from airborne images revealed clearly that there were oscillations in the regrowth and losses of seagrass at the eastern section. Seagrass beds extended towards the lagoon in some years and regressed in other years. At the western section there was a marked regression in seagrass beds to the seaward section of the backreef because of high turbidity and siltation from foreshore reclamations.

Moreover, massive changes from consolidated rubble to sand and rubble occurred at the western section in 1989 and 1991. The *in situ* surveys attributed this change to *Echinometra mathaei*. In addition, the loss of large isolated patches of corals was a result of *A.planci* predation. There was some loss of live coral cover because of hydrodynamic influence which was greater on the more exposed eastern section in contrast to the protected western section.

However, losses at the seaward section of most habitats resulted from physical damage caused by increased water movement over the reef flat during storms and cyclones. In contrast, losses towards the landward sections of habitats were related to siltation, sand dredging or flood.

6.3 SUGGESTIONS FOR FUTURE INVESTIGATIONS

(a) The manual digitisation of different habitats from airborne images proved to be a tedious and time consuming task. A more sensitive method of classification that could identify different shades of grey levels and different texture patterns should be developed for analysis of airborne images of coral reefs.

(b) The benefits of Geographical Information Systems (GIS) to graphically display time series of airborne images have been demonstrated in this study. Future investigations should focus on combining other ancillary data such as tidal flow, current speed and direction, fishing pressure, salinity, temperature, wind speed and wind direction, with GIS and image processing techniques to investigate important factors in shaping habitat distribution on coral reefs. This should also further help determine the variability caused by different environmental regimes.

(c) Future investigations should include multispectral satellite data (see Appendix 6.1) or airborne multispectral data.

The integration of the spectral information with the high spatial resolution (5-10m) should show marked improvement in the detection of small scale habitat changes such as algae and other mixed pixels. There is an opportunity provided by the Japanese satellite ADEOS in 1996. The spatial resolution of multispectral and panchromatic data will be 16m and 8m respectively.

(d) Research is required on field radiometry to understand the spectral characteristics of the different substrata on the reef. In particular, spectral information of homogeneous stands of habitats are required for long term monitoring. An attempt made in 1991 was unsuccessful because of poor weather conditions.

(e) It will be useful if future *in situ* survey methods could include monitoring large entities that are identifiable from satellite or airborne data. This will enable the comparisons of data at the same resolution.

(f) It will be of interest to monitor reefs that are isolated and have no human influences. This will enable the assessment of long term patterns of natural disturbance that are not human-induced or influenced by human activities using both methods. This will provide a control reef which could then be used to assess the different degree of human disturbances. Several reef types should be used as controls to eliminate any differences in environmental parameters.

(g) There is a need to understand the importance of monitoring resources for sustainable development and would therefore be necessary to continue the monitoring programme.

6.4 FINAL CONCLUSIONS

This thesis began by addressing the questions of whether remote sensing methods can be used to assess long term changes on coral reefs. The aim has been to introduce the techniques of remote sensing in studying long term patterns of reef communities. The intention also has been to integrate the two types of methods and to appraise the synergy to be derived from combining them.

Both survey methods revealed significant changes in community structure on their own. On the one hand, the contribution of remote sensing method is critical to the advancement of our knowledge of long term changes on coral reef. The two-dimensional synoptic view provided by this method is impossible to achieve by any other means. On the other hand, the *in situ* survey provided some results that could not be obtained from remote sensing methods. Information on species distribution of echinoderms and attributing the causes of change to the substratum as a result of *E.mathaei* excavations could not be acquired from remote sensing methods alone. Although each method has its own limitations, this study has shown the benefits of complementing conventional small scale ecological *in situ* survey methods with a broad scale and long term study using remote sensing methods.

Tsunami and cyclones played a major role in eliminating zones of corals which previously dominated Suva Reef. There is a significant role of *Acanthaster planci* in the death of corals. The *E.mathaei* was shown to make a significant contribution to the destruction of the reef framework and as a result there were increases in coral rubble because of the excavations by *E.mathaei*. In contrast, there are cyclic changes of seagrass which are able to recover after a major disturbance such as flood. Probably the most outstanding long term changes were those caused by the tsunami which were to shape the habitat structure of Suva Reef for many years.

Years		* sea	* sand	** sea	** sand	*** sea	*** sand
1951/1967	%	16.4 (-)	58.3 (+)	3.3 (+)	4.6 (+)	5.2 (+)	13.8 (-)
	Rate	1.0	3.6	0.2	0.3	0.3	0.9
1967/1971	%	6.9 (-)	36.8 (-)	11.2 (+)	21.1 (-)	4.4 (+)	12.9 (-)
	Rate	1.7	9.2	1.0	1.9	1.1	3.2
1971/1978	%	47.6 (+)	16.3 (+)	-	-	4.2 (-)	5.4 (+)
	Rate	6.8	2.3			0.6	0.8
1978/1979	%	4.5 (+)	6.1 (+)	-	-	-	-
	Rate	4.5	6.1				
1979/1982 OR 1978/1982	%	41.0 (+)	9.3 (+)	4.0 (+)	9.9 (+)	4.1 (+)	2.2 (-)
	Rate	13.7	3.1	1.0	2.5	1.0	2.2
1982/1984	%	15.8 (-)	37.0 (-)	23.4 (+)	5.5 (+)	5.1 (-)	18.9 (+)
	Rate	7.9	18.5	11.7	2.7	2.6	6.3
1984/1986	%	15.9 (-)	34.3 (+)	18.0 (-)	173.0 (+)	50.3 (-)	312 (+)
	Rate	7.9	17.2	9.0	86.6	25.1	156
1986/1989	%	26.1 (+)	37.1 (-)	6.6 (+)	83.2 (-)	54.0 (+)	346 (-)
	Rate	8.7	12.4	2.2	27.7	18.0	173
1989/1990	%	21.5 (+)	108.7 (+)	2.6 (-)	52.2 (-)	2.1 (+)	15.3 (-)
	Rate	21.5	108.7	2.6	52.2	2.1	15.3

* Eastern Suva Reef
** Western Suva Reef
*** Nasese Shoal

Years		* cor	* alg	** cor	** alg
1951/1967	%	52.2 (-)	104.0 (+)	34.7 (-)	51.1 (-)
	Rate	3.3	6.5	2.2	3.2
1967/1971 OR 1967/1978	%	32.9 (+)	140.0 (-)	15.9 (+)	38.4 (+)
	Rate	8.2	35.0	2.4	3.5
1971/1978	%	8.3 (-)	79.1 (+)	-	-
	Rate	1.2	11.3		
1978/1979	%	0.2 (-)	51.1 (-)	-	-
	Rate	0.2	51.1		
1979/1982 OR 1978/1982	%	5.6 (+)	23.2 (+)	2.5 (+)	14.4 (-)
	Rate	1.9	7.7	0.6	3.6
1982/1984	%	14.6 (-)	13.5 (+)	6.4 (-)	2.7 (+)
	Rate	7.3	6.8	3.2	1.4
1984/1986	%	6.7 (+)	27.3 (-)	16.2 (-)	96.8 (+)
	Rate	3.3	13.7	8.1	48.4
1986/1989	%	0.3 (-)	6.2 (-)	5.7 (+)	110.0 (-)
	Rate	0.1	2.1	1.9	36.7
1989/1990	%	13.6 (-)	10.7 (+)	1.9 (-)	25.0 (+)
	Rate	13.6	10.7	1.9	25.0

Appendix:4.1 Changes in substratum on Suva Reef and Nasese Shoal. sea=seagrass, cor=live corals, alg=algae

Years		* rub	* rb	** rub	** rb
1951/1967	% Rate	41.9 (+) 2.6	112.9 (+) 7.1	72.3 (+) 4.5	10.2 (-) 0.6
1967/1971 OR 1967/1978	% Rate	35.1 (+) 8.9	31.8 (-) 7.9	7.8 (-) 0.7	11.6 (-) 1.0
1971/1978	% Rate	28.8 (+) 4.1	22.9 (-) 3.3	-	-
1978/1979	% Rate	11.5 (-) 11.5	9.6 (-) 9.6	-	-
1979/1982 OR 1978/1982	% Rate	3.5 (-) 1.1	1.2 (-) 0.4	73.9 (-) 18.4	5.1 (+) 1.3
1982/1984	% Rate	5.7 (+) 2.8	24.5 (+) 12.2	34.7 (-) 17.4	4.2 (+) 2.1
1984/1986	% Rate	88.2 (-) 44.1	76.6 (+) 38.3	78.9 (+) 39.4	5.7 (+) 2.9
1986/1989	% Rate	29.1 (+) 9.7	11.4 (-) 3.8	4.9 (+) 1.6	11.7 (-) 3.9
1989/1990	% Rate	32.2 (-) 32.2	22.9 (-) 22.9	21.7 (-) 21.7	5.3 (+) 5.3

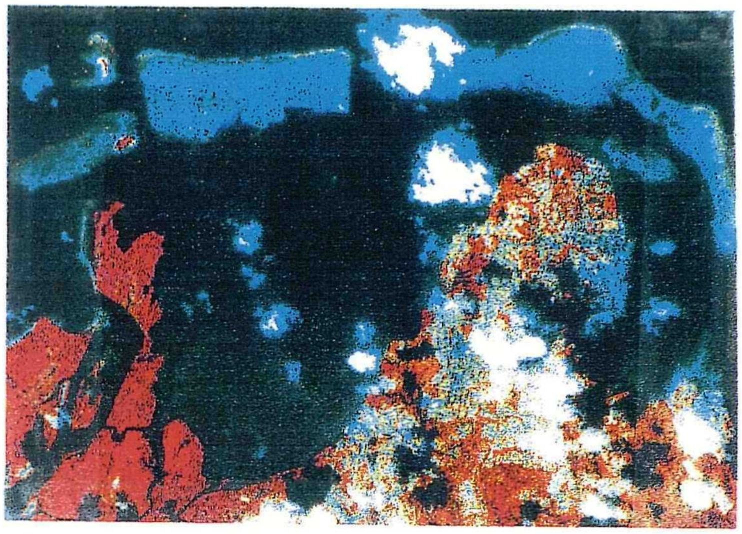
Years		* cp	* s/r	** cp	** s/r
1951/1967	% Rate	9.6 (-) 0.6	6.3 (-) 0.4	51.8 (-) 3.2	112.7 (-) 7.0
1967/1971 OR 1967/1978	% Rate	14.3 (-) 3.4	33.8 (-) 8.5	19.1 (-) 1.7	96.9 (+) 8.8
1971/1978	% Rate	9.0 (-) 1.3	5.1 (+) 0.7	-	-
1978/1979	% Rate	11.7 (+) 11.7	5.1 (+) 5.1	-	-
1979/1982 OR 1978/1982	% Rate	31.5 (-) 10.5	2.9 (+) 0.9	6.6 (-) 1.7	15.5 (-) 3.9
1982/1984	% Rate	12.9 (-) 6.4	16.7 (+) 8.4	15.0 (+) 7.5	2.9 (-) 1.5
1984/1986	% Rate	12.9 (+) 6.4	4.3 (+) 2.2	18.0 (-) 9.0	26.5 (-) 13.3
1986/1989	% Rate	11.1 (+) 3.7	2.0 (-) 0.7	53.8 (+) 7.9	40.4 (+) 13.5
1989/1990	% Rate	10.9 (+) 10.9	6.0 (-) 6.0	47.7 (-) 47.7	15.4 (+) 15.4

Years		* bz	* pool	** bz	** pool
1951/1967	% Rate	8.1 (-) 0.5	50.7 (-) 3.2	-	51.0 (+) 3.1
1967/1971 OR 1967/1978	% Rate	2.4 (-) 0.6	17.5 (+) 4.4	-	74.5 (-) 6.8
1971/1978	% Rate	10.8 (-) 1.5	10.3 (+) 1.5	-	-
1978/1979	% Rate	7.8 (-) 7.8	2.7 (-) 2.7	-	-
1979/1982 OR 1978/1982	% Rate	21.0 (-) 7.0	9.1 (-) 3.0	-	8.3 (+) 2.1
1982/1984	% Rate	8.6 (+) 4.3	11.8 (-) 5.9	-	0.8 (-) 0.4
1984/1986	% Rate	35.9 (+) 18.0	11.7 (-) 5.8	-	20.2 (+) 10.1
1986/1989	% Rate	22.9 (-) 7.6	1.3 (+) 0.4	-	18.9 (-) 6.3
1989/1990	% Rate	3.7 (+) 3.7	4.1 (+) 4.1	-	6.7 (-) 6.7

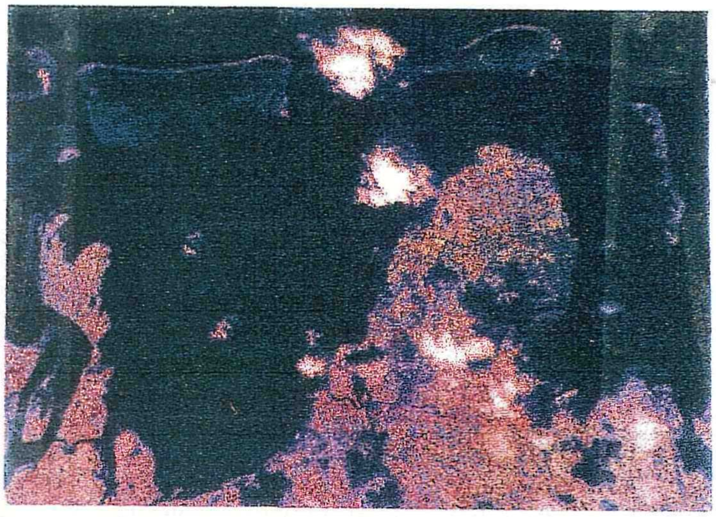
* Eastern Suva Reef
** Western Suva Reef

Appendix:4.1 cont'd. Changes in substratum on Suva Reef and Nasese Shoal. rub=rubble, rb=rubble bank, cp=coral pavement, s/r=sand & rubble, bz=boulder zone, pool=tidal pool.

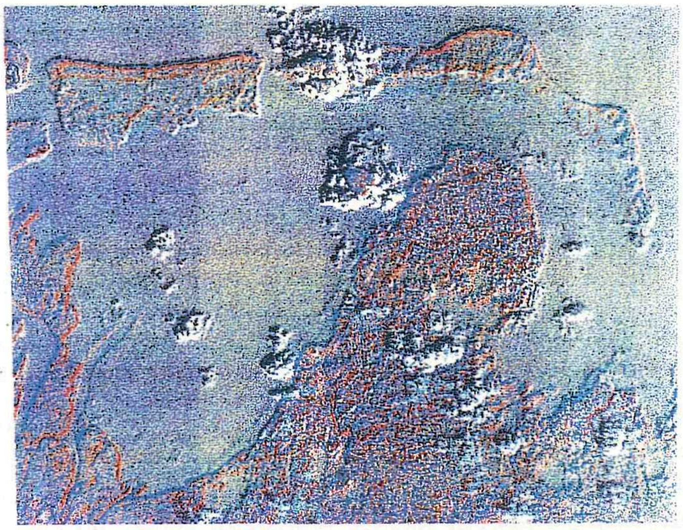
A



B



C



APPENDIX 6·1 SPOT satellite image of Suva Area (August, 1990)
A. Multispectral image (XS1, XS2 and XS3)
(XS3=red, XS2=green & XS1=blue)
B. XS3 channel
C. Multispectral image analysed by gradient filter

LIST OF REFERENCES

Adey W.H.P., Adey P., Burke R. and Kaufman L. (1977) The Holocene reef systems of eastern Martinique, French West Indies. *Atoll Res. Bull.* 218:1-40.

Agassiz A. (1899) The islands and coral reefs of Fiji. *Bull. Mus. comp. Zool. Harv.* 33:1-167.

Allum J.A.E. (1980) Photogeology: the early days. *Geoscience Canada* 7:155-158.

Antonius A. (1981) Coral reef pathology: A review. *Proc. 4th Int. Coral Reef Symp.* Manila 2:7-14.

Avery G. (1965) Measuring land use changes on USDA photographs. *Photogramm. Eng.* 31:620-624.

Badgeley P.C., Miloy L. and Childs L. (eds.) (1969) *Oceans from space.* Houston Gulf Pub.

Baines G.B.K. (1977) Draft outline of a study of the impacts of current and proposed sand dredging in the Suva area. Unpub. ms. 4pp.

Bajpai I. (1979) The coastal ecosystem -man's impact. Keynote address. *Proc. 2nd South Pacific Conference on National Parks and Reserves*, Sydney 1:140-147.

Bak R.P.M and Criens S.R. (1981) Survival after fragmentation of colonies of *Madracis mirabilis, Acropora palmata* and *A.cerviconis* (Scleractinia) and the subsequent impact of coral disease. *Proc. 4th Int. Coral Reef Symp.* 2:221-227, Manila.

Ball D.F., Hornung M. and Mew G. (1971) The use of aerial photography in the study of geomorphology and soils of upland areas. *In* Goodier, R. (ed) *The Application of Aerial Photography to the work of the Nature Conservancy.* Natural Environment Research Council, Swindon pp.66-67.

Ball M.H., Shinn E.A., Stockman K.W. (1967) The geologic effects of Hurricane Donna in South Florida. *J. Geol.* 75:583-597.

Banner A.H. (1968) A freshwater "kill" on the coral reefs of Hawaii. *Hawaii Inst. Mar. Biol. Tech. Rept.* 15:1-29.

Barrett E.C. and Curtis L.F. (1992) *Introduction to Environmental Remote Sensing* (3rd edn). Chapman and Hall, London, New York.

Bina R.T. (1982) Remote Sensing data for management of coral reefs offshore, Philippines - an application study. *Unpublished paper presented at the Workshop of Remote Sensing of Great Barrier Reef Region (Australia). Townsville, Australia, James Cook University* pp. 1-4.

Bina R.T. and Ombac E.R. (1979) Effects of tidal fluctuations on spectral patterns on Landsat Coral Reef imageries. *Proc. 13th Int. Symp. on Remote Sensing of Environment.* Ann Arbor, Environment Research Institute pp. 1293-1308.

Bina R.T., Carpenter K., Zacher W., Jara R. and Lim J.B. (1978) Coral Reef Mapping using Landsat data : Follow up studies. *Proc. 12th Int. Symp. on Remote Sensing of Environment.* Manila, Philippines. Ann Arbor, Environment Research Institute pp. 2051-2070.

Birkeland C. (1984) A contrast in methodologies between surveying and testing. In: *Comparing coral reef survey methods.* UNESCO Reports Marine Science 21, Paris. pp. 11-26.

Birkeland C. (1989) The influence of echinoderms on coral reef communities. *In:Jangoux M., Lawrence J.M.(eds)Echinoderm studies* 3:1-79.

Bouchan C. (1981) Quantitative study of the scleractinian coral communities of a fringing reef of Reunion Island (Indian Ocean). *Mar. Ecol. Prog. Ser.* 4: 273-288.

Bradbury R.H., Loya Y., Reichelt R.E. and Williams W.T (1986) Patterns in the structural typology of benthic communities on the two coral reefs of the central Great Barrier Reef. *Coral Reefs* 4:161-167.

Broadie J.E. (1992) Enhancement of larval and juvenile survival and recruitment in *Acanthaster planci* from the effects of terrestrial runoff: a review. *Aust. J. Mar. Freshwater Res.*, 43:539-554.

Brown B.E and Howard L.S. (1985) Assessing the effects of "stress" on reef corals. *Science* 199:1302-1310.

Brown B.E. (1987) Worldwide death of corals-natural cyclical events or man-made pollution. *Mar. Pollut. Bull.* 18:9-13.

Brown B.E (1988) Assessing environmental impacts on coral reefs. *Proc. 6th Int. Coral Reef Symp.* 1:71-80.

Carpenter R.C. (1990) Mass mortality of *Diadema antillarum.* I. Long term effects on sea urchin population dynamics and coral reef algal communities. *Mar. Biol.*104:67-77.

Carpenter R.C (1981) Grazing by *Diadema antillarum* (Phillipi) and its effects on the benthic algal community . *J. Mar. Res.* 39:749-765.

Chesher R.H. (1969) Destruction of Pacific corals by a sea star. *Science* 165:280-283.

Collins W.G. and El-Beck A.H.A. (1971) The acquisition of urban landuse information from aerial photographs of the city of Leeds. *Photogrammetric* 27:71-92.

Connell J. (1978) Diversity in tropical rain forests and coral reefs. *Science* 199:1302-1310.

Curran P.J. (1985) *Principles of Remote Sensing.* Longman Group Ltd. 282pp.

Curran P.J. (1978) Oblique false colour photograph of fog in Cheddar Gorge. *Weather* 33:63-64.

D'Elia F.D., Buddemeir R.W. and Smith S.V. (1991) Workshop on Coral Bleaching, Coral Reef Ecosystems and Global Change: *Report of Proceedings. Maryland Sea Grant.*

Dahl A.L. and Salvat B. (1988) Are human impacts, either through traditional or contemporary uses, stabilizing or destabilizing to reef community structure. *In : Proc. 6th Int. Coral Reef Symp.* 1:63-69.

Dahl A.L. (1985) Traditional environmental management in New Caledonia: a review of existing knowledge. *SPREP Topic Review 18. South Pacific Commission, Noumea.* 17pp.

Dahl A. (1972) Ecology and community structure of some tropical reef algae in Samoa. *Proc. Int. Seaweed Symp.* 17:36-39.

Dai C.F. (1988) Coral communities of Southern Taiwan. *Proc. 6th Int. Coral Reef Symp.* 2:647-652. Australia.

Dana J.D. (1846) Zoophytes. *U.S. Exploring Expe.* (1838-1842) 7:1-1740.

Dartnall A.J. and Jones M (eds.) (1986) A manual of survey methods: Living resources in coastal areas. *Australian Institute of Marine Science, Townsville.*

Davis C.K. and Neal J.T. (1963) Descriptions and airphoto characteristics of desert landforms. *Photogramm. Eng.* 29:621-631.

Davis W.M. (1920) The islands and coral reefs of Fiji. *Geo. Jour.* 55(1):34-45, (3):200-220, (5):377-388.

Dickie R., Fennery R.M., Schon P.W. (1991) Ports Authority of Fiji Planning Manual, Engineering Dept., Ports Authority Of Fiji, Suva.

Dodge R.E., Logan A. and Antonius A. (1982) Quantitative reef assessment studies in Bermuda: a comparison of methods and preliminary results. *Bull. Mar. Sci.* 32: 745-760.

Done T.J., Dayton P.K., Dayton A.E. and Steger R. (1991) Regional and local variability in recovery of shallow communities : Moorea, French Polynesia and Central Great Barrier Reef. *Coral Reefs* 9:183-192.

Done T.J. (1992a) Constancy and change in some Great Barrier Reef coral communities: 1980-1990. *Amer. Zool.* 320:655-662.

Done T.J. (1992b) Effect of tropical cyclone waves on ecological and geomorphological structures on the Great Barrier Reef. *Continental Shelf Res.* 12: 859-872.

Done T.J. (1990) Transition matrix models of crown of thorns and corals. *In R.H.Bradbury (ed.), Acanthaster and the coral reef. A theoretical perspective. Lecture notes in Biomathematics* 88: 291-297.

Done T.J. (1987) Simulation of the effects of *Acanthaster planci* on the population structure of massive corals in the genus *Porites* : evidence of population resilience? *Coral Reefs* 6:75-90.

Done T.J (1983) Coral zonation : Its nature and significance. *In Perspective on coral reefs, Barnes D.J. (ed.), Australian Institute of Marine Science, Townsville,* 277pp.

Done T.J. (1982) Patterns in the distribution of soft corals across the central Great Barrier Reef. *Coral Reefs* 1:229-236.

Done T.J.(1981) Photogrammetry in coral ecology: a technique for the study of change in coral communities. *Proc. 4th Int. Coral Reef Symp.* 2:315-320 Manila.

Dustan P. and Halas J.C. (1987) Changes in the reef coral community of Carysfort reef, Key Largo, Florida: 1974-1982. *Coral Reefs* 6:91-106.

Eastman J.R. (1992) IDRISI technical references, version 4.0, Clarke University, Massachusettes, U.S.A., pp.213.

Ebert T.A. (1983) Recruitment in echinoderms pages:169-203 *In: Jangoux M & Lawrence J.M. (eds.) Echinoderm Studies* Vol.1, Balkema, Rotterdam.

Edwards R.W. and Brown M.W. (1960) Aerial photographic method for studying distribution of aquatic macrophytes in shallow waters *Ecol. J.* 48:161-163.

El-Ashry M.T.(ed.) (1977) Air photography and coastal problems. *Benchmark Papers in Geology,* Hutchinson-Ross Publ. Co., Stroudsburg, PA, vol. 38, 425pp.

Ellefsen R. and Davidson R. (1980) Monitoring the aerial growth of San Jose, Costa Rica. *Proc. 14th Int. Symp. on Remote Sensing of Environment.* Univ. Michigan, Ann Arbor, pp.1243-1249.

Endean R. (1976) Destruction and recovery of coral reef communities. *In: Biology and Geology of Coral Reefs, Jones, O.A. & Endean R. (eds.) Academic press, New York,* pp. 215-254.

Endean R (1969) Report on investigation made into aspects of the current *Acanthaster planci* (Crown of thorns) infestations of certain reefs of the Great Barrier Reef. *QlD Dept. Primary Industries, Fisheries Branch, Brisbane*, 30pp.

Ewing G.C. (ed) (1965) Oceanography from space. *Proc. Conf. Woods Hole Oceanographic Inst.* August 1964.

Fezer F. (1971) Photo interpretation applied to geomorphology. *Photogrammetrica* 27:7-53

Finkel H.J. (1961) The movement of barchan dunes measured by aerial photogrammetry. *Photogramm. Eng.* 27:439-444.

Flood P.G. (1974) Sand movements on Heron Island, a vegetated sand cay, Great Barrier Reef Province, Australia. *Proc. 2nd Int. Coral Reef Symp.* 2:387-394.

Gardiner J.S. (1898) The coral reefs of Funafuti, Rotuma, and Fiji together with some notes on the structure of coral reefs in general. *Proc. Phil. Soc. Camb.* 9(8):417-503.

Gendronneau L. (1986) First dynamic study in Suva Harbour and Laucala Bay, Fiji. *Institute of Marine Resources Technical Report, University of the South Pacific, Fiji.*

Gladfelter W.B. (1982) White band disease in *Acropora palmata*: Implications for the structure and growth of shallow reefs. *Bull. Mar. Sci.* 32:639-643.

Glynn P.W. (1984) Widespread coral mortality and the 1982/1983 El Nino warming event. *Environ. Conserv.* 1:133-146.

Glynn P.W., Almodovar L.R. and Gonazalez J.G. (1965) Effects of Hurricane Edith on marine life in La Parguero, Puerto Rico. *Carib. J. Mar. Sci.* 4:335-345.

Glynn P.W. (1990) Coral Mortality and disturbances to coral reefs in the tropical eastern Pacific. *In P. W. Glynn (ed.), Global consequences of 1982-83 El Nino-Southern Oscillation.* pp. 55-126. Elsevier Oceanography Series 52.

Glynn P.W. and Weerdt W.H. (1991) Elimination of two reef-building hydrocoral species in the Eastern Pacific caused by the 1982-83 El Nino-Southern Oscillation warming event. *Science* 253:69-71.

Goetz A.F.H. and Rowan L.C. (1981) Geologic remote sensing. *Science* 211:781-791.

Goodwin M.H., Cole M.J.C., Stewart W.E., and Zimmerman B.L. (1976) Species density and associations in Carribean reef corals. *J. Expt. Mar. Biol. Ecol.* 24:19-31.

Goreau T. (1969) Post pleistocene urban renewal in coral reefs. *Micronesica* 5:323-326.

Grassle J.F. (1973) Variety in coral reef communities. *In : Biology and Geology of Coral Reefs, Jones, O.A. & Endean R. (eds.) Academic press, New York*, pp. 247-270.

Gray J.S. and Mirza F.B. (1979) A possible method for detecting pollution-induced disturbance on marine benthic communities. *Mar. Pollut. Bull.* 12:142-146.

Gray J.S (1979) Pollution -induced changes in populations. *Phil. Trans. R. Soc. (ser.B)* 286:545-561.

Gray J.S (1981) Detecting pollution induced changes in communities using the log-normal distribution of individuals among species. *Mar. Pollut. Bull.* 12:173-176.

Green D.G., Bradbury R.H. and Reichelt R.E. (1987) Patterns of predictability in coral reef community structure. *Coral Reefs* 6: 27-34.

Greig-Smith P. (1964) *Quantitative plant ecology*. 2nd edit. London, Butterworth, 256pp.

Grigg R.W. and Dollar S.J. (1988) Natural and anthropogenic disturbance on coral reefs. *In: Coral Reef ecosystems, Dubinsky, Z. (ed.) Elsevier Press.*

Grigg R.W. & Maragos J.E. (1974) Recolonisation of hermatypic corals on submerged lava flows in Hawaii. *Ecology* 55:387-395.

Guilcher A., Berthois L., Doumenge F., Michel A., Saint Requier A. and Arnold R. (1969) Les recifs et lagons coralliens de Mopelia et de Bora Bora. Orstom Memoires.

Hammack J.C. (1977) Landsat goes to sea. *Photogramm. Eng. and Remote Sensing* 43(6):683-691.

Hay M.E. (1984) Patterns of fish and urchin grazing on Carribbean coral reefs: are previous results typical? *Ecology* 65:446-454.

Hibbs A.R. (1982) Evaluation of the utility of Landsat in characterising coral reefs using J.P.L.'s image processing techniques. *Unpublished progress report. Pasadena, California. Jet Propulsion Laboratory*: 1-14.

Hoffmeister J.E. (1925) Some corals from American Samoa and Fiji Islands. *Pep. Dep. Mar. Biol. Carneigie Inst. Wash.* (publ. 340) 22:1-90.

Hopley D. & Stevenick A.V.(1977) Infrared aerial photography of coral reefs. *Proc. 3rd. Int. Coral Reef Symp. Miami* pp. 305-311.

Hopley D. (1978) Aerial photography and other remote sensing techniques. *In: Stoddart D.R. and Johannes R.E (eds.) 1978 Coral Reefs Research Methods. Unesco. Paris.* pp.23-44.

Howard J.A. (1970) *Aerial photo ecology*. Faber and Faber, London.

Howarth J.P. and Wickware G.M. (1981) Procedure for change detection using Landsat digital data. *Int. Journ. Remote Sensing* 2: 277-291.

Hsu S.Y. (1971) Population estimation. *Photogramm. Eng.* 37:449-454.

Hughes T.P., Reed D.C. and Boyle M.J. (1987) Herbivory on coral reefs : community structure following mass mortalities of sea urchins. *J. Exp. Mar. Biol. Ecol.* 113:39-59.

Hughes T.P. and Jackson J.B.C (1985) Population dynamics and life histories of foliaceous corals. *Ecol. Monogr.* 55:141-106.

Hutchings P.A. (1986) Biological destruction of coral reefs. A review. *Coral Reefs* 4:239-252.

Jackson J.B.C (1991) Adaptation and diversity of reef corals. *Bioscience* 41:475-482.

Johannes R.E (1975) Pollution and degradation of coral reef communities. *In: Tropical Marine Pollution, Wood, E.J.F. & Johannes, R.E. (eds.), Elsevier, Amsterdam,* pp.13-50.

Jupp D.L., Mayo K.K., Kuchler D.A., Claasen D. and Kenchington R.A. (1985) The application and potential of remote sensing to planning and managing the Great Barrier Reef of Australia. *In: Proc.18th Int. Symp. Remote Sensing of Environment, France. Ann Arbor, Environment Research Institute* pp. 121-137.

Jupp D.L. (1984) Report on the application and potential of remote sensing in the Great Barrier Reef Region. *GBRMPA Technical Report, Great Barrier Reef Marine Park Authority, Townsville, Australia.*

Jupp D.L.B (1983b) Remote Sensing by Landsat as support for management of the Great Barrier Reef. *Final report to the Great Barrier Reef Marine Park Authority, Townsville, Australia.* (Unpublished) pp.1-50.

Jupp D.L.B. (1983a) Remote Sensing application and potential for management of the Great Barrier Reef *In: J.T. Baker, R.M. Carter, P.W. Sammarco & K.P. Stark (Eds) Proc. Inaugural Great Barrier Reef Conference. Townsville, Australia. James Cook University Press :* 509-515.

Kelly M.G. and Conrad A. (1969) Aerial photographic studies of shallow water benthic ecology. *In: Remote Sensing of Ecology, Univ. Georgia Press, Athens,* pp. 173-184.

Kelly M.G. (1969) Aerial photography for the study of nearshore ocean biology. *In: Am. Soc. Photogram. and Soc. Photo. Sci. and Eng. New Horizons in aerial colour photography.* pp.347-356.

Kershaw K.A. (1964) Quantitative and dynamic ecology, 2nd edit. London, Arnold, 308pp.

Kidson C. and Manton M.M. (1973) Assessment of coastal change with the aid of photogrammetric and computer aided techniques. *Estuar. and Coast. Marine Science* 1:271-283.

Kiene W.E (1988) A model of bio-erosion of the Great Barrier Reef. *Proc. 6th Int. Coral Reef Symp.* 3:449-454 Australia.

Kinzie R.A. and Snider R.H. (1978) A simulation study of coral reef survey methods. *In: Coral reef: research methods*, Stoddart D.R. & Johannes R.E. (eds.), UNESCO Monogr. on Oceanographic Methodology 5, pp.231-250.

Knowlton N., Lang J.C., Rooney M.C. and Clifford P. (1981) Evidence for delayed mortality in hurricane-damaged Jamaican staghorn corals. *Nature* 294:251-252.

Knowlton N, Lang J.C. and Keller B.D. (1990) Case study of natural population collapse: Post hurricane predation on Jamaican staghorn corals. *Smithsonian Contrib. Mar. Sci.*, 31:1-25.

Kuchler D.A., Bour W. and Douillet P. (1988) Ground verification method for bathymetric satellite image maps of unsurveyed coral reefs. *ITC Journal* 2:196-199.

Kuchler D.A (1985a) Geomorphological separability, Landsat.MSS and aerial photographic data, Heron Island, Reef, Australia. PhD Thesis, Dept. of Geography, James Cook University, Townsville, Australia.

Kuchler D.A (1985b) Classification system : reef cover and zonation for use with remotely sensed data, GBR, Australia. *GBR Marine Park Authority Technical Report, Great Barrier Reef Marine Park Authority, Townsville, Australia.*

Kuchler D.A (1987) Geomorphological separability, Landsat.MSS and aerial photographic data: Heron Island, Great Barrier Reef, *GBRMPA Technical Report*, no. 10, 12pp.

Kumpf H.E. and Randall H.A. (1961) Charting the marine environments of St. John, U.S. Virgin Islands. *Bull. Mar. Sci.* 11:543-551.

La Riccia M.P. and Rauch H.W. (1977) Water well productivity related to photo-lineaments in carbonates of Frederik Valley, Maryland. *In:* Dilmarker R.R. and C'sallany S.C. (eds) *Hydrologic Problems in Karst Regions.* Western Kentucky University, pp.228-234.

Lang J.C., Lasker H.R., Gladfelter E.H., Muller R.G. (1992) Spatial and temporal variability during periods of "recovery" after mass bleaching on Western Atlantic coral reefs. *Amer. Zool.* 32:696-706.

Leatherman S.P. (1993) Coastal Change *In: Atlas of satellite observations related to global change.* Gurney R.J., Foster J.L., Parkinson C.L. (eds.) London, Cambridge University Press, 470pp.

Lessios H.A, Robertson, D.R., and Cubit J.D. (1984) Spread of *Diadema* mass mortality through the Caribbean. *Science* 226:335-337.

Licuanan W.Y. and Gomez E.D (1988) Coral Reefs of the North-Western Philippines: A physiognomic-structural approach. *Proc. 6th Int. Coral Reef Symp. Australia* 3:275-279.

Likens G.E. (ed.) (1987) *Long term studies in ecology: Approaches and alternatives. Springer-Verlag, New York.* 214pp.

Lo C.P. and Chan H.F. (1980) Rural population estimation from aerial photographs. *Photogramm. Eng. and Remote Sensing* 43:337-345.

Loya Y (1972) Community structure and species diversity of hermatypic corals at Eilat, Red Sea. *Mar. Biol.* 13:100-123.

Loya Y. (1976) Recolonisation of Red Sea corals affected by natural catastrophes and man-made pertubations. *Ecology* 57: 278-289.

Loya Y. (1978) Plotless and transect methods. In : *Coral reef: research methods*, Stoddart D.R. & Johannes R.E. (eds.), UNESCO Monogr. on Oceanographic Methodology 5, pp. 197-217.

MacIntyre I.G., Graus R.R., Reinthal P.N., Littler M.M., Littler D.S. (1987) The Barrier Reef sediment apron: Tobacco Reef, Belize. *Coral Reefs* 6:1-12.

Maniere R., Jaubert J. and Mission Oceanographique Francoise Au Moyen - Orient (1985) Coral Reef Mapping in the Gulf of Aqaba (Red Sea) using computer image processing techniques for coral reef survey. *Oceanologica Acta* 8(3):321-330.

Marsh L.M., Bradbury R.H., and Reichelt R.E. (1984) Determination of the physical parameters of coral distribution. *Coral Reefs* 2:175-180.

Maxwell W.G.H. (1968) *Atlas of the Great Barrier Reef.* Amsterdam. Elsevier.

Mayer A.G. (1924) Structure and ecology of Samoan reefs. 340:1-25.

McClanahan T.R. and Muthiga N.A. (1989) Patterns of predation of a sea urchin, *Echinometra mathaei* (de Blainville), on Kenyan coral reefs. *J. Exp. Mar. Biol. Ecol.* 126:77-94.

Moran P.J (1986) The *Acanthaster* phenomenon. *Oceanogr. Mar. Biol. Ann. Rev.* 24:379-480.

Morrissey J.I (1980) Community structure and zonation of macroalgae and hermatypic coral reef flat of Magnetic Island (Queensland, Australia). *Aquat. Bot.* 8:91-139.

Naylor E. and Hartnoll R.G. (eds.) (1979) Cyclic phenomena in marine plants and animals. *Proc. 13th European Mar. Biol. Symp.* Pergamon Press, New York.

Neumann A.C.(1966) Observations on coastal erosion in Bermuda and measurement of the boring rate of the sponge *Cliona lampa. Limnolog. Oceanog.* 11:92-108.

Nontji A (1986) Coral reef pollution and degradation by LNG plant in South Bontang Bay (East Kalimantan), Indonesia. *In: Proc. MAB-COMAR Regional Workshop on Coral Reef Ecosystems: Their Management Practices and Research\Training Needs, Soemodihardjo, S. (ed.) Lembaga Ilmu Pengetahuan Indonesia and Unesco. MAB-COMAR, Jakarta.* pp. 92-98.

Ogden J.C., Brown R.A., Salesky N. (1973) Grazing by the Echinoid *Diadema antillarum* Philippi: Formation of Halos around West Indian Patch Reefs. *Science* 182:715-717.

Orgoskey C.E. (1978) Aerial photographic methods for the detection of submerged vegetation in coastal New Jersey. *Proc. Amer. Soc. Photogramm.*, Fall Mts., Falls Church, VA, pp. 423-430.

Orme G.R., Flood P.G. and Ewart A. (1974) An investigation of the sediments and physiography of Lady Musgrave Reef: a preliminary account. *Proc. 2nd Int. Coral Reef Symp. Brisbane* 2:371-386.

Orth R.J., Moore K.A. and Gordon H.H. (1979) Distribution and abundance of submerged aquatic vegetation in the lower Chesapeake Bay, Virginia. Office of Res. and Develop., EPA, Washington, D.C., Report No. 600/8-79-029/SAVI.

Owen D (1971) *Acanthaster planci* starfish in Fiji: a survey of incidence and biological studies. *Fiji Agric. J.* 33:15-23.

Palca J. (1987) Bleaching of Caribbean corals, a cause for concern. *Nature* (London) 330:307.

Pearson R.G. (1981) Recovery and Recolonization of Coral Reefs. *Mar. Ecol. Prog. Ser.* 4:105-122.

Penn N. (1983) The environmental consequences and management of coral sand dredging in the Suva Region, Fiji. PhD Thesis, University of Wales. 252pp.

Perkins R.D. and Enos P. (1968) Hurricane Betsy in the Florida-Bahama area: geological effects and comparison with Hurricane Donna. *J. Geol.* 76:710-717.

Philipson W.R. and Liang T. (1982) An airphoto key for major tropical crops. *Photogram. Eng. and Remote Sensing* 48:223-233.

Pichon M (1978) Recherches sur les peuplements a dominance of d'anthozoires dans les reifs coralliens de Tuler (Madagascar). *Atoll Res. Bull.* 222:1-447.

Pichon M and Morrissey J. (1981) Benthic zonation and community structure of South Island Reef, Lizard Island (Great Barrier Reef) *Bull Mar. Sci.* 31:581-593.

Pilon P.G., Howarth P.H. and Bullock R.A. (1988) An enhanced classification approach to change detection in semi-arid environments. *Photogramm. Eng. and Remote Sensing* 54(12): 1709-1716.

Polycn F.C. (1976) NASA/COSTEAU ocean bathymetry experiment - remote bathymetry using high gain Landsat data. *NASA Contract Report, CR-ERIM-118500-I-F* : 1-18.

Poole R.W. (1974) *An introduction to quantitative ecology*. New York, McGraw-Hill, 532pp.

Porter J.W., Woodley J.D., Smith G.J., Neigel J.E., Battey J.F.and Dallmeyer D.G. (1981) Population trends among Jamaican reef corals. *Nature* 294:249-250.

Potts D.C. (1981) Crown of thorns starfish: man-induced pest or natural phenomenon? *In : Kitching R.L., Jones R.E.(eds.) The ecology of pests. CSIRO, Melbourne*, pp. 55-86.

Press N., Kampschuur W. and Duncan W (1980) Contribution to photogeology and remote sensing to mineral exploration in Ireland. *Transactions, Institution of Mining and Metallurgy, Section B* pp.50-51.

Randall R.H. and Eldredge L.G. (1977) Effects of typhoon Pamela on the coral reefs of Guam. *Proc. 3rd. Int. Coral Reef Symposium. Miami* 2: 585-591.

Randall (1972) Chemical pollution in the sea and the crown of thorns starfish (*Acanthaster planci*) *Biotropica* 4:132-144.

Robinson D.E. (1971) Observations on Fijian coral reefs and the crown-of-thorns starfish. *J. Roy.*

Soc. NZ. 1:99-112.

Rosen B.R. (1971) Principal features of reef coral ecology in shallow water environment of Mahe, Seychelles. In: Stoddart D.R. and Yonge C.M. (eds.) Regional variation in Indian Ocean Coral Reefs. *Symp. zool. Soc. London* no.28 Academic Press. pp. 263-299.

Rutzler K. and MacIntyre I.G. (1982) The habitat distribution and community structure of the barrier reef complex at Carrie Bow Cay, Belize, I. Structure and commmunities. *In: Rutzler K and MacIntyre I.G. (eds.) Smithsonian Institution Washington. D.C. pp.9-45.*

Ryland J.S. (1979) Introduction to the coral reefs of Fiji. *In Proc. Seminar Workshop on utilization and management of inshore marine ecosystems of the Tropical Pacific Islands,* November 24-30, 1979, Univ. of the South Pacific, Suva pp. 13-22.

Ryland J.S. (1981) Reefs of the Southwest Viti-Levu and their Tourism Potential. *Proc. 4th Int. Coral Reef Symp.* Manila 1:293-298.

Ryland J.S., Wrigley R.A and Muirhead A. (1984) Ecology and colonial dynamics of some Pacific reef flat. Didemnidae (Ascidiacea). *Zool. J. Linnean Soc.* 80: 261-282.

Salvat B. (ed.)(1987) Human impacts on coral reefs: facts and recommendations. *Antenne Museum E.P.H.E., French Polynesia,* pp. 253pp.

Sauer E.K. (1981) Hydrogeology of glacial deposits from aerial photographs. *Photogramm. Eng. and Remote Sensing* 47:811-822.

Scoffin T.P., Stearn C.W., Boucher D., Frydle P., Hawkins C.M., Hunter I.G., and MacGeachy J.K. (1980) Calcium carbonate budgets of a fringing reef on the west coast of Barbados. *Bull. Mar. Sci.* 30:475-508.

Shepherd S.A. and Womersley H.B.S. (1981) The algal and seagrass ecology of Waterloo Bay, South Australia. *Aquat. Bot.* 11:305-371.

Sheppard C.R.C (1980) Coral cover, zonation and diversity on reef slopes of Changos Atolls, and population structures of major species. *Mar. Ecol. Prog. Ser.* 2:193-205.

Singh A. (1989) Digital change detection techniquers using remotely sensed data. *Int. J. Remote Sensing* 10 (6) : 989-1003.

Smit G.S. (1978) Shifting cultivation in tropical rainforests detected from aerial photographs. *I.T.C. Journal*:603-633.

Smith V.E., Rogers, R.H. and Reed L.E. (1975b) Automated mapping and inventory of Great Barrier Reef zonation with Landsat data. *In: Proc. Ocean '75 Conf. Engin. Ocean Environ., Washington D.C: Washington Univ.* 775-781.

Smith S.V. and Henderson R.S. (eds.) (1976) An environmental survey of Canton Atoll lagoon. Naval Undersea Research and Development Centre, San Diego, NUC TP 395. 192pp.

Sokal R.R. and Rohlf (1973) *Introduction to Biostatistics*. W.H. Freeman and Company.

Stanley R.M. (1982) *World War II Photo Intelligence.* Sidgwick and Jackson, London, Charles Scribner's Sons.

Steers J.A. (1945) Coral reefs and air photography. *Geog. J.* 106:232-235.

Steneck R.S. (1986) The ecology of coralline algal crusts: convergent patterns and adaptive strategies. *Ann. Rev. Ecol. Syst.* 17: 273-303.

Stephens P.R., Daigle J.L. and Cihlar J. (1982) Use of sequential aerial photographs to detect and monitor soil management changes affecting cropland erosion. *J. Soil and Water Conserv.* 37:101-105.

Stephenson T.A, Tandy G., Spender M (1931) The structure and ecology of Low Islands and other reefs. *Sct. Repts. Gt. Barrier Reef Exped. 1928-1929.* 3:17-112.

Stoddart D.R. (1963) Effects of Hurricane Hattie on the British Honduras reefs and cays, October 30-31; 1961. *Atoll Res. Bull.* 95:1-142.

Stoddart D.R. (1969) Ecology and morphology of recent coral reefs. *Biol. Rev.* 44:433-498.

Stoddart D.R. (1974) Post-hurricane changes on the British Honduras reefs: Resurvey of 1972. *Proc. 2nd Int. Coral Reef Symp. Australia 2:473-483.*

Teichert C. and Fairbridge R.W. (1948) The Low Isles of the Great Barrier Reef: a new analysis. *Geogr. J.* 111:67-88.

UNESCO. (1984) *Comparing coral reef survey methods.* UNESCO Reports Marine Science 21; Paris, 170pp.

Vakamoce V.C. (1987) Seasonal changes in the large brown algal vegetation and the associated mobile invertebrates on a fringing coral reef, Magnetic Island, Great Barrier Reef Region, Australia. MSc Thesis, James Cook University of North Queensland. 135pp.

Veron J.E.N. and Done T.J. (1979) Corals and coral communities of Lord Howe Island. *Aust. J. Mar. Freshwater Res.* 30:203-236.

Veron J.E.N and Pichon M (1976) *Scleractinian of eastern Australia. Part I : Families Thamnasteriidae, Astrocoeniidae, Pocilloporidae.* Australian Institute of Marine Science, Townsville, 86pp.

Vuki V.C. (1991) A fish consumption survey of Dravuni, Great Astralobe Reef, Fiji. Marine Studies Programme Technical Report, 1. University of the South Pacific, Fiji.

Walbran P.D., Henderson R.A., Jull A.J.T. and Head M.J. (1989) Evidence from sediments of long-term *Acanthaster planci* predation on corals of the Great Barrier Reef. *Science* 245:847-852.

Walker F. (1964) *Geography from the Air.* Methuen and Co. Ltd.

Warwick R.M. (1986) A new method for detecting pollution effects on marine macrobenthic communities. *Mar. Biol.* 92: 557-562.

Weinberg S. (1981) A comparison of coral reef survey methods. *Bijd. Dierk.* 51: 199-218.

Wells J.(1957) Coral reefs. *Memoirs Geol. Soc. America* 1 (67)609 - 630.

Wells S. (1988) *Coral reefs of the world. Vol.3: Central and Western Pacific.* UNEP/IUCN.

Welsted J. (1979) Air photo interpretation in coastal studies. Examples from the Bay of Fundy, Canada. *Photogrammetrica* 35:1-28.

Williams E.H. Goenaga C. and Vicente V. (1987) Mass bleachings on Atlantic coral reefs. *Science* 238:877-878.

Willis B.L. (1985) Phenotypic plasticity versus phenotypic stability in reef corals *Turbinaria mesenterina* and *Pavona cactus*. *Proc. 5th Int. Coral Reef Symp.* Tahiti 4:107-112.

Wisumperuma K (1989) Remote sensing technique for coastal studies and environmental monitoring *Proc. of the Regional Seminar on the Application of Remote Sensing Techniques to Coastal Studies and Environmental Monitoring*, Hanoi, Vietnam. Sept., 1989 pp.206-210.

Witman J.D (1992) Physical disturbance and community structure of exposed and protected reefs: A case study from St. John, U.S. Virgin Islands. *Amer. Zool.* 32:641-654.

Woodley J.D., Chornesky E.A., Clifford P.A., Jackson J.B.C., Kaufman L.S, Knowlton N, Lang J.C., Pearson M.P., Porter J.W., Rooney M.C., Rylaarsdam K.W., Tunnicliffe V.J., Wahle C.M., Wulff J.L., Curtis A.S.G., Dallmeyer M.D., Jupp B.P., Koehl M.A.R, Neigel J. and Sides E.M. (1981) Hurricane Allen's impact on Jamaican coral reefs. *Science* 214:749-755.

Wulff J.L (1985) Dispersal and survival of fragments of coral reef sponges. *Proc. 5th Int. Coral Reef Symp.* 5: 119-124.

Yamaguchi M. (1973) Early life histories of coral reef asteroids with special reference to *Acanthaster planci* (L.) *In: O.A. Jones & Endean R. eds. Biology and Geology of coral reefs* 2:, vol. 11, Academic Press, New York.

Yoshioka P.M. and Yoshioka B.B (1987) Variable effects of hurricane David on the shallow water gorgonian of Puerto Rico.
Bull. Mar. Sci. 40:132-144.

Zainal A.J.M.M. (1993) Monitoring changes in shallow-water habitats off the coast of Bahrain using Landsat TM. Phd Thesis. Imperial College, University of London. 198pp.

Zann L., Broadie J., Berryman C. and Naqasima M (1987) Recruitment, Ecology, Growth and Behaviour of Juvenile *Acanthaster planci* (L.) (Echinodermata: Asteroidea). *Bull. Mar. Sci.* 41(2):561-575.

Zann L.P. (1992) The state of the marine environment in Fiji. Report on the marine environment. National Environmental Management Project, Fiji.

Zann L., Brodie J. and Vuki V. (1990) History and dynamics of the crown of thorns starfish *Acanthaster planci* (L.) in the Suva area, Fiji. *Coral Reefs* 9:135-144.