

**Reef island geomorphology:
Formation, development, and prospectives of islands in
Eta atoll, South Maalhosmadulu, the Maldives**

Mohamed Ali



A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy
School of Geography and Oceanography, University College, University of New South Wales

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Reef Island

Formation, development, and

The New South Wales

Reef Island



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Frontispiece. Part of the eastern periphery of Eta atoll. The view, looking southwestwards show the seaward side of Kunfunadhoo (foreground), Eydhafushi (centre), and Maaddoo. An extensive faro is seen in the background. The 'transverse' nature of the individual reef platforms and the lagoonward positioning of the islands are evident.

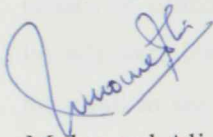


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DECLARATION

I hereby declare that this submission is my own work and to the best of my knowledge it contains no material previously published or written by any other person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by colleagues, with whom I have worked at UNSW or elsewhere, during my candidature, is fully acknowledged.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.



Mohamed Ali

SECRET

1. The purpose of this document is to provide information regarding the status of the project. The project is currently in the planning stage and is expected to be completed by the end of the year. The project is being managed by the Project Manager and is being funded by the Government. The project is being implemented by the Project Team and is being monitored by the Project Committee. The project is being evaluated by the Project Review Board. The project is being reported to the Project Steering Committee. The project is being reviewed by the Project Audit Committee. The project is being audited by the Project Audit Firm. The project is being reviewed by the Project Review Board. The project is being reported to the Project Steering Committee. The project is being reviewed by the Project Audit Committee. The project is being audited by the Project Audit Firm.

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Project Manager

ABSTRACT

The geomorphological development of reef islands in Eta atoll, a typical 'open' atoll in the Maldives, Indian Ocean is examined. Eta atoll comprises 90 patch reefs and faros, 55 located in the lagoon and 35 around the margin. Islands occur in both locations. The geomorphic characteristics of 50 islands are described and related to locational and environmental factors. Island morphodynamics are considered at three time-scales: short-term (seasonal and episodic events); medium-term (decades to century); and long-term (centennial to millennial).

The physical attributes of islands were obtained from morphometric measurements, surveying and mapping. Fieldwork was carried out between December 1995 and January 1999. Beach profiles were surveyed over two seasons to assess short-term changes. Medium-term changes were examined through comparative mapping of 1969 and 1999 aerial photographs, and from surveys done 100 years ago. Vegetation and soil depth patterns, with radiocarbon dating of sediments were used to infer island development during the Mid- to Late-Holocene.

Results from 20 islands suggest the first islands formed about 4500 years B.P. There were three phases of island initiation and growth from 4500 to 3000, around 2400, and 1550 years B.P. Islands were initiated either by 'nodal accumulation', or episodic storm/swell events. Evidence for a fall in sea level as an initiating mechanism is lacking. Subsequently, islands have grown concentrically or laterally, in a symmetrical or asymmetrical manner, from an initial core. Some islands have migrated, mostly in a lagoonward direction.

Over the last 100 years no overall atoll-wide morphodynamic trends were evident although the magnitude of change was greatest on linear islands, islands with sandy shorelines, and those on faros. Three patterns of sediment movements occur with seasonal (short-term) changes; 'circulating', 'semi-circulating' and, 'oscillating'. These patterns occur on circular islands, small elongated islands, and at one or both ends of elongated or linear islands. Both externally and locally generated swell and storm events have variable and localised impacts.

Models of island growth and development are proposed. Criteria to determine decadal-scale island stability and instability and longer-term island equilibrium are discussed. Potential applications of the study for vulnerability assessments to the impacts of climate change and sea level rise, and to island management and strategic planning are outlined.

The experimental design was a 2 (sex) x 2 (age) x 2 (group) factorial design. The dependent variable was the number of correct responses. The independent variables were sex, age, and group. The subjects were 24 children, 12 boys and 12 girls, aged 8 and 9 years. They were divided into two groups of 12 children each. The first group was the control group and the second group was the experimental group. The control group received no treatment and the experimental group received a treatment. The treatment was a program of 10 sessions of 15 minutes each. The treatment was designed to improve the children's reading skills. The children in the experimental group were given a reading test before and after the treatment. The children in the control group were given a reading test only once. The results of the reading test were compared between the two groups. The results showed that the children in the experimental group had a significant improvement in their reading skills compared to the children in the control group.

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المستطاع على المؤمن أن يفتخر بما آتاه الله من النعم والبركات في الدنيا والآخرة

ACKNOWLEDGEMENTS

All Praise and Thanks be to Allah for granting me...

The wisdom to seek some knowledge on the wonders of reef islands;

*The patience to bear the frustrations, despairs, and overcome numerous
impediments encountered during the course of this study;*

The courage to brave the elements; the sun, rain, wind and, sea during the fieldwork.

Most sincere appreciation is extended to my Supervisor, Professor Roger McLean. I am privileged to have benefited from his unfathomable knowledge on reef islands, with his feedback, comments and suggestions on the numerous draft chapters. I learnt much from his insistence on facts and eye for detail. Similarly, I thank Professor David Gillieson, for being my Co-Supervisor for the first year, during and after which he provided much assistance with the satellite imagery processing. Dr Paul Kench, Co-supervisor from 1996 provided helpful advice and comments on the draft chapters. I sincerely thank Associate Professor Colin Woodroffe, who introduced me to 'real' reef island research and to Professor David Hopley, who assisted me in the preparatory stage of this study.

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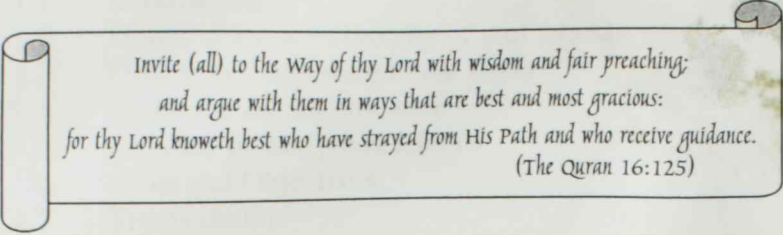
The Government of Maldives financed the fieldwork component, and with assistance from the United Nations Development Programme (UNDP) funded three years of my university tuition fees and 1.5 years' stipend. In this regard, I am grateful to Hon. Ismail Shafeeu, the then Minister of Planning, Human Resources and Environment, and Mr Hussein Shihab, the then Deputy Minister of the same Ministry, for providing me with the opportunity to undertake this study.

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DEDICATION



Invite (all) to the Way of thy Lord with wisdom and fair preaching;
and argue with them in ways that are best and most gracious:
for thy Lord knoweth best who have strayed from His Path and who receive guidance.
(The Quran 16:125)

*This thesis is dedicated
to the memory of my parents;*

*They must have had a dream, but ...
They were gone before their dreams were realised,
That leaves me to carry their hopes and seek new expectations.*

*Though meagre, this effort is hoped to be a foundation and an inspiration,
To take up the challenge to study the islands...
The very basis of our past, present and future continuance...and
To patiently persevere to triumph over any insurmountables, and
To quest for knowledge and wisdom in ways that benefit society and future generations.*

PEDIGREE

The pedigree is a diagram showing the relationships between individuals in a family across several generations. It is a tool used by geneticists to study the inheritance of traits and diseases. The pedigree is composed of symbols representing individuals and lines representing their relationships.

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- Male: A square symbol.
- Female: A circle symbol.
- Unknown sex: A diamond symbol.
- Proband: A square or circle with a central dot.
- Carrier: A square or circle with a horizontal line through the center.
- Affected individual: A square or circle with a diagonal line through the center.
- Consanguinity: A double line between two individuals.
- Adoption: A dashed line between two individuals.
- Stillborn: A square or circle with a diagonal line through the center and a small 'S'.
- Deceased: A square or circle with a diagonal line through the center and a small 'D'.

The lines in a pedigree represent the relationships between individuals. A horizontal line represents a mating pair. A vertical line represents a parent-child relationship. A diagonal line represents a sibling relationship. A double line represents a consanguineous relationship. A dashed line represents an adoption. A small 'S' indicates a stillborn child. A small 'D' indicates a deceased individual.

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CHAPTER 1

Introduction

1.1 Introduction

Reef islands, coral islands and atoll islands are to all intents and purposes the same thing. All three can be defined as discrete, morphologically coherent deposits of reef-derived bioclastic material located on reef platforms, and exposed above the level of the sea at high tide. Such islands are found in low to mid-latitude regions of the world and especially within the tropics of the Pacific and Indian Oceans. They occur on fringing reefs, barrier reefs, and atolls as well as on table reefs and faros (ringed-shaped reefs).

Scientific interest in the formation of atolls and reef islands has prevailed for more than two hundred years and it continues to this day. In 1777 Captain Cook seemed to have wondered about the formation of such features (Stoddart and Steers 1977, p.59). And, in the 19th and early 20th Century naturalists/scientists/explorers such as Charles Darwin (1842), J.D. Dana (1872), J. Stanley Gardiner (1903), Alexander Agassiz (1903), F. Wood-Jones (1912), and W.M. Davis (1928) examined and discussed the origin and development of reefs and reef islands. At the time no distinction was made between atoll structure and the surface morphology of atolls, although subsequently Stoddart (1973) has emphasised that distinction.

Specific issues raised by these studies with regards to surface morphology and especially reef islands, the subject of this thesis, included:

- *how they formed and when;*
- *how and why they differ locally, regionally and globally;*
- *what factors influence their present features and characteristics; and much more recently*
- *what impacts would sea level rise and other consequences of climate change have on such islands.*

Given the diversity and numbers of islands involved globally, it is unlikely that universal answers to these questions will be forthcoming. According to Stoddart (1965) there are about 425 atolls distributed round the world. The total number of islands on these atolls is not known, but would reach several thousands. For instance, on one atoll, Raroia in the Tuamotus, there are about 280 islets (Newell 1956). In the Maldives, more than 1200 islands occur on 26 atolls. One of these atolls is 924 km² Eta atoll, which has about 60 islands. This atoll is also the focus of this study.

1.2 Distribution and diversity of reef islands

While generically appropriate the term 'reef island' (and its equivalents) does not do justice to the great variations in island morphology and materials and their size, shape and detailed features. These variations are recognised by local names such as sand key or cay, motu and low isles. In the Maldives different types of reef islands are distinguished by names such as *fushi*, *finolhu* and *rah*.

In order to get some appreciation of the variability of reef islands, Stoddart and Steers (1977) suggested that reef island distribution patterns should be considered at three spatial scales: world (global), regional and local.

Global scale

Stoddart and Steers (1977) note that there are large variations in the frequency of islands in different atoll provinces. For instance, in the Tuamotus, atolls commonly have 100-300 islands each, whereas atolls in the Marshalls, Kiribati and Tuvalu have more than 20 and in the Carolines they generally have less than 10 islands. They also note that Guilcher (1971) had called attention to wide differences in the abundance of coral islands on barrier reefs. For example, islands are common but small on the British Honduras (Belize) reefs, while islands are very rare on the barrier reefs of New Caledonia, and Mayotte and also on the outer ribbon reefs of the Great Barrier Reef (here most islands are located on patch reefs within the lagoon). In contrast, islands cover a greater proportion of the reef platforms in some Pacific atolls, like Bora-Bora or Maupiti, as well as on some open-ocean atolls such as Diego Garcia, in the Indian Ocean which have a continuous or almost continuous island rim. Other reefs have no islands at all.

Stoddart and Steers (1977) therefore conclude that at a global scale there is no simple pattern in the distribution of reef islands.

There is also no unambiguous relationship with tidal range or storminess in the global distribution of reef islands. While Stoddart and Steers (1977) believed that reef islands are more generally found in areas of low tidal range rather than high, Guilcher (1988) found that the sand cay distribution in the tropical world does not always fit with tidal range. Similarly, reef islands occur within the tropical cyclone belt in both hemispheres as well as outside of the storm belts. They also occur in areas of monsoonal circulation and equatorial calms, as in the Maldives.

Regional scale

At the regional scale, a zonation of island types has been shown to exist both along and across Australia's Great Barrier Reef and the British

Honduras (Belize) reef provinces. Such zonations have been attributed to differences in reef platform heights (Spender 1930), or to the degree of exposure of reef platforms to wave action (Steers 1932; Stoddart 1965b). Similarly, along the Laccadive-Chagos chain, marked changes in island and atoll characteristics were recognised by Darwin (1842), Gardiner (1903), and Sewell (1936a, b), and thought to be related to latitudinal variations in tectonic, climatic and other environmental factors.

With regards to the Maldives, an atoll chain located between the Laccadive and Chagos archipelagos, Woodroffe (1993) notes that the atolls to the north are broad banks, discontinuously fringed by reefs with small peripheral reef islands, and with numerous patch reefs and faros in the lagoon. In the south of the Maldives group, atoll lagoons are deeper, faros and lagoonal patch reefs are rarer, continuity of the atoll rim increases, and the islands occupy a larger proportion of the atoll rim. Commenting on these latitudinal contrasts in morphology, Woodroffe (1993) suggests that different environmental factors have been and may still be controlling reef growth, sediment production/transport and island formation.

Local scale

In atoll situations there are at least two local scales: whole atoll and individual reef platform. In the first case, the distribution and nature of islands commonly reflects the importance of the trade winds in island building. Stoddart and Steers (1977) note that on many Pacific atolls, islands are concentrated on the windward side, with relatively few islands on the leeward side. In the Indian Ocean, they believe that the situation is 'complicated' by seasonal reversal in monsoon winds. Specifically in the case of the Maldives, Darwin (1842) assumed that monsoonal effects have placed islands on the eastern side of the northern atolls, and on the southeastern side of the southern atolls. Gardiner (1903) and Sewell (1936a, b) came to similar conclusions too.

Secondly, islands on individual reef platforms show considerable variation in size, shape, proportion of reef platform area occupation, orientation and position. In noting such variations, Woodroffe (1993) maintains that reef islands in the Maldives differ from many of the reef islands on other coral atolls, and goes further to advocate that 'reef growth and island formation may differ in detail from atoll to atoll'.

In this thesis, such variations are recognised not only at the atoll-scale but also on individual reef platforms. And in the case of Eta atoll an attempt is made to explain these variations.

1.3 Conceptual approach to the study

Conceptual framework

The conceptual framework developed for this study is shown in Figure 1.1. Several components (called compartments) and their linkages are illustrated. All are directed towards 'island formation and development'. Three major controls are identified: the external boundary conditions, and the more localised geological and biophysical influences.

The external controls (Compartment 1) include atmospheric and ocean forcing, which in the long term produces sea level changes on the one hand and provides the energy regime that drives the waves, tides and currents on the other. These help to determine the characteristics of the reef platform as well as the transport of reef-derived sediments over the platform. Long term sea level changes influence Holocene reef growth (Compartment 2) with reefs either keeping up, catching-up or giving up with sea level rise. Holocene reef growth is also influenced by the antecedent geological and topographic conditions.

The interactions between Holocene reef growth and coastal processes result in reef platform development (Compartment 3). This is the platform on which islands develop. On the reef platform *in situ* biological processes produce the surface features and the sediments which dominantly comprise skeletal products of a host of reefal organisms covering a great range of sizes and shapes.

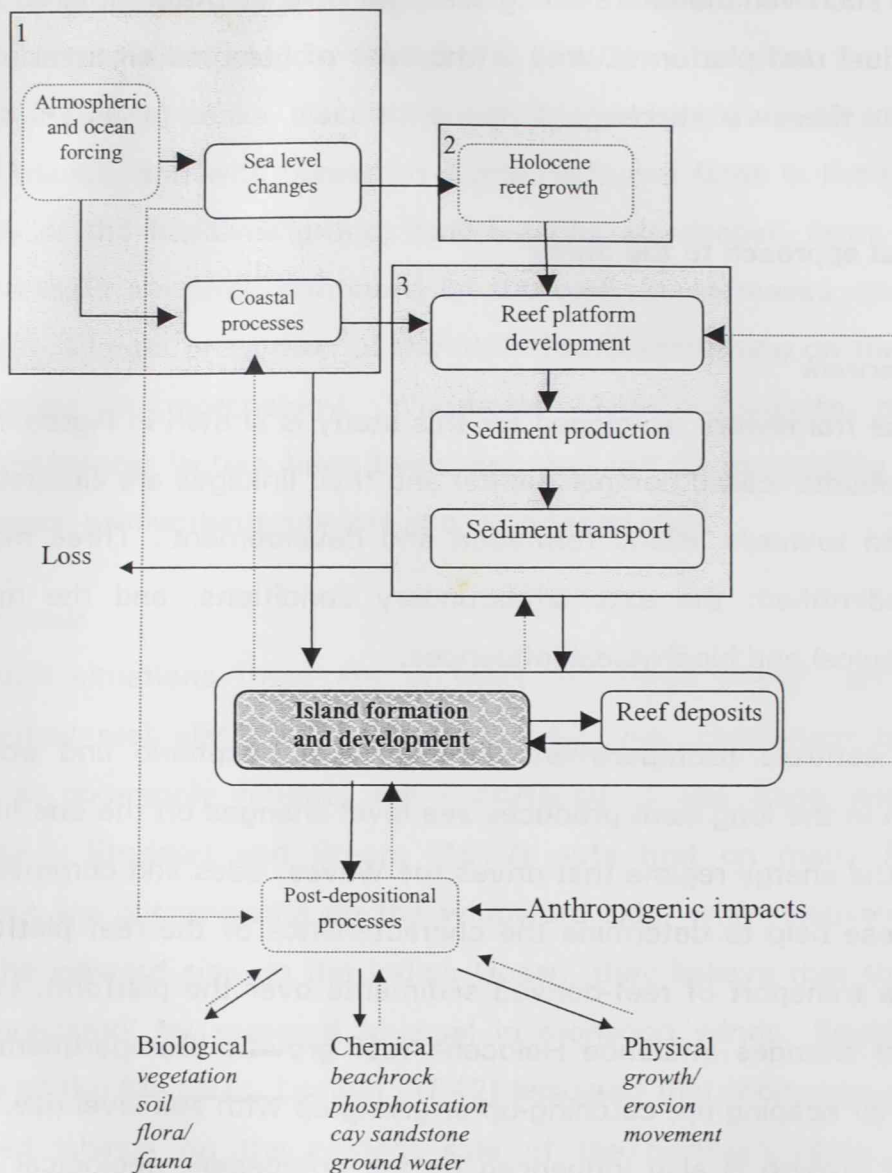


Figure 1.1 Environmental processes and conditions associated with island formation and development. Compartment (1) shows the external controls (2) geological controls, and (3) biophysical controls.

Materials produced on the reef platform are subjected to entrainment and transportation. In the transportation process, some sediments may be permanently lost over the reef crest and into deep water, and would not be available for island building. Other sediments may go into temporary storage on the reef platform, or are deposited as islands, under favourable conditions. Constant exchange of sediments can take place between the island and the surrounding reef deposits (see Figure 1.1).

Feedback effects also occur and these influence some of the processes that have gone into island building. Thus the very presence of islands on reef platforms can modify the prevailing coastal processes that operate on reef platforms and on island margins. Moreover, because the island occupies space on the reef platform, the area for sediment production and sediment transport is reduced.

Following the formation and development of reef islands, three groups of natural post-depositional processes can operate. These are identified at the bottom of Figure 1.1. Vegetation colonisation and succession together with soil development, including the formation of phosphatic rock and cay sandstone (see p.40 for definition) can serve to stabilise the island's surface. Island shorelines can also be stabilised by vegetation growth (e.g. mangroves and beachrock formation). However, erosion and accretion can also take place, which may result in a significant increase or decrease in island size. Movement of the island with relation to the reef platform can also occur.

Although three groups of post depositional processes have been identified in Figure 1.1 those processes are usually interrelated, and often complement each other. Feedbacks are also shown. Anthropogenic impacts can significantly affect the development of islands, by interfering with the sediment balances, transport routes, and other processes and conditions including coastal and post-depositional processes.

The conceptual framework outlined above provides a schematic and an expansion of Hopley's (1982, p.355) conclusion on reef islands:

In the long term, reef islands are merely a temporary store of sediments in a total reef system, a store that may increase or decrease in size according to internal storage characteristics (cementation and vegetation), internal reef factors (changing morphology and reef top smoothness), or completely external factors over which the reef itself has no control (sea level and climatic changes).

Temporal and spatial scales

It is evident from the conceptual framework that there are several time scales involved in the morphodynamic development of islands. In this research three main time frames are used: short-term, medium-term and long-term.

'Short-term' applies to processes and changes that occur from hours to years, and include irregular episodic storm and swell events as well as the seasonal changes in weather and climate associated with the westerly and easterly monsoons. Both storm and seasonal impacts are generally felt on the margins of islands and adjacent reefs. Data on such impacts comes from field observations and measurements as well as from personal reports.

'Medium-term' refers to the decadal to century time scale and may involve regime shifts in some of the atmosphere and ocean boundary conditions that affect coastal processes (as shown in Compartment 1, Figure 1.1). In some circumstances, including this thesis, reef island changes and trends are easier to describe than explain. In the present case the magnitude of changes over a 30-year period, based on two sets of vertical aerial photographs taken in 1969 and 1999 provide one set of data. The other set comes from a comparison of these data with baseline maps and photographs published by Gardiner (1903) and Agassiz (1903) and based on their fieldwork in 1899 and 1901-02 respectively. Results from an

analysis of information over the decade to century time scale can be used to obtain some measures of island stability and instability.

'Long-term' refers to the centennial to millennial time scale, and in the context of this thesis it is concerned with the origin and development of reef islands. Changes in external controls such as sea level, and coastal processes are included within this time frame. Analyses of vegetation and soil distributions together with geomorphic and stratigraphic data are used to infer island development patterns over the last few thousand years. Models derived from such analyses are constrained by radiometric dating.

The time frames described above fit comfortably with the spatial emphasis of the thesis, which is primarily concerned with the 'local scale', although it is important to set the study area within the 'regional scale' context of the Maldives. As defined earlier, the 'local scale' is concerned with the spatial distribution of reef platforms and islands over the atoll as a whole, as well as considering the smaller scale features of individual reef platforms and islands.

1.4 Problems and significance

Reef islands on coral reefs and atolls comprise some of the lowest-lying terrestrial land in the world. They form the only habitable land on atolls and provide a whole range of functions extending over agriculture, water resources, to tourist resorts. They also provide an important part of the coral reef system, as implied in Figure 1.1.

Not only has it been widely suggested that these islands are especially vulnerable to projected sea level rise as result of global warming, but it is also clear that the existing islands are subjected to pronounced changes as a result of episodic events, such as tropical cyclones.

At a time when there is increasing human pressure on reef islands, and there is also considerable uncertainty about their future, a clearer understanding of island morphodynamics could have both direct management applications and longer-term strategic planning benefits. One objective of this thesis is to provide improved understanding of the formation and development of reef islands, their contemporary morphodynamics and future conditions, with specific reference to one atoll in the Maldives.

The Maldives located in the Indian Ocean about 700 km southwest of Sri Lanka, extend from just south of the equator up to about 7° N. They consist of a double chain of atolls either side of an inner sea, tapering to single atolls to the north and south. The archipelago comprises 26 geographical atolls, which in addition to their local names, are identified by a letter from the Greek alphabet, starting from α (Ihavandhippolhu) in the north to ψ (Addu) in the extreme south (Figure 1.2).

There are about 1200 islands scattered throughout the chain. The total population of 260,000 people is dispersed over 200 islands, with nearly 70,000 people in the capital islands of Male' in North Male' Atoll (λ). Eta atoll, the site of this research is located about 70 km northwest of Male' on the western side of the double chain of atolls.

A number of surveyors, naturalists and scientists have visited the Maldives. Captain Moresby carried out the earliest hydrographic survey of the Maldives in the 1830s. The most detailed descriptions of the geography, geology and ecology of the whole group are those of Gardiner (1903, 1931). Agassiz (1903) Sewell (1936a, b) and Scheer (1969, 1971, 1974) have also examined the archipelago, and there are detailed accounts of Addu Atoll (ψ) resulting from an expedition there in 1964 (Stoddart 1966). A list of these visits together with others from the 1830s to 1980 is given in Appendix 1.

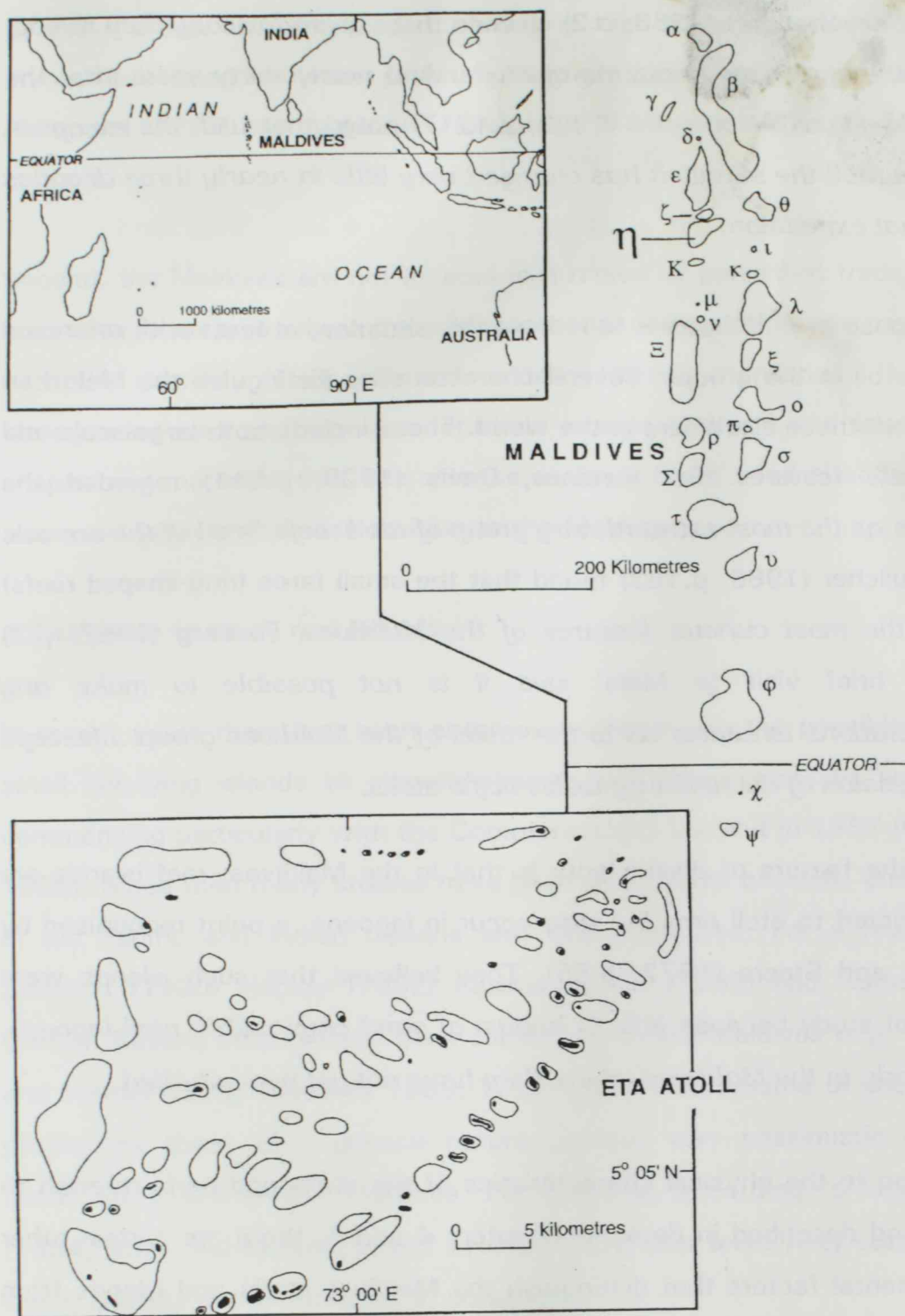


Figure 1.2 Setting of the Maldives in the Indian Ocean (top), and the chain of atolls of the Maldives (right). A close up of the study site, Eta atoll (η) (bottom), including the reef platforms and the islands they carry, is shown in this figure.

In spite of several large expeditions visiting the Maldives in the last 100 years or so, Stoddart (1966, p.2) claimed that *...paradoxically they remain one of the least known groups of atolls*. And nearly thirty years after the 1964 expedition, Woodroffe (1993, p.1217) noted that *with the exception of Addu Atoll the situation has changed very little in nearly three decades since that expedition*.

The purpose of this thesis is to redress this situation, at least with reference to one atoll in the group. Several characteristics distinguish the Maldivian atolls from those elsewhere in the world. These include both large-scale and small-scale features. For instance, Davis (1928, p.511) regarded the Maldives *as the most extraordinary group of atoll reefs in all of the oceans*, while Guilcher (1988, p.163) found that the small faros (ring-shaped reefs) remain *the most curious features of the Maldives*. Fosberg (1957, p.7) after a brief visit to Male' said *it is not possible to make any generalisations whatever as to the atolls of the Maldives group ...(except) an impression of dissimilarity with Pacific atolls*.

One of the factors of dissimilarity is that in the Maldives, reef islands are not restricted to atoll rims but also occur in lagoons, a point recognised by Stoddart and Steers (1977, p.65). They believed that such islands were worthy of study because *little is known of sand cays within atoll lagoons, particularly in the Maldives where they have not yet been studied*.

In addition to the physical characteristics of the atolls and reefs referred to above, and described in detail in Chapters 4 and 5, there are certain other environmental factors that distinguish the Maldives atolls and islands from others. Just two will be mentioned here.

First, the Maldives is not within a tropical cyclone belt, although storms occasionally occur. Whereas many studies of reef island development have

been carried out in cyclone prone areas, few have been undertaken outside of those areas. One implication of this is that the usual models, which invoke atoll island formation *primarily through the action of large storms* as Richmond (1993) has suggested, may need to be reviewed in the Maldives context.

Second, the Maldives are not located in a region of persistent trade winds, but rather in an area where there is a seasonal reversal of winds associated with the westerly (*Hulhagu*) and easterly (*Iruvai*) monsoons. Thus, the strong windward and leeward contrasts in reef platform and island size, shapes and materials that characterise atolls in trade wind situations may also need to be reviewed in relation to the Maldives.

1.5 Urgency to study reef islands

In recent years there has been enormous publicity on the possible fate of small low-lying islands to climate change and consequent sea level rise, commencing particularly with the Commonwealth Summit in 1987 (Gayoom 1998). Since then many studies have been undertaken on atolls and islands in the Pacific and Indian Oceans and Caribbean Sea. For a review see Stoddart (1990) Hopley (1992) Bijlsma *et. al.* (1996) and Nurse *et. al.* (1998). Several studies have been carried out in the Maldives (e.g. Pernetta and Sestini 1989; Edwards 1989; Woodroffe 1989). Some of the studies particularly those of a general nature express very pessimistic outlooks about the future of the Maldives. For instance, according to Leatherman (1994, p.2): *Submergence and erosion (from sea level rise) can convert many islands in the Maldives to sandbars.*

More recently, the Intergovernmental Panel on Climate Change (IPCC) has prepared two reports that include comments on atolls and reef islands. In the first, Bijlsma *et. al.* (1996, p.302) commented that:

Although recent reviews on coral islands have emphasised their vulnerability and resilience such islands remain among the most sensitive environments to long-term climatic change and sea level rise.

And in the second, Nurse *et. al.* (1998, p.346) note that *...the response of islands to the impacts of climate changes will vary within regions and even within countries. Islands are not passive systems; they will respond dynamically in variable and complex ways to sea level and climate changes. For example, the extent to which relative sea level rise will affect coastal recession rates will depend on many factors, including the rate of sediment supply relative to submergence; the width of existing fringing reefs; the rate of reef growth; whether islands are anchored to emergent rock platforms; whether the islands are composed of sand or rubble; the presence or absence of natural shore protection structures, such as beachrock or conglomerate outcrops; the presence of biotic protection, such as mangroves or other strand vegetation; the health of coral reefs; and, the tectonic history of the island.*

Several of the factors in the above quotation will be addressed in this thesis.

Finally it is important to recognise the need for detailed study of particular areas because as Woodroffe and McLean (1993, p.69) have stated:

...rarely in atoll environments is there sufficient understanding of contemporary process regimes or of retrospective change to provide a firm basis for prospective evaluation.

Accordingly, there is a need not only to know about the present morphology and dynamics of reef islands, but also about their past evolution and recent trends. This knowledge is essential if the perspectives of reef islands, like those in the Maldives, are to be seriously discussed under the projected climate change and sea level rise scenarios. The urgency for such studies has been recognised in the Maldives by President Gayoom and expressed in a series of addresses including those to the Commonwealth Heads of Government Meeting in Vancouver and the United Nations General Assembly in October 1987. These together with other addresses over the last decade have recently been published under the title: *The Maldives: A Nation in Peril* (Gayoom 1998).

1.6 Aims and Objectives:

The broad aim of this thesis is to examine the geomorphology of uninhabited reef islands of Eta atoll, and to suggest models of their development, based on that examination.

The conceptual framework together with the issues raised above suggests there are several fundamental questions that need to be answered.

- What are the physical characteristics of the islands and how are they related to environmental and geographical factors?
- How did the reef islands initially form and when did they originate?
- How have the islands developed through time and what changes are taking place at the present time?

The specific objectives of the study are therefore:

- 1) To describe the geomorphic characteristics of the islands in Eta atoll, (Maldives) and to relate those characteristics to the nature of the underlying reef platform, and to identify any spatial patterns in island and reef platform characteristics around the atoll.
- 2) To establish the mechanism(s) of island initiation and the approximate age of island formation.
- 3) To identify island growth and development patterns over the long-term (centennial to millennial time scales) and to examine the extent and magnitude of changes that occur on islands over the medium-term (decadal to century time scale) and short-term (yearly and episodic event scale).
- 4) To outline possible applications of the findings for: (a) vulnerability assessment studies; (b) management and strategic planning purposes; and (c) future research.

To address the questions raised above and achieve the specific objectives, a step-wise approach is followed, which includes analyses of:

- The geographic and morphometric characteristics of the reef platforms and islands, and the geologic and geomorphic characteristics of the islands;
- The short-term morphodynamic changes that occur on the islands, including regular seasonal changes and irregular unusual/episodic events, based on field measurements, observations and historical data;
- The medium-term (decades to century) changes evident on the islands based on sequential aerial photographs and historical data;
- The long-term (century to millennia) morphodynamic changes of the islands based on the pattern of vegetation distribution and soil depth, together with radiometrically dated samples to establish a geochronology of reef island development in Eta atoll.

1.7 Thesis outline

This chapter has introduced the thesis problem by highlighting the necessity to acquire a comprehensive understanding of the geomorphological development of reef islands and the urgency with which this should be done in the Maldives. It has also identified some of the differences between atolls and islands in the Maldives and those elsewhere in the Pacific and Indian Oceans, as well as identifying some of the differences in the environmental conditions including climatic conditions that affect the Maldives. The conceptual framework which guides this study and the aims and objectives of the research have also been presented. An outline of the thesis structure, which follows the research design, is shown in Figure 1.3.

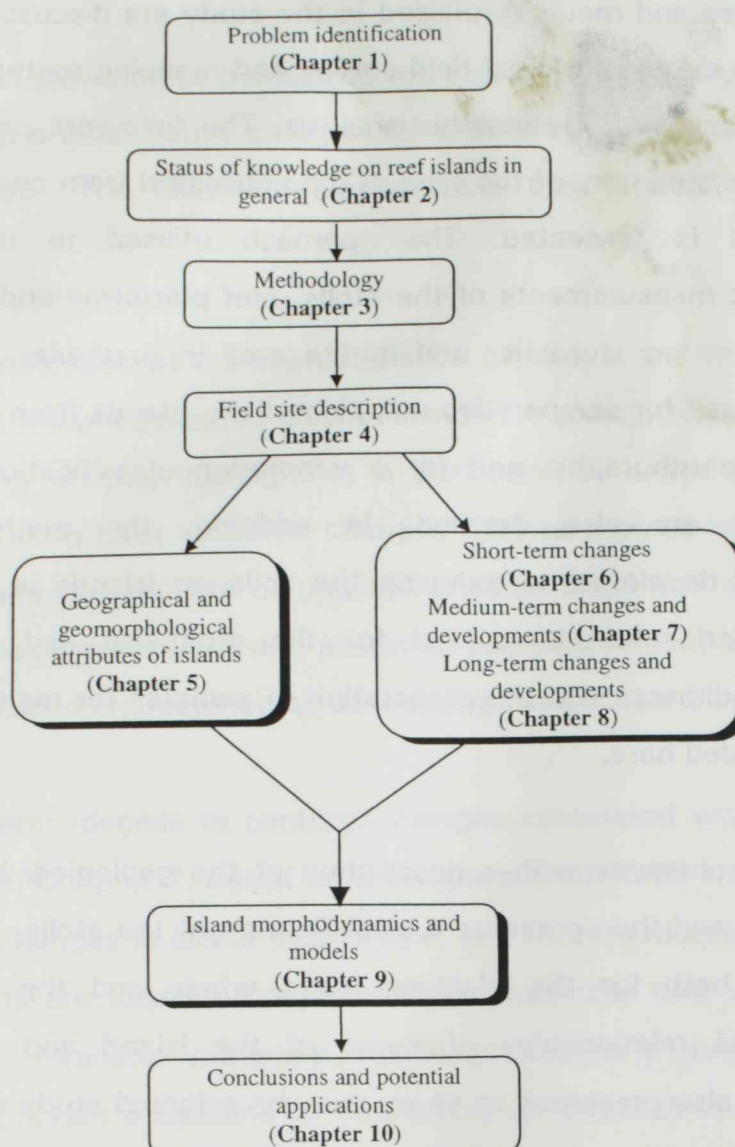


Figure 1.3 Flow diagram of thesis structure

Chapter 2 provides a review and synthesis of relevant studies on reef island development and morphodynamics. It summarises several models of island development and theories on the mechanisms by which islands can be initiated. Following this, the processes that result in island growth and change, and the processes that serve to stabilise island margins and surfaces are reviewed. The chapter concludes with a discussion on the concepts of 'equilibrium' which have recently been developed or applied to reef islands.

The techniques and methods utilised in the study are discussed in Chapter 3. These include conventional field survey and mapping methods, sediment sampling, coring and stratigraphic analysis. The fieldwork program is also outlined and a summary of the type of data collected from nearly 50 islands on Eta atoll is presented. The approach utilised to undertake the morphometric measurements of the atolls, reef platforms and islands, both in the Maldives as a whole, and in Eta atoll in particular are indicated. Techniques used for comparative mapping of the islands from the 1969 and 1999 aerial photographs, and for a vegetation classification of a 1988 SPOT image are also detailed. In addition, the methodology and nomenclature developed to examine the soils on islands is outlined. The techniques and methods utilised for the grain-size and compositional analysis of sediments and the preparation of samples for radiometric dating are also provided here.

Chapter 4 commences with a description of the geological background of the Maldives, and then presents a classification of the atolls, reef platforms and islands, both for the Maldives as a whole and the study site in particular. The relationships of some of the island and reef platform attributes are also presented to show that the selected study area (Eta atoll) is representative of the typical 'open-atoll' in the Maldives. The setting of Eta atoll within the context of the Maldives is also demonstrated through a discussion of the north-south latitudinal gradients in some environmental and morphological factors. Relevant climatic and hydrographic information for Eta atoll is also presented.

Chapter 5 provides a more substantial examination of the geographic, geomorphic and geologic characteristics of the islands and reef platforms of Eta atoll, and explores some of the interrelationships between reef platform and island characteristics, such as size, shape, and position. The sediment characteristics of both unconsolidated and lithified materials, and the

topography and elevation of the islands are also identified here. The chapter concludes with a quantitative categorisation of island shape and size using Cluster Analysis. The identified clusters and their spatial patterns are discussed.

Following identification of the characteristics of islands and reef platforms, the associated morphodynamics of the islands are presented in Chapters 6, 7 and 8, each chapter highlighting a particular time scale. Chapter 6 examines the short-term seasonal changes that take place on the islands over a year, and the impacts of unusual/episodic swell and storm events. The types of seasonal erosion and accretion patterns evident on the islands are related to island characteristics, as identified in Chapter 5.

The medium-term (decade to century) changes associated with the islands are examined in Chapter 7. Based on a comparison of 1969 and 1999 aerial photographs, changes in island size, shape, and other noticeable aspects of selected islands are examined here. In many instances nett changes have been minimal. Available materials including Gardiner's descriptions and sketch maps provide a baseline of conditions on Eta atoll in 1899. These are analysed to identify the type, extent and pattern of changes over a 100-year period for a few islands.

Following on from the identification of the short- and medium-term changes, Chapter 8 investigates the long-term developments of the islands, from their initial formation. Evidence of how the islands have evolved is provided by an examination of the vegetation patterns and soil development. These data provide a relative chronology of the island growth, which is supplemented by radiocarbon dating of island sediments to establish an absolute time-scale of island development. The main phases of island building, including the main modes of island growth are also identified and discussed here.

Chapter 9 provides a review of reef island morphodynamics and models based on the evidences presented in previous chapters. It examines four mechanisms of island formation and identifies those that are appropriate for Eta atoll. It then proposes some models of island growth and development, the latter including island movements and erosion operating over the long-term. Following this, the notion of decadal scale island stability and instability is developed which forms an introduction to a consideration of the concept of 'equilibrium'. The phases of reef island equilibrium are described and examples from Eta atoll discussed.

The major findings of the study are presented in Chapter 10. These are addressed with regard to the four specific aims identified earlier in this chapter (p.15). Conclusions relating to the morphometric, geomorphic, geologic and geographic characteristics of the islands are first highlighted. Aspects of formation and development of the islands are then summarised. The relevance of these findings to two significant applications is then detailed. One identifies some of the attributes that need to be taken into account in any vulnerability assessment of reef islands to climate change and sea level rise. The second indicates those conclusions that have particular application to island management and strategic planning. Finally, a number of outstanding issues that emerge from this study on reef island morphodynamics are raised and some future research studies suggested.

CHAPTER 2

Formation and development of reef islands: Review and analysis

2.1 Introduction

This chapter reviews some of the literature on the characteristics and morphodynamics of reef islands. In particular, it discusses the main processes of island formation and subsequent change, first, emphasising island initiation and growth over the long-term, and then changes that can take place over the medium-term and short-terms. The processes that seek to stabilise island surfaces and margins such as vegetation growth, soil development and beachrock formation are also discussed. The presence or absence and location and extent of such features are later used to give an indication of island stability and instability. This serves as an introduction to the final part of the chapter, which comprises a review of 'equilibrium' concepts, which have recently been developed or applied to reef islands. However, the chapter begins with a brief discussion on the classification of reef islands, which serve to demonstrate the great variations in reef island characteristics.

It should be noted that this review is a selective one and deals only with references felt important to the themes of this thesis. Other references are included in appropriate sections of the substantive chapters. It should also be recognised that the literature on reef islands is nowhere near as voluminous as that on reefs to which the islands are so intimately connected.

2.2 Definition and classification of reef islands

Although reef islands can be defined as morphologically coherent accumulations of biogenic sediments that form on top of sea level reef platforms and are emergent at high tide, the size, shape, morphology and detailed characteristics of reef islands vary enormously.

As a result there have been several attempts at classifying reef islands, which Nunn (1994) groups together as 'low coral islands'. Stoddart and Steers (1977) provided a comprehensive review of reef islands classification up to that time. They dealt specifically with those of Spender (1930) and Fairbridge (1950) before presenting a classification of their own which included seven classes based on morphology and sediment character as the main criteria with vegetation a secondary criteria.

These criteria together with the number of islands on reef tops and their degree of complexity were later used by Hopley (1982) to develop a division of reef island types for Australia's Great Barrier Reef. Four types were identified:

- A. Unvegetated Solitary Islands
 - 1. Linear sand cays
 - 2. Linear shingle cays
 - 3. Compact sand cays
 - 4. Compact shingle cays.
- B. Vegetated Solitary Islands
 - 1. Sand cays
 - 2. Mixed sand and shingle cays
 - 3. Shingle cays
 - 4. Mangrove cays.
- C. Multiple Islands.
- D. Complex Low Wooded Islands.

A more recent classification by Richmond (1993, p.1185) which refers specifically to islets on atolls in the Central Pacific recognised *four types of islets based on morphology, sediment and rock characteristics, and position on the reef rim*, as follows:

Type I islets are analogous to sand cays and occur primarily adjacent to reef passages on the leeward rim and, more rarely, atop lagoon patch reefs.

Type II islets are typically U-to boomerang-shaped and develop on high energy complex bends of the atoll rim.

Type III islets are narrow, elongated, gently curved to sinuous in plan-shape, and are composed primarily of several parallel ridges which are often separated by a central depression.

Type IV islets are complex landforms developed around cemented rubble and reef flat deposits.

Both of these classifications are relevant in the present context as the criteria applied by Hopley (1982) are similar to those used to classify islands in the Maldives, while that of Richmond (1993) deals specifically with atolls and helps to distinguish between atoll islands in the Central Pacific and those in the Maldives.

But missing from the criteria of these two classifications are two important factors. First, the location of islands with respect to the atoll and not just the island's position on the reef platform. And second the nature of the reef platform on which the island(s) is(are) located. After studying islands in the Maldives Woodroffe (1993) introduced the notion of '*peripheral*' and '*lagoonal*' islands, a distinction which has significance in the context of this thesis. Implied is an energy-related factor suggesting that different processes operate on islands on the atoll periphery to those located inside the atoll. Woodroffe (1993) also distinguishes islands on patch reefs from those on faros. Both of these aspects are significant in the Maldives and figure in the classifications developed in Chapter 4.

2.3 Origin and formation of reef islands

Although there is great variation in the nature and characteristics of reef islands, it appears that the islands are all geologically young (mid to late Holocene in age) and the sequence of events leading to their formation is generally comparable.

2.3.1 Models of island formation

Based on data from the Cocos (Keeling) Islands, McLean and Woodroffe (1994) proposed a three stage model relating sea level change to reef growth, reef flat formation and island formation (Figure 2.1a). In the case of Cocos the first stage from about 8000 to 4500 years BP was a phase of rapid vertical reef growth as the reefs strived to 'catch-up' with a rapidly rising sea level. The second phase from about 4500 to 3000 years BP was a phase of reef flat formation as reefs caught up with sea level and consolidated. And the third phase starting around 3500 years ago and continuing to the present was a phase of reef island formation.

While this model appeared applicable to many atolls including the atoll of Tarawa in Kiribati, McLean and Woodroffe (1994) also noted that the rates of upward reef growth could vary between and within atolls and that this variation is likely to have ramifications for the absolute timing of stage two and three. In fact they suggested that lags in all three stages could be expected and cited the case of Funafuti atoll where reef upgrowth, reef flat formation and island development all lagged behind those for Cocos. In this case all 21 samples from island deposits around the atoll that were radiocarbon dated had conventional ages of less than 2000 years B.P.

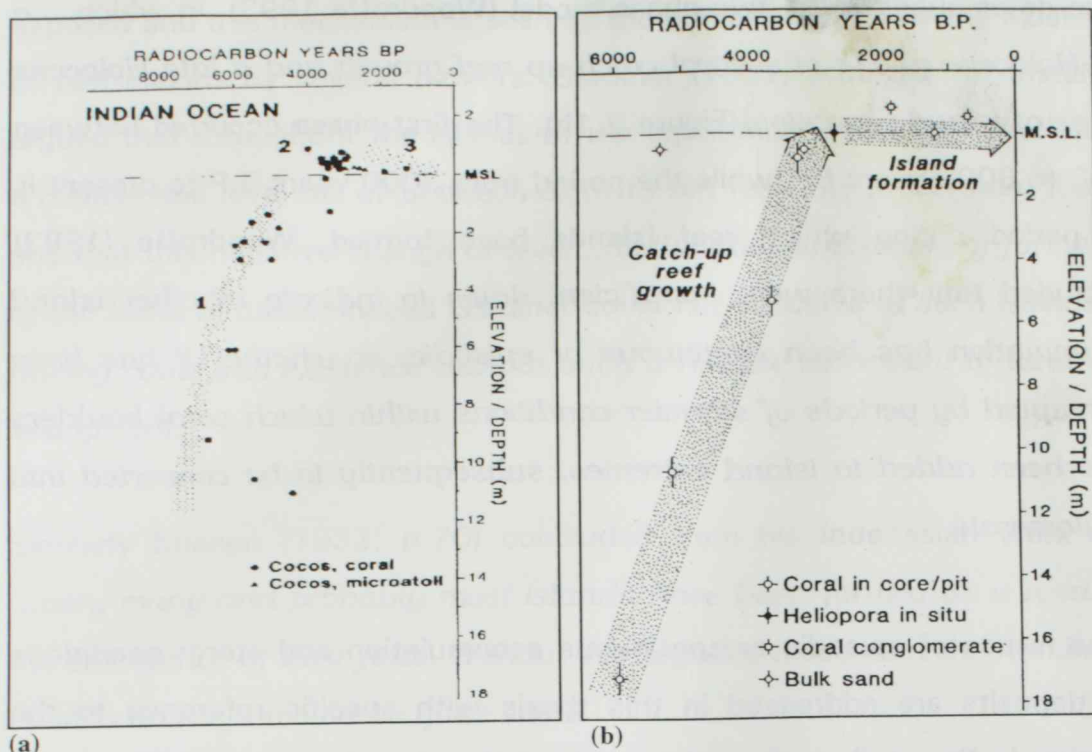


Figure 2.1 (a) Age-depth plot of radiocarbon dates from the Cocos (Keeling) Island, showing the three-phases of Holocene development (source: McLean and Woodroffe 1994, p. 281). (b) Age-depth plot of radiocarbon dates from the Maldives. The data show a phase of vertical catch-up reef growth followed by phase of island building, based on island sediment data obtained from the southern atolls, and reef growth data from Male' (Source: Woodroffe (1993, p. 1223).

Whether there is a lag between stages two and three of the above model appears to depend on local circumstances. Whereas Hopley (1982, p.317) suggested *...a cay may form as soon as there is sufficient area on a reef flat*, Chivas *et. al.* (1986) believed that in the case of Lady Elliot Island the southern-most island on the Great Barrier Reef, there was a gap in island building until 3200 year B.P, even though the reef platform was believed to have existed for at least 6500 years. Chivas *et. al.* (1986) concluded that island growth would not commence on reef platforms until the reef is sufficiently established by coral growth and sedimentation to provide a foundation close to sea level.

As for the Maldives, only limited radiocarbon datings of islands and reef materials have been available up to the present time. An age-depth plot of these dates suggested a two-phase model (Woodroffe 1993), in which ...a *mid-Holocene phase of vertical catch-up reef growth and a late Holocene phase of island formation* (Figure 2.1b). The first phase occurred between 6000 to 3000 years BP, while the period from 3000 years B.P to present is the period during which reef islands have formed. Woodroffe (1993) concluded that there were *insufficient dates to indicate whether island accumulation has been continuous or episodic; or whether it has been interrupted by periods of stormier conditions within which coral boulders have been added to island extremes, subsequently to be converted into conglomerate.*

These issues of episodic or continuous accumulation and storm conditions and deposits are addressed in this thesis with specific reference to the situation in Eta atoll, well to the north of the sites from which Woodroffe (1993) obtained his samples for radiometric dating.

2.3.2 Mechanisms promoting island initiation

Several theories on the mechanisms of reef island initiation have been suggested. Four will be discussed here. The first two involve sea level–reef platform interactions in the Mid-Holocene with island initiation either resulting from a fall in sea level; or as a response to the operation of a high energy 'window'. The second two do not invoke any change in sea level or reef platform level but rather emphasise the accumulation of sediments under present conditions either at a nodal point related to prevailing wave conditions or to the accumulation of sediments resulting from cyclone or storm wave activity.

Fall in sea level

As sea level falls, accumulated sediments on reef platforms may become exposed and this mechanism is seen as the primary reason for the existence of reef islands by several authors. Gardiner (1931, p.35-36) for instance, argued that throughout the islands of the equatorial belt of the Indo-Pacific a relative sea level fall of between eight to ten feet *...is universally found*, and that this negative change of level *...is the dominant cause of formation of the islets of atolls*. Indeed Gardiner could not conceive of such islands as *having come into existence without such a relative movement of land and sea* (p. 36).

Similarly Kuenen (1933, p.70) concluded from his Indonesian work that *...very many and probably most islands have been formed as a result of the emergence of their flats. Without the negative movement the number of islands on reefs would be quite small*.

Support for such an explanation has been widespread. In the Gilbert and Ellice Islands (now Kiribati and Tuvalu) Schofield (1977, p.531) suggested that *...a net fall of 2.4m since 2760 years B.P has been of major importance in reef and atoll islet growth*. As a result he believed that the *...islets have been built from sand taken from the shallow margins of the lagoonal floor as a direct result of this fall*.

On the Great Barrier Reef, sea level fall is seen as one of the main mechanisms of island accumulation though a fall in sea level *...while not mandatory for the accumulation of sediment masses, it is certainly a highly influential factor* (Hopley 1982, p.354-355). However, on Cocos (Keeling) Islands where there is good evidence for a sea level higher than present, Woodroffe *et. al.* (1999, p.85) suggests that the fall of sea level *...appears to have had little effect on the pattern of island accretion*.

In this thesis evidence for island formation as a result of a higher sea level relative to present is examined for Eta atoll in Chapter 9.

High energy 'window'

A concept of a high energy 'window' acting locally on reef platforms was initially proposed by Neumann (1972) who suggested that while some reefs were growing to catch up with sea level, their protective role would have been reduced and higher energy would have acted on certain reef platforms in their lee.

Once this 'window' was closed as reef platforms reached to sea level, energy levels would be reduced on leeward reefs. Thus, theoretically the high energy 'window' was able to initially promote coral rubble and boulder deposition on the more exposed side of inner reef platforms, while the 'window' was open, changing to sand deposition with closure of the 'window' and the consequent reduction in energy.

This concept has been applied to the cays on the inner shelf lagoon west of the ribbon reefs of the Great Barrier Reef. In this situation McLean and Stoddart (1978) argued that the cays formed once the level of reef tops and sea level coincided at about 5000 years B.P.

However, Hopley (1982,1984) considers that the existence of a high energy 'window' (when outer barrier reef was not quite at sea level) may have given less protection to the inner shelf reefs on which the oldest islands are located. This may have been an important factor at an early stage, although he shows that the radiocarbon ages from the ribbon reefs indicate that the outer reef did not lag behind the nearshore reefs on the northern Great Barrier Reef, though the high energy 'window' may have operated at a local scale.

Nodal accumulation

Wave diffraction and refraction on and around reef platforms has been identified as an important mechanism of island development, where sediment deposition is concentrated in a nodal region; this is generally located towards the leeward side of the reef platform.

Flood (1986, p.13) summarised the process this way:

Wind-induced waves, which break on the reef rim, refract around the reef and reform as smaller waves, which travel across the reef top. The pattern of refracted waves tends to converge towards the leeward side of the reef top and where the energy of the waves is least (the nodal point) sediment is deposited and builds the cay.

Figure 2.2 illustrates the basic processes. The shape of reef platform has a very important influence on the shape, position and stability of the cay and Gourlay (1990) has suggested that lens-shaped reefs produce more stable leeward islands compared with islands on circular reefs (see Figure 2.3) though Hopley (1982) has also shown that deposition from wave convergence can take place 'along the centre of the reef', and not just on the leeward side.

Hopley also makes two further points. First, that reef island formation requires a ready supply of biogenic sediments, and second, that in addition to wave convergence the ability of the waves to transport sediment is a prerequisite for island formation. Where waves do not have the competency to transport the available sediment (such as across large reefs) islands may not form. Thus, on the Great Barrier Reef at least ...*leeward sand cays thus form where there is a tendency for both a centripetal convergence of refracted waves and sufficient power to transport sand-sized sediment to this focal point* (Hopley 1982, p.318).

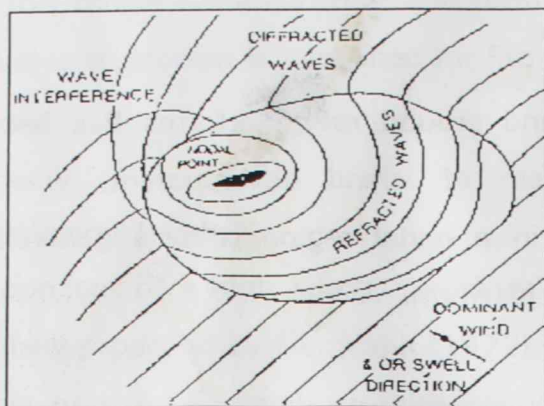
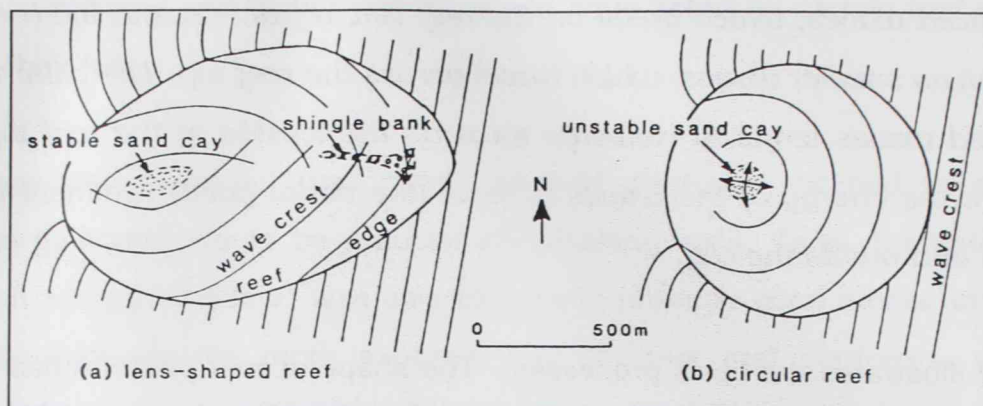


Figure 2.2 Reef island formation processes. Outline of reef platform shown in heavy line; island shown in stipple with stable vegetated portion in black (From: Flood 1986, Figure 2).



Figures 2.3 Influence of reef platform shape on location and shape of islands. Lens-shaped reefs (a) produce more stable leeward islands, compared with islands on circular reefs (b) where the focal zone readily shifts with changes in wave direction and wave period (From: Gourlay 1988, p.493).

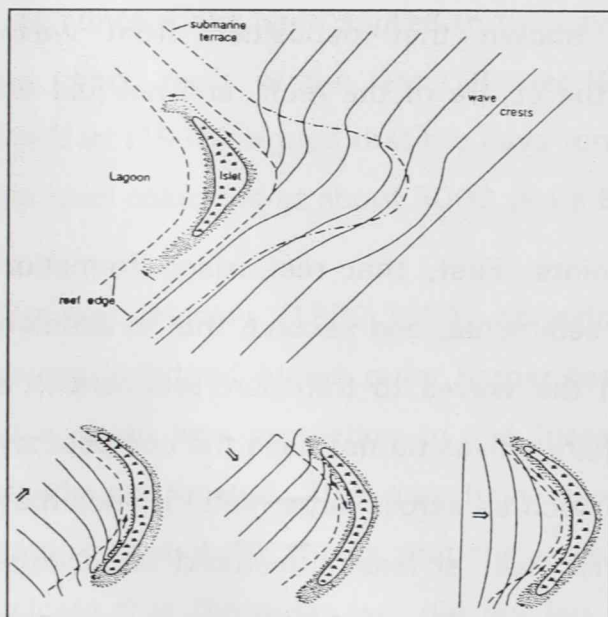


Figure 2.4 Schematic diagram illustrating wave effects on boomerang-shaped islets on atoll rim. In the top diagram a submarine terrace and sharp convex-seaward bend in the reef combine to refract ocean swell causing convergence at the bend (single arrow depict longshore transport directions). The lower sketches depict three different directions of lagoon generated waves where longshore drift is reduced near the apex of the bend resulting in deposition (double arrows indicate direction of lagoon wave approach). (From: Richmond 1993, Figure 7).

In another case relating reef platform shape and wave refraction Richmond (1993) showed the formation of 'boomerang-shaped' islands (Type II) at convex-seaward bends, on atolls as illustrated in Figure 2.4.

These examples relate specifically to the interaction of unidirectional waves on reef platforms, which are typical of trade wind situations. In the Maldives, where reversals in the monsoonal winds cause changes in wave directions, it can be expected that the position of nodal accumulation would be more variable and that island morphodynamics would reflect this bidirectionality.

Tropical cyclones and storms

A number of studies have identified the role of storms as being important in island formation. Gourlay (1988, p.494) suggested with reference to the Great Barrier Reef that *...extreme events such as cyclones may initiate the formation of a cay.*

In the Central Pacific, Richmond (1993, p.1185) has shown that atoll islets *...are composed mostly of storm-derived carbonate debris from adjacent reefs.* He goes on to say that atoll islets *...begin as a product of catastrophic storms and remain precariously balanced between the destructive forces of wave, currents, bioerosion and chemical dissolution and the constructive effort of reef-produced calcium carbonate sediments.* While catastrophic storms can have a constructive effect on reef islands, and the rubble bank formed during Cyclone Bebe (October 1972) on Funafuti atoll in Tuvalu is often cited as an example (Baines and McLean 1976), they can also have a destructive effect. As Bayliss-Smith (1988, p.389) has shown in the case of the atoll of Ontong-Java in the Solomon Islands, *...a hurricane tends to erode existing islands but at the same time produces the material for their reconstruction.*

Synopsis

The foregoing review has separated out four possible mechanisms of reef island initiation though in most cases authors accept that they do not operate exclusively. Each of these mechanisms will be evaluated in the context of Eta atoll, recognising that the environmental setting of the Maldives differs from most other reef areas cited here. For instance, most previous studies have been undertaken in trade wind locations where there are unidirectional waves on reef platforms and distinct windward and leeward sides. Moreover, the islands discussed have frequently been located in areas subjected to tropical cyclones. Whether the models developed in these situations are equally applicable to the Maldives, where winds and wave activity reverses seasonally with the monsoons and in a region outside the recognised belt for tropical cyclone generation, is considered later in this study.

2.4 Island growth and development

2.4.1 Processes and examples

The material that goes to make up reef islands comprises bioclastic sediments derived from the breakdown of calcareous organisms on adjacent reef platforms. Two broad sizes of skeletal materials are often produced, clasts of coral gravel, rubble and boulders, and sand-sized material comprising a range of taxa including coralline algae, molluscs, foraminifera, sponges, crustaceans, echinoids and hard and soft corals.

In the long-term provided there is a steady supply of sediments, a favourable base for the accumulation of the sediments, and waves competent to transport the available sediment, there is the potential for reef island growth.

For instance, with reference to Onotoa atoll in Kiribati, Cloud (1952, p.49) suggested that, *an island should continue to grow in width as long as there is a base for it to spread lagoonward on and a supply of sediment for building*. If that happened it is possible, as Spender (1930, p.290) suggested for the reefs in Bay of Batavia that they *were developing towards an easily defined final form*, and that here the cay was growing to cover the entire reef. These quotations raise a question: Is there an optimal size that an island can grow to on a reef platform?

On occasions more than one island develops on a reef. For the Australian continental shelf Fairbridge (1967) outlined an evolutionary sequence of coral island development involving more than one island. Commencing with a simple unstable sand cay on a reef flat to leeward (Type I) the cay is stabilised through vegetation establishment (Type II). To windward a shingle cay with or without vegetation forms (Type III). Type IV has several features; the sand cay itself, shingle spits on the lee of the reef platform, and shingle ramparts both old and new to windward. A mangrove swamp develops between the sand cay and shingle ramparts. Type V is termed 'coral island', which occupies a much larger proportion of the reef platform, with complex geomorphological developments such as two-tier terrace developments, shingle beach ridges, karst surface, and sand dunes.

In this model a fall in sea level takes place between Types IV and V. This evolutionary model of a 'coral island' (Type V) deals with several kinds of reef islands on the same reef platform, a situation that is quite unusual on Eta atoll. More commonly solitary islands occur there.

Once islands have been initiated, their mode of growth can vary. Concentric growth, lagoonwards growth, seaward growth and growth in both lagoonward and seaward directions have been reported.

Chivas *et. al.* (1986) have provided details of the concentric growth of rubble ridges at Lady Elliot Island on the southern Great Barrier Reef. This island began accumulating about 3200 years ago and has expanded gradually since then. A slight asymmetry in the pattern of concentric growth is illustrated by the arrangement of ridges. The island now occupies about 30% of the reef platform area.

Another example of concentric growth, this time on sand islets is given by Richmond (1993, p.1189). He cites examples from the western side of Funafuti atoll, Tuvalu, where *...Islet positioning on the reef platform represents a long-term centre of depositional equilibrium where sediments from adjacent reefs, both leeward and windward contribute to concentric growth. Because such islets develop at the confluence of multiple wave/current directions they develop a concentric beach ridge pattern.*

Two types of lagoonward growth have been described from reef islands. The first is where extension takes place to the lee of an initial island core in the manner illustrated in Figure 2.4. The second type is where the island migrates lagoonward as result of erosion to seaward. Exposure of relict beachrock on seaward shores of reef islands have been used as indicators of such lagoonward migration, for instance by McKee (1959) at Kapingamarangi atoll in the Federated States of Micronesia.

Evidence of seaward island-building as a result of repeated cyclones has been presented by McLean (1974) for Funafuti atoll, while the accumulation and island extension oceanward on West Island in the Cocos (Keeling) Islands has been recently been described (Woodroffe *et. al.* 1999).

In the case of West Island detailed levelling, stratigraphic analysis and radiocarbon dating have shown that the island has been accumulating for most of the past 3500 years. The central part of West Island appears to

have formed first, with oceanward accretion up until about 2000 years B.P. Since then, they suggest, that gradual oceanward accretion with lesser lagoonward extension has continued in the last 2000 years, with the island extending laterally to the south with a sequence of lagoonward recurving spits.

Clearly in the case of West Island oceanward extension has not been the sole form of island growth but has been accompanied by lagoonward and lateral growth.

2.4.2 Models of reef island evolution

The above examples demonstrate that there are a number of ways in which reef islands can develop. Woodroffe *et. al.* (1999) have provided a comprehensive review of atoll reef-island formation and response to sea level change and have proposed a series of possible alternatives of the ways in which reef islands may have developed in the last 3000-4000 years. These alternatives are illustrated in cross-section in Figure 2.5, which includes an extended caption summarising the possible modes of island growth and development.

2.5 Post-island formation processes

Once a reef island is formed there are a number of processes that can stabilise its surface and margins. Both biological and physico-chemical processes are involved, including vegetation colonisation, soil development, beachrock and phosphate rock formation. The results of these processes can also provide evidence on reef island change and development.

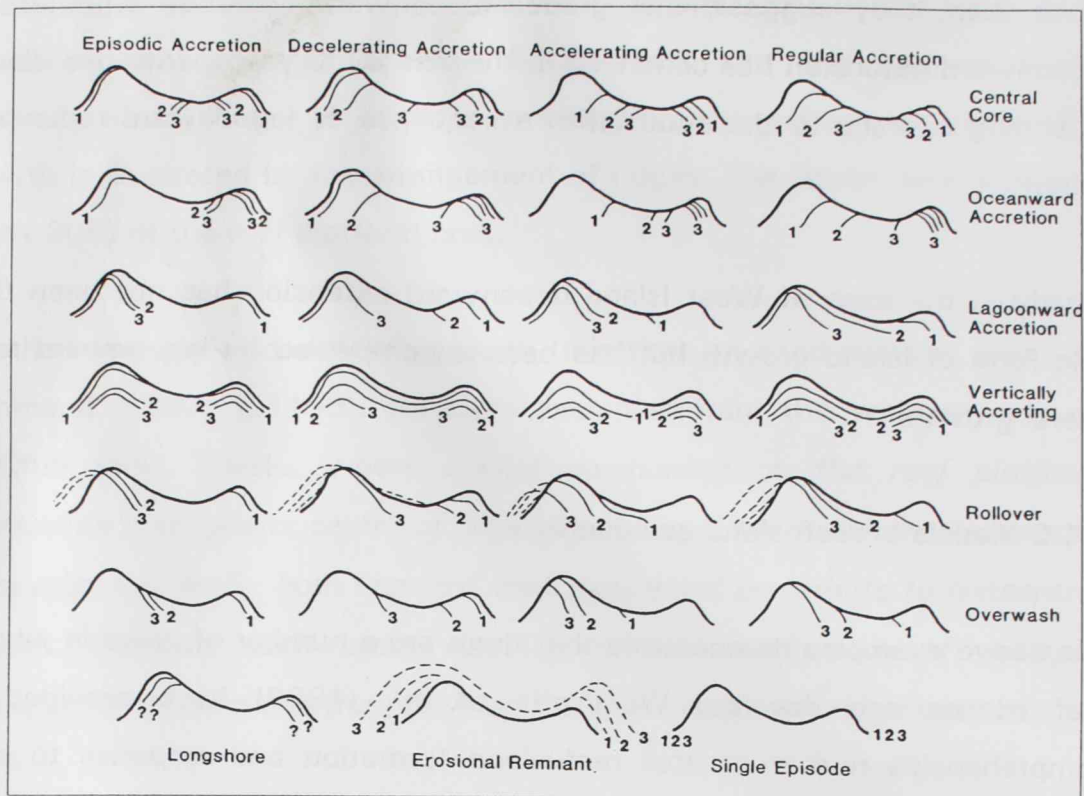


Figure 2.5 Models of island evolution. Schematic scenarios of reef island accumulation indicated by isochrons of deposition in thousands of years. Oceanward shore to left; lagoonward to right. (From Woodroffe *et al.*, 1999, p.88).

In this diagram the first four scenarios infer gradual deposition over the last 3000 to 4000 years, but differ in the rate of accretion with time as suggested by the headings along the top of the diagram. An island may have been characterised by regular accretion, with little change in the volume of accumulation and hence rate of progradation. Alternatively it may have experienced accelerating accretion, decelerating accretion, or episodic accretion with a distinct phase of more rapid build-up separated by slower build up or erosion.

Several different modes of accretion can be envisaged and these are identified on the right hand side. For instance, the island might initiate as a central core, with subsequent accretion to oceanward and to lagoonward. Alternatively the island might be dominated by oceanward accretion or lagoonward accretion. In these three scenarios the dominant mode of accretion is horizontal, but an alternative is that the island can build up through vertical accretion, with gradual addition of sediment over the entire island surface.

As shown in the last three rows, reef islands may undergo a process of rollover, with erosion on the oceanward shore, and deposition of that sediment on the lagoonward shore, and migration into the lagoon. A similar effect may occur through overwash, though in this case the sediment transported is likely to comprise new sediment rather than that eroded from the island.

Rather than the incremental changes through time envisaged in the above scenarios an island might have been formed by a single episode of deposition with little or no subsequent change in island morphology. Another alternative is that an island represents an erosional remnant, being the nucleus of a once bigger island. It may be that such cross-island analysis is inappropriate because longshore sediment movement may dominate, and particular parts of an island may vary in age substantially along the length of its shoreline.

2.5.1 Island surfaces

Vegetation succession

Vegetation provides some stability to islands by helping to cover and bind the loose unconsolidated sediments that initially form islands. Vegetation succession begins with seeds brought by wind, sea and birds (Stoddart and Steers 1977). Initial colonising of substrate by plant species may be slow at the start but the numbers then increase rapidly and logarithmically, before stabilising.

While attempts have been made to relate vegetation distribution to stages in development of vegetation on new islands, Stoddart (1962), remarked that the succession in space is also a succession in time and this is a concept used in the present thesis. That is that spatial patterns may represent chronological sequences (Fosberg 1976). In fact, Stoddart *et al.* (1978a) used vegetation patterns to identify changes on reef islands in the northern Great Barrier Reef province, and indicated that vegetation was influenced by the stage in island development and vice-versa.

There have been many studies of reef island vegetation, including taxonomic studies and those used to test the theory of island biogeography. From such studies two things are clear. First, that there is a limited number of vegetation types on reef islands, and second that those types are surprisingly similar throughout the reef world, though they may be given different names locally.

Thus, in the Caribbean on British Honduran (Belize) islands Stoddart (1962) classified the vegetation as: *strand plants, marginal thicket and interior thicket*. And on reef islands on the Great Barrier Reef, Heatwole (1976) distinguished *strand vegetation*: (sparse ground layer of a mixture of

grasses, vines, succulents and herbs), *herb flat*: (a low vegetation of dense cover, consisting of strand vegetation, and a variety of other herbs, grasses, and small woody plants), *shrubs and shrub ring*: (a ring of tall shrubs or trees around the periphery between strand vegetation and herb flat or forest), and *forest*: (which occurs on most heavily-vegetated islands with groves of *Pandanus*, or *Pisonia*).

These two examples, together with others from the Maldives (see Chapter 4) are sufficient to provide some validity to the development of an 'ideal' model of vegetation succession on reef islands as suggested by Gray (1993) and shown in Figure 2.6. This vegetation succession represented from an island cross-section is shown in Figure 2.7. Such a model has been applied to reef islands in Eta atoll and the successional stages used as criteria for relative stability and age of reef islands there (Chapter 8). The link between vegetation and soils has been noted by Gardiner (1931, p.30): *...the islets of atolls have a vegetation arranged in zones in relation to their subsoils.*

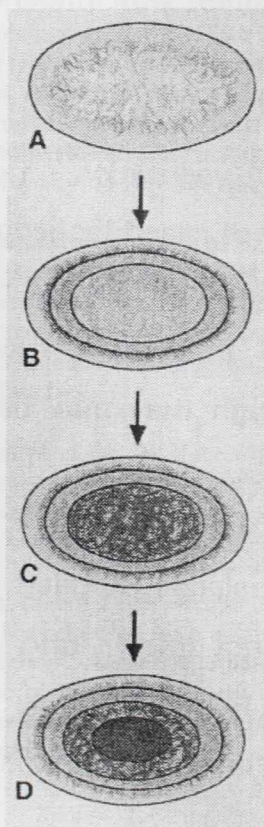


Figure 2.6. Four main stages in the development of plant life on a coral cay. An island of bare sand is colonised by low-lying pioneer grasses and vines (A). Dunes, which form around the edge of the island, are crowned by a ring of shrubs (B) which shelter the interior and provide suitable conditions for the growth of a woodland (C). Eventually the woodland begins to be displaced by a central forest (D) (From: Gray 1993, p.63).

(N.B. For legend see the following figure (Figure 2.7)).

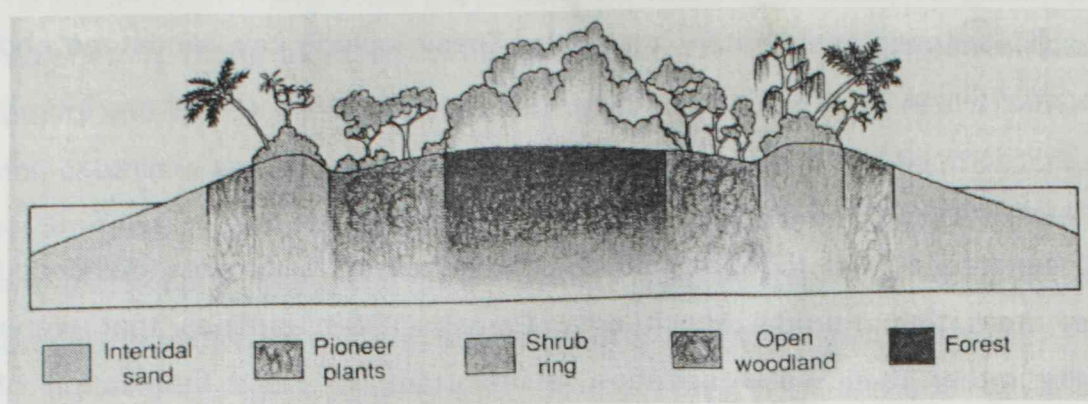


Figure 2.7 Vegetation zonation on a cross-section through a mature sand cay (From: Gray 1993, p. 63). This simple model shows that a central forest area is located in the interior of the island, with open woodland on either side of it. Shorewards of the open woodland, shrub rings occur seawards of which are pioneering plants. Intertidal sand occurs on the outside. This diagram represents increasing maturity from the beach towards the interior of an island.

Soil development

In order to investigate soil development on reef islands and to be able to use this criteria for interpreting island development, a suitable soil survey method had to be identified, appropriate for making comparisons with different parts of individual islands.

Since reef islands are relatively young compared to most other landforms, and the parent material being reef-derived sediments, the processes of formation and development of soil on such islands differ from those on mainland or older landforms. While there are examples of soil surveys of reef islands using conventional techniques such as soil series developed on Orders, Suborders, Great Group, Subgroup, Family and Series (Morrison 1990) such a methodology is of limited use for making comparative analysis and for correlating soils with island maturity and development at a rapid reconnaissance level. In the case of the present research about 50 islands had to be surveyed in a few weeks, and the techniques developed by Hosking and McLean (1991) for investigating soils of Tuvalu were used in modified form (see Chapter 3).

Other types of 'soils' also serve to stabilise island surfaces and/or consolidate loose sedimentary materials. These include cay sandstone and phosphatic rocks.

Cay sandstone and phosphatic rocks

Cay sandstone is a term applied to lithified island sediments developed away from the intertidal beach area. Parnell (1988) outlines that water quality rather than water agitation is important for rapid lithification of sediments near the water interface. Similarly Stoddart and Steers (1977) suggest that cay sandstone is formed at the watertable with calcite derived from groundwater. This implies that cay sandstone may only occur on islands of certain size (that is of a sufficient size for a freshwater lens to develop).

When phosphatic derivatives from guano interact with island sediments, vegetal litter and water, phosphatic rock may be formed. The types, processes and distribution of phosphatic rocks have been discussed in detail by Stoddart and Scoffin (1983), while Rodgers (1992) deals with the formation of phosphatic rocks on atoll islands in Tuvalu.

Both cay sandstone and phosphatic rock developments on islands, like vegetation and soils, may indicate relative stability of an island and may be capable of being used criteria for distinguishing the patterns of island development.

2.5.2 Island margins

The margins of reef islands are also subjected to several processes that work directly or indirectly to stabilise island shores. Both biological and physico-chemical activities can be involved.

The presence of mangroves, particularly on reef flat in sheltered areas, and *Pemphis* in more exposed situations serve as baffles to reduce wave activity and induce sedimentation. Examples of this role from reef island and atoll situations and their relationship to sea level change has been described by Stoddart (1980), Woodroffe (1987) and Ellison and Stoddart (1991). Sea grass beds have the same effect, and in the Maldives they are particularly common 'carpets' on reef flats around islands.

On the other hand, beachrock plays a more complex role. For instance, being dependent on the severity of wave conditions and sediment availability, it can have either a protective role or one that does not impede shoreline erosion.

Several processes may be involved in the formation of beachrock though Hopley (1982) has identified three broad groups:

- 1) organic, involving microbial action or algae;
- 2) inorganic from freshwater, involving the watertable where grains get coated with calcite forming the initial bonding, and
- 3) inorganic from seawater, involving CO₂ degassing and aragonite and magnesium calcite precipitation.

The processes of beachrock formation appear to be able to act rapidly, as quick as six months (Hopley 1982) or they take several hundred years (Pirazzoli 1987).

Since beachrocks form in the intertidal zone, they may record previous position(s) of beach(es) on islands if separated from the present shore. Analysis of the location of fossil beachrocks may be used to infer the pattern of island development including erosional trends and the movements of islands. In this thesis evidence of changes of islands over the medium and longer terms is provided by beachrock exposures. Though beachrocks

are able to withstand wave action or even storms (Stoddart 1971a), they may offer only partial protection to islands because they form a solid ramp over which waves can pass without much reduction in energy and hence assist in shore erosion.

2.6 Recent changes and contemporary morphodynamics

Superimposed on island growth and development and the processes, which tend to stabilise islands, are the medium- and short-term changes, which may either continue, reverse or maintain the longer term trends. Moreover, over these time scales secular changes in some of the external factors identified in Figure 1.1, are unlikely to be major, but they can occur and, it is important to determine island responses. What nett effect such changes have had on reef islands in the past may serve as useful analogues for evaluating possible future changes.

That changes or variations in prevailing wind-wave conditions can have an effect on island position and shape has been shown theoretically by Gourlay (1988) and demonstrated by empirical studies of shifts in climate regime on islands in Jakarta Bay (Verstappen 1954) and the southern Great Barrier Reef (Flood 1986). In the latter case the annual wind energy vector has oscillated within a 45 degree arc from the SSE in the early 1960s to ESE in the late 1970s, and as consequence of this Flood (1986) argued that the change in wind-induced wave direction produced a change in the position of the nodal point on Erskine Cay and a reorientation of the leeward tail of the cay.

Decadal scale changes in the shape of cays in the southern and northern Great Barrier Reef by Flood (1977) and Stoddart *et. al.* (1978b), identified shoreline advance or retreat by comparing island shapes in 1972-73, with those illustrated on maps produced by Steers in 1929 and 1936. In these

instances, no attempt was made to explain the changes. Nevertheless, these examples together with others from the Great Barrier Reef and Central Pacific confirm that short-term adjustments and medium term secular changes to reef islands are continuing to take place.

In several instances the direction of island change has been inferred, though again the reasons for the changes have not always been established. For instance, in the Maldives, Gardiner (1903 p.381) observed that *...islands on the rim reefs are generally washing away on their seaward faces and growing outwards on their reefs towards the inner part*. And after examining some islands in the Maldives, the latter process was confirmed by Sewell (1936a) who calculated a lagoonward extension rate of 1m per year for a period of 75 years. Stoddart and Steers (1977, p.99) also indicated that the process of *bodily migration of reef islands across reef flats from the sea may go so far as to push them off the reef into the lagoon*. Similarly, on Ringutoru Islet of Kapingamarangi, Wiens (1962) observed a one-foot (30.5cm) per year lagoonward land building over a 40 year period and a slightly slower rate at Likeip Village in northern Marshalls.

More concrete data on recent changes is available from some islands impacted by tropical cyclones. For instance the rubble bank deposited during Tropical Cyclone *Bebe* (1972) in Funafuti atoll provide a good example of storm deposition contributing to oceanward island extension along several kilometres on the southern side of Funafuti island (Maragos *et al.* 1973; McLean and Hosking 1991).

This example and others are included in a comprehensive review on the geological effects of hurricanes on coral reefs and reef islands by Scoffin (1993). That both island erosion and island construction can occur as a result of cyclones and storms is illustrated in the following brief quotation

from his review: *Sand cays may be washed away and former storm ridges may migrate to leeward across reef flats to link with islands* (p.203).

Two further points can be noted from Scoffin's review. First, that the violence of a given storm relative to normal fair weather conditions influences the extent of damage; the length of time since the previous major storm influences the amount the coral debris created; and the length of time after the hurricane and before a subsequent storm influences the degree of stabilisation of reef top storm deposits and hence their chance of preservation. And second, that differences in reef-top geomorphology and the three dimensional structure and geometry of reefs in hurricane belt versus non-hurricane belt areas are not well known. The emphasis in this thesis is on features of 'reef-top geomorphology' (islands) in a non-hurricane belt area (the Maldives), the results of which may go some way to make these differences more well known.

2.7 Reef island equilibrium

Since Stoddart and Steers (1977) considered reef islands to be equilibrium landforms continually adjusting to the controlling forces, there has been some discussion on the nature of that equilibrium and for instance how severe episodic storm impacts could be incorporated into an equilibrium concept applicable to reef islands.

Stoddart and Steers (1977, p.97-98) recognised that certain types of reef islands are restricted to certain reef areas, defined in terms of exposure to wave action. *While reef islands may thus be arranged together in an apparent series, into which all islands may at some point be fitted, the series is one of location and not of stage; it represents a series of equilibrium positions, not an evolutionary succession.*

In short, they rejected the notion of an 'evolutionary succession' such as that proposed by Fairbridge (1967) and outlined earlier in this chapter (section 2.4.1). Bayliss-Smith (1988) believed the type of equilibrium Stoddart and Steers (1977) envisaged for reef islands was a 'steady state' equilibrium between process and form. However, Bayliss-Smith (1988) did have some difficulty with the application of a steady state concept, because of the impact of catastrophic storms on the atoll of Ontong-Java, where he was working.

As noted earlier (section 2.3.3) Bayliss-Smith (1988) recognised that hurricanes tend to erode existing islands, but at the same time produce the material for their reconstruction. Thus, rather than continually being in equilibrium, some reef islands would appear to be in disequilibrium for years or decades, with either a surplus or a deficit in the supply of coarse sediments available to sustain the island's shoreline. Furthermore, he noted that the state of reef islands depends on:

- The relaxation time or rate of recovery of the island after a given pulse of input; and
- The recurrence interval of such inputs.

He also distinguished between the responses of shingle islands (motu) and sand cays, noting that the former were characterised by a 'dynamic equilibrium', and suggested that island responses would differ under Mid-Holocene and Late Holocene conditions. In his model the Mid-Holocene was characterised by frequent storms, high wave energy and high reef productivity which kept motu building and sand cays in a steady state. Late Holocene conditions were characterised by less frequent storms, lower wave energy and lower reef productivity resulting in nett erosion of motu and the ultimate disappearance of sand cays.

The role of storms in island initiation and building and further development of the 'equilibrium' concept within the context of atoll islands was advanced by Richmond (1993). In section 2.3.3 it was noted that he had commented that reef islands can remain precariously balanced between destructive forces and constructive forces.

Hence, during the development of islands, they may not attain 'self-regulating' equilibrium, but may reach an 'optimum' state and remain in that state until they pass through one or more thresholds. The 'optimum' state, for them is usually a comparatively short-lived period where unstable effects amplify each other (Wright and Thom 1977).

Building on from the types of equilibrium identified by Bayliss-Smith (1988), particularly for islands in storm-frequent areas, Richmond (1993) ascribed three types of equilibria for islands of the Central Pacific thus:

- 1) Steady State Equilibrium;
- 2) Dynamic Equilibrium and;
- 3) Dynamic Metastable Equilibrium.

Each equilibrium state was associated with a different island type (Figure 2.8), and the 'equilibrium' states are representative of fluctuations over a century or so rather than millennia as considered by Bayliss-Smith (1988).

According to Figure 2.8, the simple sand cay classed as Type I does not change substantially in area over time although fluctuations in size vary over short periods. This is the 'steady state' equilibrium, characterised by constant fluctuations in size and shape with no long-term mean trend, and where an island oscillates about an average form and central point of deposition on the reef platform.

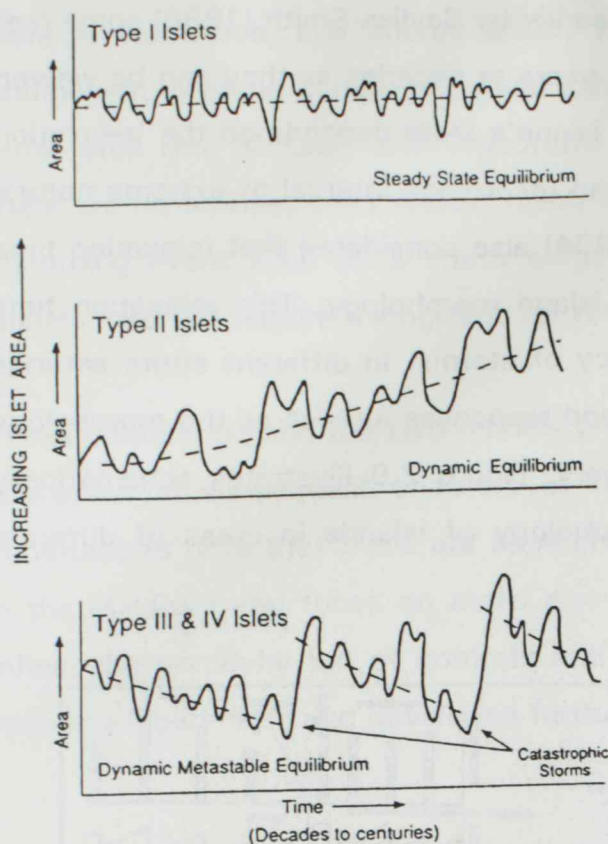


Figure 2.8 Sketches of hypothetical equilibrium conditions for the variation in area of atoll islands in Central Pacific. Dashed lines represent the longer-term mean trend. Various types of islands are identified with each of the three types of equilibria. (From Richmond 1993, p. 1192).

Type II islands, which are boomerang-shaped islands formed at convex-seaward bends of atoll rim, vary in size about a mean and gradually increase in area over time. 'Dynamic' equilibrium operates on these islands where a net enlargement trend occurs over a long term.

Types III and IV islands which are narrow and elongated, and complex islands tend to decrease in size until a threshold event occurs leading to a rapid increase in size. This is then followed by a return to a slow reduction in area. Richmond (1993) identified this condition as the 'metastable' equilibrium where seaward erosion and lagoonward deposition takes place on these islands, and readjustment occurs with major catastrophic changes.

Thus in one region, indeed on one atoll, different islands can be at different stages of development. As shown earlier by Bayliss-Smith (1988) some reef islands can be in disequilibrium for years or decades as they can be viewed as geomorphic systems where the island's state depends on the 'relaxation time' (rate of recovery) and on mean recurrence interval of extreme natural events. McLean and Woodroffe (1994) also considered that relaxation time was important in controlling reef island morphology. This relaxation time was very much related to frequency of storms. In different storm settings they argued storm impacts and island responses as well as the morphology of reefs and reef islands would vary. Figure 2.9 illustrates schematically some of the features of the morphology of islands in areas of different storm frequency.

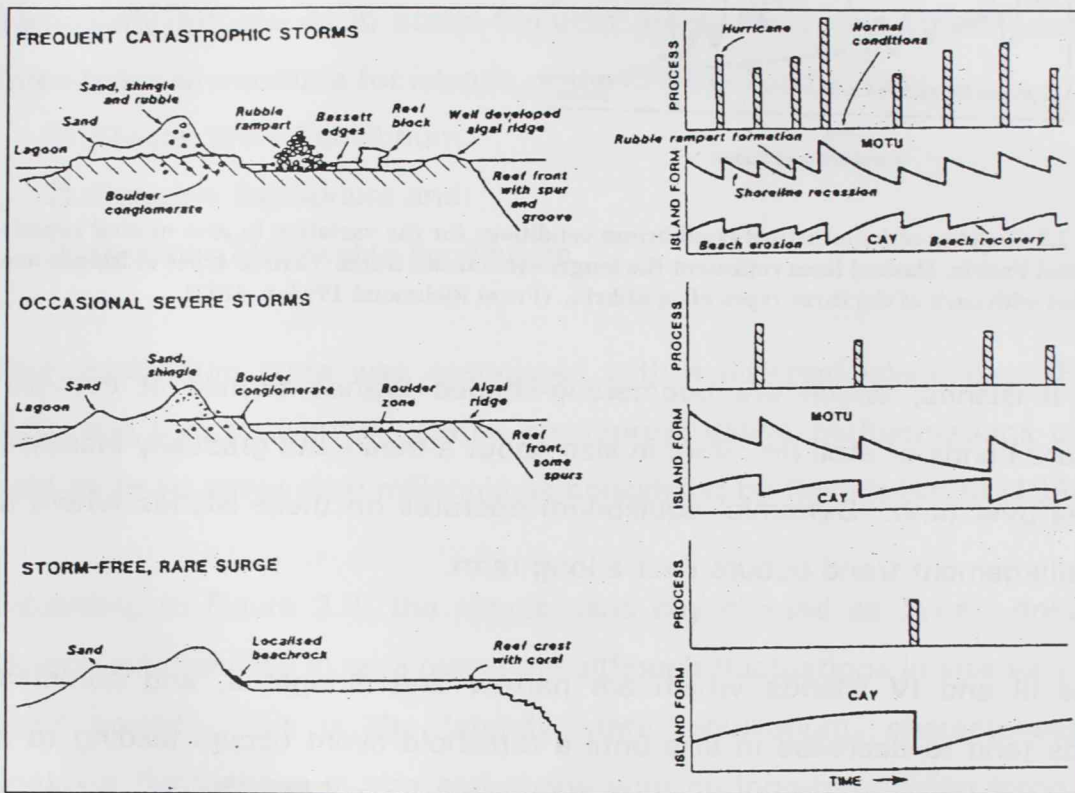


Figure 2.9 The morphology of reefs and reef islands in areas of different storm occurrence, and the response of form to process. In area where storms are frequent (top), abundant coral shingle and boulders, rubble ramparts and reef blocks occur. In areas with occasional severe storms (centre), less extensive boulder depositions are present on reef flats. In areas of rare storm events (bottom), the islands are composed of sand and with no significant reef flat deposits. (Source: McLean and Woodroffe 1994, p.293).

The situation of the Maldives is included in the bottom panel of Figure 2.9. Here in storm-free, low energy areas, where coral rubble is not a major component in island construction and sand cays may be found even on the outer atoll rim. McLean and Woodroffe (1994) also suggest that where there are no storms, cays should reach a stable equilibrium, though a rare disturbing event such as a storm surge can cause devastation on these islands, and will require a long time for recovery.

These comments, and the two models presented in Figures 2.8 and 2.9 are addressed in subsequent chapters of this thesis. For the moment it is important to note that there are apparent differences between reef islands in the Maldives and those on atolls elsewhere. Such differences will likely reflect the particular set of controls and condition outlined in Chapter 1.3 including Figure 1.1, and developed further in Chapters 4 and 5.

2.2 Fieldwork

Fieldwork was carried out on four occasions. The dates and descriptions of the visits are as follows:

- 10 to 16 December 1995, a reconnaissance visit to the atoll at end of a wider survey of atolls in the Maldives.
- 29 February to 10 March 1996, detailed surveys and sediment sampling.
- 20 to 24 October 1996, beach profile surveys and sediment sampling.
- 21 November to 6 December 1996, island mapping and soil sampling.
- 1 to 12 April 1997, survey of beach profiles, mapping and soil sampling.
- 20 to 25 January 1999, sediment sampling for radiocarbon dating and geochemistry.

CHAPTER 3:

Methodology and approach

3.1 Introduction

The methods and approaches utilised to gather and analyse information about the morphology and dynamics of islands in Eta atoll are outlined in this Chapter. This includes field methods as well as those used both in the office including morphometric measurements from maps and aerial photos, and laboratory work performed on the sediments for compositional and grain-size analyses. Other manual and computer-based analyses of data were also carried out and these are detailed below.

3.2 Fieldwork

Fieldwork was carried out on six occasions, including one reconnaissance trip, as follows:

- 10 to 16 December 1995, a reconnaissance visit to Eta atoll as part of a wider survey of atolls in the Maldives;
- 29 February to 10 March 1996, transect surveys and sediment sampling;
- 16 to 28 October 1996, beach profile surveys and sediment sampling;
- 26 November to 8 December 1996, island mapping and soil profiling;
- 1 to 12 April 1997, resurvey of beach profiles, mapping and soil profiling;
- 20 to 25 January 1999, sediment sampling for radiocarbon dating and photography.

In total, fieldwork covered 48 of the 60 islands in Eta atoll, but the same activities were not carried out on each island, nor on each visit. The number of islands studied varied with the type of activity, as well as logistics and other considerations. Emphasis was given to the uninhabited islands of the atoll, though subsurface sediment samples were collected/observed from a few inhabited islands, which provided a home base for some of the fieldwork. Figure 3.1 indicates the islands visited on each leg of fieldwork.

A reconnaissance trip to the area was made in December 1995, as part of a broader visit to several atolls. The first serious fieldwork was undertaken in March 1996, when sediment sampling and transect surveys were carried out. During this trip 45 islands were visited at a rate of about four to five islands a day. '*Maafari*', the research vessel of the Environment Research Unit (Ministry of Planning, Human Resources and Environment), was used as a base for these first two trips. On all other occasions after arriving at Kunfunadhoo by air, a small (6m) mechanised open *dhoni* was used to travel to islands during the day and returning to a close by inhabited island for the evening.

During the October 1996 visit, the initial beach profile surveys were conducted on 42 islands to establish a baseline for seasonal changes. During the November-December 1996 visit, geomorphological mapping was conducted on ten islands and soil profiling was done on nine of these and one inhabited island. Due to logistic constraints, in April 1997, resurveying of beach profiles for seasonal change was possible on only 27 of the initial 42 islands, with geomorphological mapping on eight, and soil profiling on seven of them. In January 1999, a brief visit was made to six islands to collect sediment samples for radiocarbon dating, and to take photographs of relevant features.

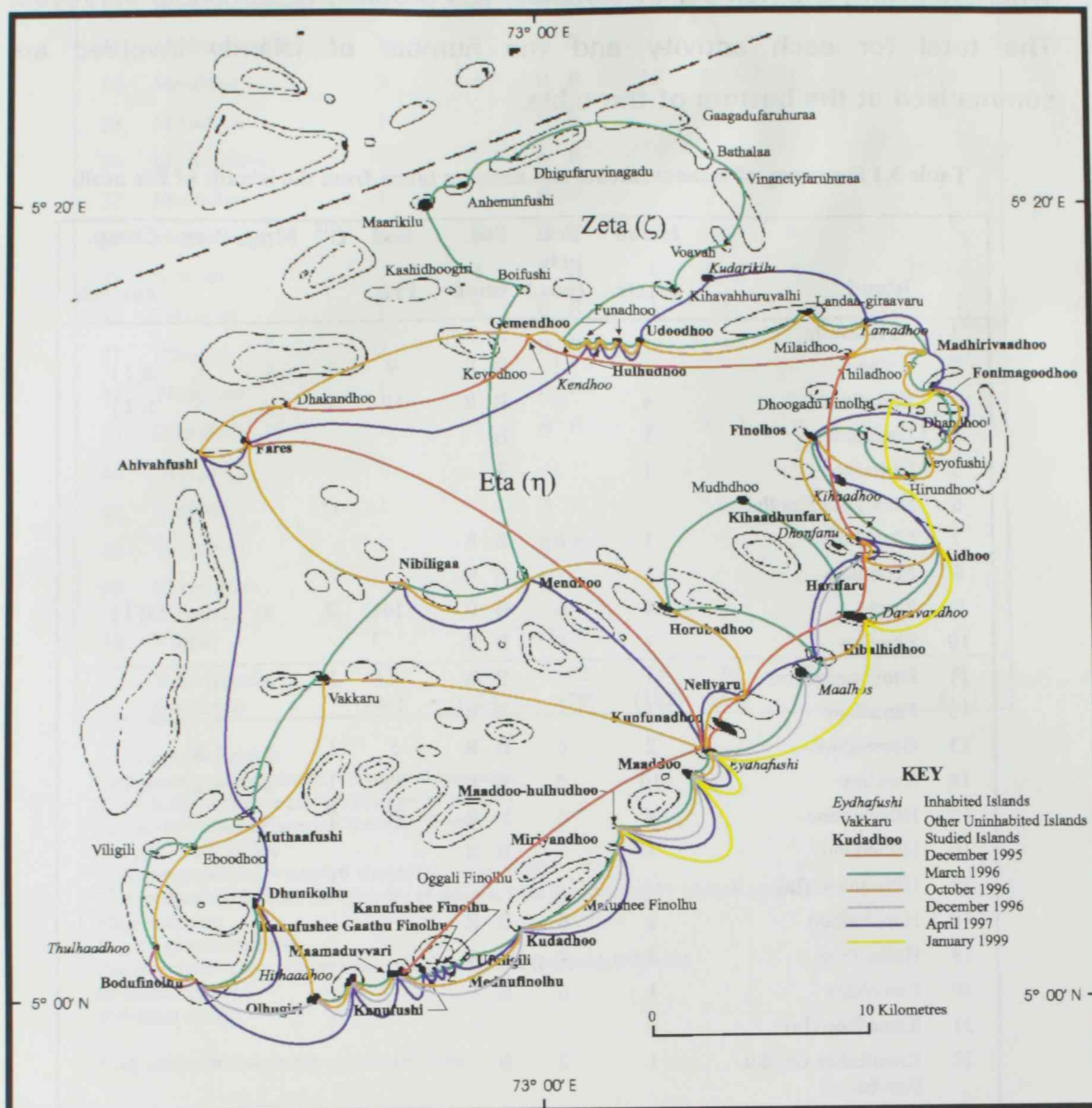


Figure 3.1 Islands visited on each leg of the fieldwork carried out in Eta atoll.

Table 3.1 summarises the type of data collected from the islands. The table indicates the number of islands involved with different activities, and also where relevant, the number of samples, soil profiles, or transects surveyed. The total for each activity and the number of islands involved are summarised at the bottom of the table.

Table 3.1 Summary of measurements and samples taken from the islands of Eta atoll.

Island	Island trsects	Bch. prfs. (nos.)	Sed. smpls	Soil Prfs.	C ¹⁴	Mpg.	Veg.	Comp. analysis
1 Ahivahfushi			B			x		
2 Aidhoo	3	2	B R	9	2	x	x	2(I)
3 Bodufinolhu	4	6	B R	10	1	x	x	1(I)
4 Dhakandhoo	1		B					
5 Dhandhoo	1		B					
6 Dhoogadu Finolhu					1*			
7 Dhunikolhu	1	6	B R					
8 Eboodhoo	1		B R					
9 Fares	4	6	B R	16	2	x	x	1(I)
10 Finolhos	1	6	B R					
11 Fonimagoodhoo	1	4	B R		2	x		
12 Funadhoo	1		B R					
13 Gemendhoo	2	6	B R	5	1	x	x	
14 Hanifaru	10	5	B R	13	1	x	x	1(I)
15 Hibalhidhoo	4	6	B R	28	2	x	x	
16 Hirundhoo	1		B R					
17 Hithaadhoo (In)					1			
18 Horubadhoo	1	6	B R					
19 Hulhudhoo	1	4	B R					
20 Kanufushi	1	6	B R					
21 Kamadhoo (In)					1			
22 Kanufushee Gaathu Finolhu	1	2	B					
23 Kanufushee Finolhu	1	2	B R					
24 Keyodhoo	1							
25 Kihaadhunfaru	1	6	B R					
26 Kudadhoo	2	2	B R			x	x	
27 Kunfunadhoo (R)					1			
28 Landaa-giraavaru	1		B R					
29 Maaddoo	4	4	B	32	3	x	x	
30 Maaddoo-hulhudhoo	2	7	R	8	2	x	x	1(I) 1(b)
					b			

Table 3.1 (Contd.)

	Island	Island trsects	Bch. prfs	Sed. smpls	Soil Prfs.	C ¹⁴	Mpg.	Veg.	Comp. analysis
31	Maamaduvvari	4	4	B R	15	3	x	x	
32	Madhirivaadhoo	1	4	B R					
33	Medhu Finolhu	1	2	B R					
34	Mendhoo	3	4	B R	15	2 b	x	x	1(I)
35	Milaidhoo	1		B R					
36	Miriyandhoo	1	7	B R					
37	Mudhdhoo	1		B R					
38	Muthaafushi	4	6	B R	10	1	x	x	
39	Nelivaru	2	4	B R	1	2 b	x		1(I)
40	Nibiligaa	1	2	B R	1	2		x	
41	Olhugiri	2		B R	13	3	x	x	2(I)
42	Thiladhoo	1		B R					
43	Udoodhoo	2	5	B R	16	3 b	x	x	1(I) 1(b)
44	Ufuligili	1					x		
45	Vakkaru	1		B R					
46	Veyofushi	1		B R					
47	Veyofushee			B					
	Finolhu	1							
48	Viligili	1		B R					
Total islands (numbers)		43 (80)	27 (124)	42 (79)	15 (192)	20 (40)	18	15	9 (11)

x = activity undertaken

Island.trsects = island transects (number of transects);

Bch.prfs.(nos.)= Beach profiles (number of profiles)

Sed.smpls= sediment samples; B=beach, R=reef,

Soil prfs.= soil profiles

Ssnl. change (smpls) = seasonal change (no. of samples)

C¹⁴= radiocarbon datings; (2)= number of samples from the island, (b)= 1 beach sample,

Mpg.=mapping

Veg.=vegetation mapping

Comp.analysis= compositional analysis; (2)= number (I=island, b=beach)

In=Inhabited island

R=Tourist resort.

* cay sandstone sample from a remnant island.

It should be noted that often sea conditions for landing and leaving islands were not ideal, and time and safety considerations frequently constrained field activities. Rarely were island visits of sufficient duration to obtain much more than the basic survey/sample/observational data. However, as noted earlier the purpose of this study was to gather information from as many islands as possible within the atoll, rather than to do an intensive study of one or two islands.

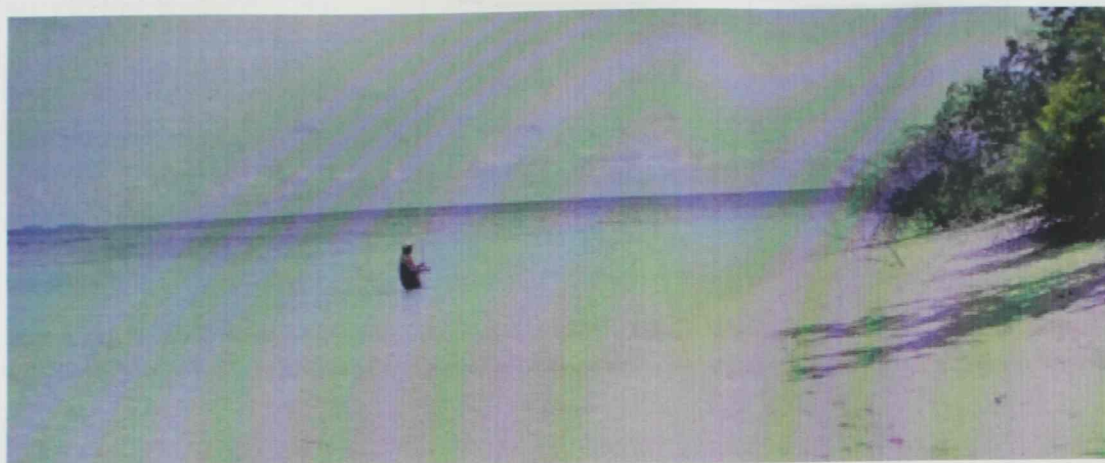
3.2.1 Island transects

In order to obtain morphologic and elevation data, cross-island surveys were carried out using a Kern level and a 5-metre staff which was also used for beach profile surveys (Figure 3.2). Cross-island transects usually started and ended just below the water level at the time of the survey. Initially, at least one transect was surveyed on each uninhabited island. Further transect surveys were conducted on 15 islands, the total number and location of transects varied with the size and the shape of islands. On elongated islands, one transect was run along the length of the island, and another one or two run at right angles to the long axis. On the more compact and circular islands two transects through the centre of the island were surveyed orthogonal to one another. Figure 3.3 shows the location of transect surveys on selected islands.

Transects were surveyed essentially in a straight line on a pre-determined bearing. This occasionally involved clearing vegetation along the line of survey, and where this was too difficult some deviation from the bearing was necessary. The lengths of transects surveyed varied from about 20m to 1000m, with distances between stations varying from 2 to 10m, depending on the nature of the island surface form and vegetation cover. The survey stations were determined on the basis of slope variations, vegetation, soil or sediment change boundaries, and paths or tracks. Selected locations on transects were marked for later soil profile examination.

Transect surveys were reduced to a common sea level in order to standardise all elevations and permit objective comparisons within and between islands. Accuracy in base level calculations is important given the low elevations of the islands. During field survey a staff position at

the water line was surveyed and the time was noted. This level was transferred to the equivalent time/elevation graph based on the daily tidal predictions for Male'/Hulule' as given by the Sea Level Centre of the University of Hawaii. All surveys were reduced to mean sea level (MSL) which became the common baseline (approximate MSL) or zero for the transects.



(a)



(b)

Figure 3.2 Beach survey techniques (a) surveying a beach profile beyond the water-line, and (b) detached beachrock outcrop.

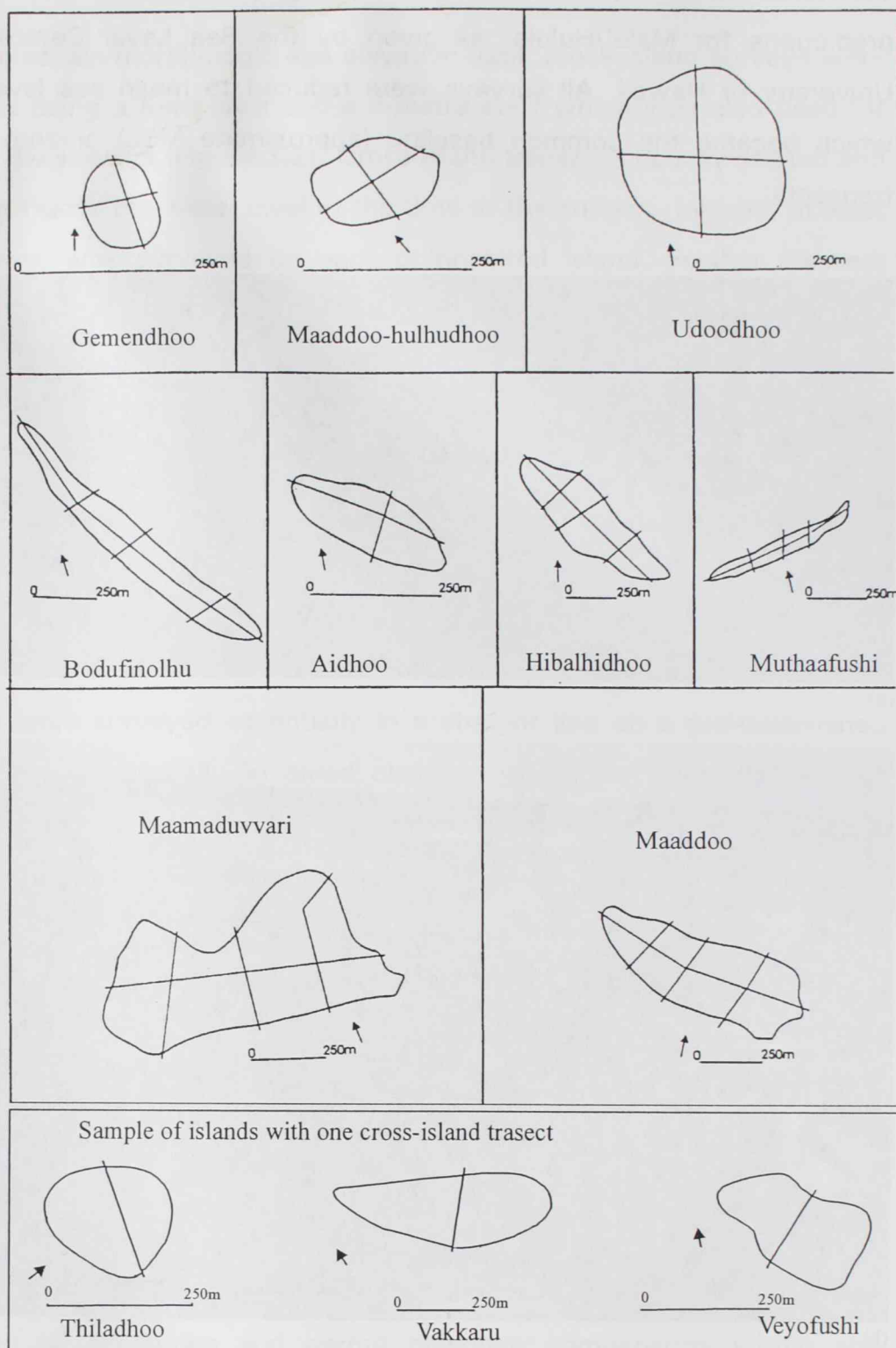


Figure 3.3 Schematic diagram of transects surveyed on selected islands. The transects were positioned to include the main topographic features of the islands. The arrow indicates north.

3.2.2 Beach profiles

Beach profiles were surveyed using the same field and reduction techniques as just described for the cross-island transects. Beach profiles were surveyed from a landward point to below the water level. A benchmark was established at the landward end of the profile on the island, for repeated surveying (Figure 3.4).



Figure 3.4 Benchmarks established on islands during October 1996 surveys. These spots were reoccupied during the April 1997 surveys. Many of these survived for the study period and could be reoccupied in the future.

Two or three profiles were normally surveyed in a radial pattern from this benchmark as shown in Figure 3.5. The figure also shows the coverage of beach slope profiles for several different shaped and sized-islands. A total of 124 beach profiles on 27 islands were surveyed in late October 1996, after 6.5 months of pronounced westerly winds. The same profiles were resurveyed in early April 1997, at the end of persistent easterly winds. Generally, beach profiles were surveyed at either end of the long axes of linear to elliptical islands and on the western and eastern sides of circular islands, noting that these are presumably the most exposed locations to the seasonal reversal of winds and waves. On three partially vegetated cays (Figure 3.5f), which are joined together at low tide, profiles were surveyed on the seaward and lagoonward sides, through the center of the

island. The surveys were carried out on the assumption that timing and interval between surveys were long enough to observe the seasonal effect. This assumption is based on local knowledge and interviews with locals, in addition to the notes made on the islands on previous visits. Details on the number of island transects and beach profiles are given in Table 3.1.

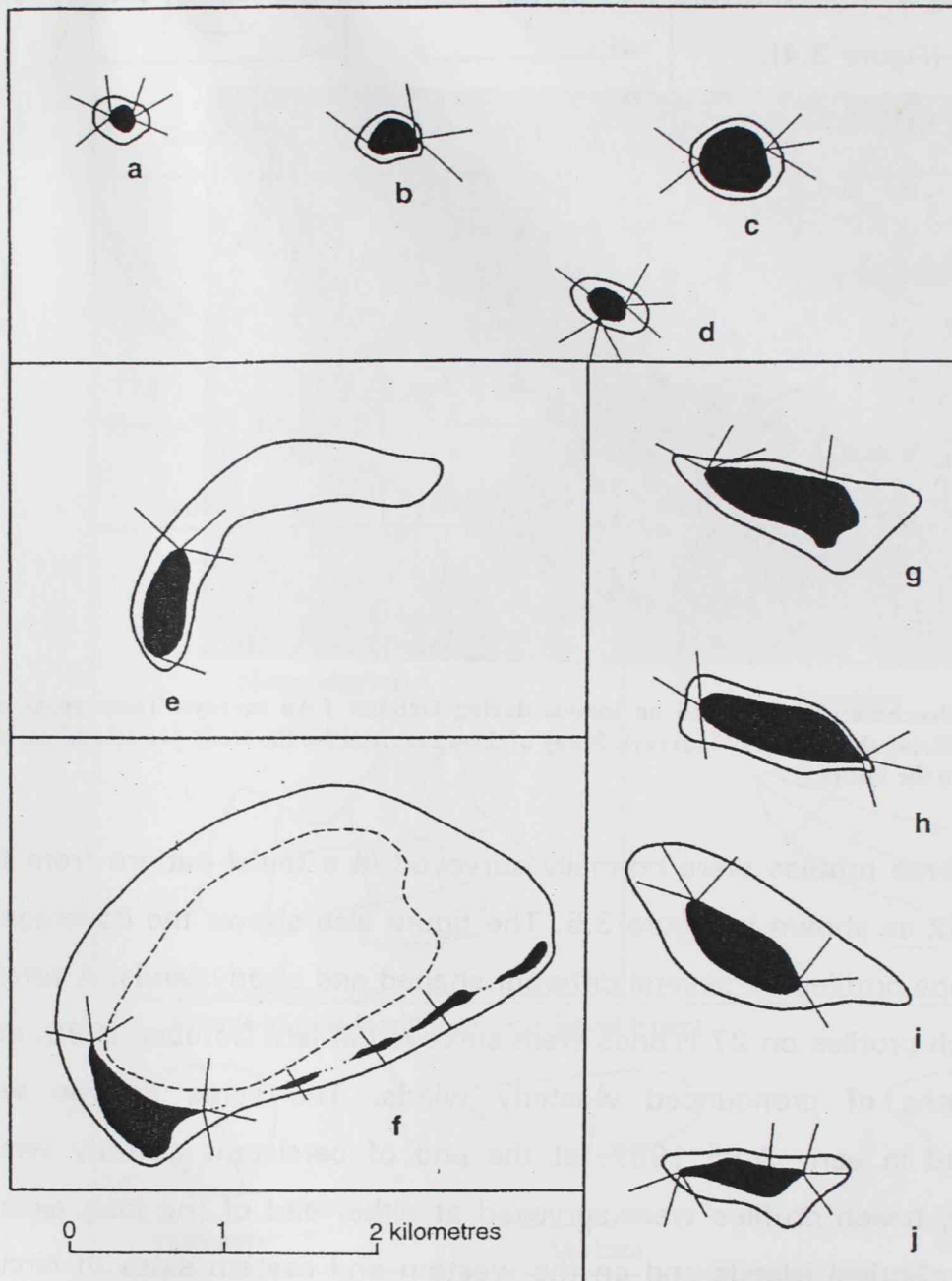


Figure 3.5 Location of beach profiles on selected islands of different size and shape characteristics. (a) Gemendhoo, (b) Hulhudhoo, (c) Udoodhoo (d) Maaddoo-hulhudhoo, (e) Fonimagoodhoo, (f) Kanufushi and islands, (g) Maaddoo, (h) Finolhos (i) Kihaadhunfaru, and (j) Miriyandhoo.

3.2.3 Sediments

Surficial sediments

Samples of surficial sediments were collected from mid-beach and reef locations on island transects and beach profiles. The samples on island transects were obtained between 29 February 1996 to 10 March 1996, and from beach profiles in October 1996 and April 1997, at about the same locations. Approximately 200 grams of sediment was scooped from the surface. Samples were primarily of sandy materials with coarser gravel and coral rubble excluded, though the presence of such material was noted in the field book. Samples were bagged, bleach added, sealed and labelled. A total of 79 samples were analysed from 43 islands. Details are presented in Table 3.1.

Soil pits and sediment cores

Subsurface stratigraphic characteristics were observed in soil pits and sediment cores located on the island transects described earlier. Soil pits were dug by spade or by using a hand auger to examine the subsurface materials, and to collect samples for radiocarbon dating, on three occasions: 26 November to 8 December 1996, April 1-10 1997, and in January 1999. Appendix 4 shows the location of soil pits and depths of soil on the islands.

Soil profiles were examined to determine texture and colour and the thickness of soil development. Profiles often extended to depths of between 1-1.5m, or until unmodified parent sand was reached. The colour identification of soils was based on nomenclature developed by Hosking and McLean (1991) as thus:

A. Dark soils:

1. dark brown (7.5YR 2/2) (10YR 3/2)
2. brown (7.5 YR 4/3)
3. grey brown (7.5YR).

B. Light soils:

1. light grey brown (7.5YR 5/3)
2. grey yellowish brown (10YR 5/3)
3. stained sand
4. unaltered sand.

In Chapter 8 the depth from the surface to unaltered sand is used as an index of relative soil maturity. In some cases, pits were cored down to about 2m, in order to obtain sediment samples at depths and to examine the nature of the stratigraphy of lower materials. To core some of these pits deeper, particularly below the water table, where the ground was not too consolidated, a 4-inch PVC pipe was driven into the ground and the open end was vacuum sealed, to recover samples. Using this technique, samples between 2-3 meters below the surface were collected from four islands.

Samples from these deeper sites as well as from open pits dug into the ground were also collected for radiocarbon dating. In many instances coring was terminated when it was impossible to core through a 'hard-pan' of clay sandstone. The depth of clay sandstone is included on the soil profiles in Appendix 4.

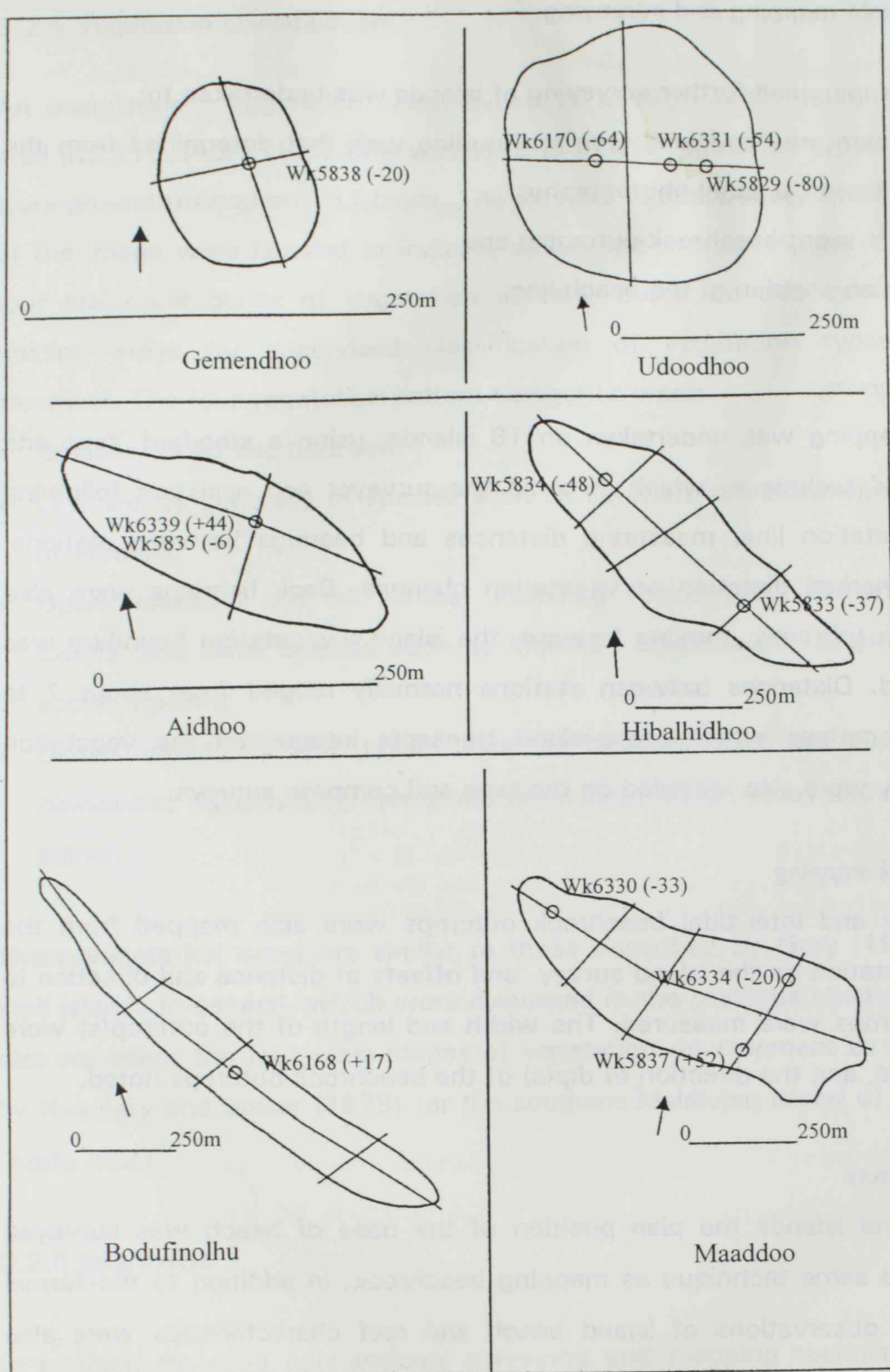


Figure 3.6 Location of soil pits on selected islands from which samples for radiocarbon dating were obtained. The figure shows the location of the soil pits in relation to the transects surveyed on six of the 20 islands from which sediment samples have been radiocarbon dated. The number refers to the Waikato Radiocarbon Dating Laboratory number and the value in brackets refers to the depth of the sample in cm, with reference to mean sea level.

3.2.4 Field mapping and surveying

Field mapping and further surveying of islands was undertaken to:

- compare present island area and outline with that determined from the 1969 vertical aerial photography;
- map present beachrock outcrops; and
- the plan position of the beach-line.

Island mapping

Field mapping was undertaken on 18 islands, using a standard 'tape and compass' technique, which involved the surveyor and assistant following the vegetation line, measuring distances and bearings between stations, which marked direction or vegetation changes. Back bearings were also taken. In this way, moving forward, the island's vegetation boundary was surveyed. Distances between stations normally ranged from about 2 to 10m. Locations where cross-island transects intersected the vegetation boundary were also recorded on the tape and compass surveys.

Beachrock mapping

Reef flat and inter-tidal beachrock outcrops were also mapped from the closest station on the island survey, and offsets of distance and direction to the outcrops were measured. The width and length of the outcrop(s) were measured, and the direction of dip(s) of the beachrock outcrops noted.

Other aspects

On several islands the plan position of the base of beach was surveyed using the same technique as mapping beachrock. In addition to the formal surveys, observations of island beach and reef characteristics were also made. Photographs were taken of relevant island characteristics and features.

3.2.5 Vegetation classification

An unsupervised vegetation classification of a 1988 SPOT image of Eta atoll (KJ:210 340/0 (13/3/88)) was used to define vegetation types. These were ground-truthed on 15 islands. The clusters of spectral signature values of the image were labelled to indicate which clusters corresponded to the four major categories of vegetation defined. Based on this information, training areas for supervised classification of vegetation types were identified. The four vegetation pattern categories were:

- Grasses, vines and bare soil;
- Low shrubs generally of species such as *Tournefortia*, *Scaevola*, *Cordia* or *Wedelia*;
- Open woodland and tall shrubs including *Tournefortia*, *Scaevola* and *Cordia*, and other species such as *Morinda*, *Hibiscus* or *Thespesia* and coconut palms;
- Dense woodland and taller trees of species such as *Guettarda*, *Hernandia*, *Calophyllum*, *Pandanus*, *Ochrosia*, *Pisonia*, *Ficus* and coconut palms.

These vegetation types are similar to those described by Gray (1993) for atoll islands in general, which were discussed in the previous chapter. They also represent the four main stages of vegetation development as outlined by Newbery and Spicer (1979) for the southern Maldivian island of Wilingili (Addu Atoll).

3.2.6 Interviews

In addition to using conventional surveying and mapping techniques and field sampling methods to gather information about the present morphology and elevation of the islands, atoll residents were interviewed to obtain information on environmental changes they had witnessed. In addition, where possible folklore and past stories about islands were also noted.

3.3 Laboratory and office-based work

Samples collected during fieldwork were subject to laboratory-analyses, which mainly dealt with sediments, for grain-size analysis, compositional analysis, and for the selection of samples for radiocarbon dating. A flow chart of procedures used is indicated in Figure 3.7.

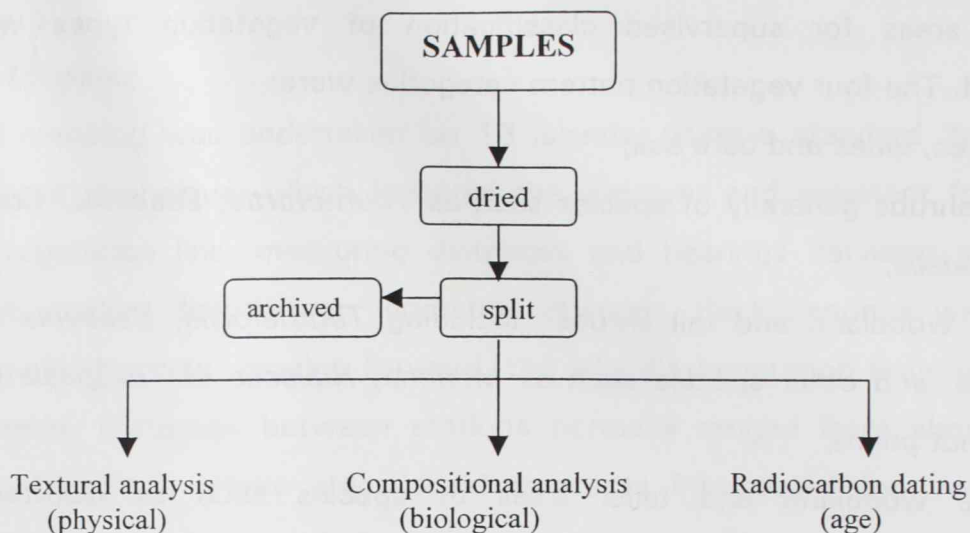


Figure 3.7 Procedures applied on sediment samples and the purposes for which sediments were analysed. The samples collected from the field were oven-dried in the laboratory, then split and one sub-sample was archived, and the other sub-sample was analysed for physical and biological characteristics and sometimes for radiometric age determination.

3.3.1 Grain-size analysis

Sediment samples were washed to remove fines, and then dried in a laboratory oven at 45°C. Sediment analysis was conducted by standard settling-tube techniques, following the procedures of Kench and McLean (1997), which provide a measure of hydraulic grain-size. Sub-samples of 15-20 gram were settled through a MacArthur Rapid Sediment Analyser (RSA). The RSA comprised a tube with a 1.87m vertical fall between the release mechanism to the balance pan. To convert the settling distribution to a hydraulic-size distribution, a sediment density parameter is input, in this case 1.8g/cm³ was used for the carbonate sediments, following Kench

(1994). Computed results and related statistics were given as printouts, which included the mean size, sorting, skewness and other parameters. A sample of the result output is shown in Figure 3.8.

3.3.2 Compositional analysis

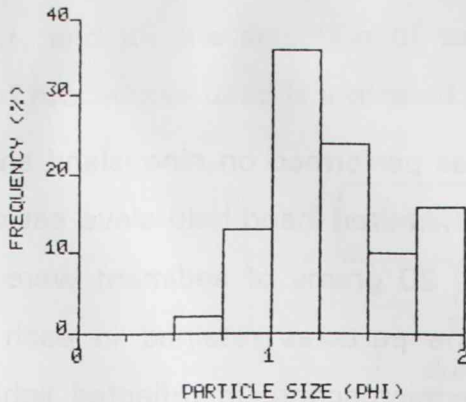
Compositional analysis of sediments was performed on nine island and two beach samples. Using a small (7.8cm diameter) hand-held sieve set of five screens (-1, 0, 1, 2, and 3 ϕ plus pan), 20 grams of sediment were hand-sieved for 5 minutes. A subset of the particles retained in each sieve fraction was identified under binocular microscope, in reflected light. The point count method (Milliman 1974) was used to determine the skeletal grains, using a gridded petri-dish (with 7x7 quadrants), each grain on the intersections was identified. Two such counts were carried out for every sample in each sieve size.

The key used to identify skeletal components was based on descriptions, illustrations and photographs in Milliman (1974), Flood and Scoffin (1978) Scoffin (1987), and Kench (1994), for the following eight groups: Corals; Molluscs (including both pelecypods and gastropods); foraminifera; *Halimeda*; (both fragments and whole plates); Echinoderms, Bryozoans, and Crustaceans; Coralline algae; Alcyonarians; and, others and unknowns.

3.3.3 Radiocarbon dating

Radiocarbon dates were obtained for a total of 39 samples submitted to the University of Waikato Radiocarbon Dating Laboratory, and one from the Quaternary Dating Research Centre, Australian National University. Thirty four sediment samples from soil pits, four beach samples, and one cay sandstone from a remnant island, and a piece of coral in phosphatic rock from one island were dated. Samples were washed and dried in an oven at 45°C before dispatching. Duplicate samples were retained.

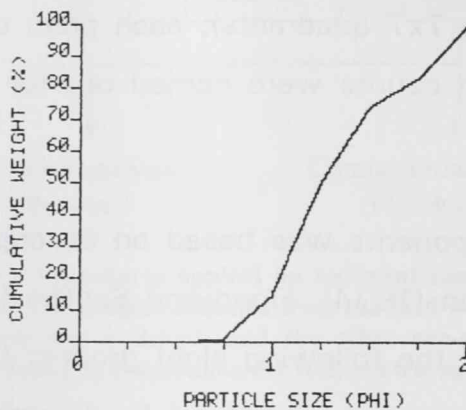
SAMPLE IDENTIFICATION: 96-22/10/12

SIZE DISTRIBUTIONRESULTS

SIZE (PHI)	SIZE (MM)	CUM. WEIGHT (%)	INTERVAL (%)	CUM. FREQ (%)
0.25	0.84	0.00	0.00	0.00
0.50	0.70	0.00	0.01	0.01
0.75	0.59	0.14	1.57	1.58
1.00	0.50	1.35	12.88	14.47
1.25	0.42	4.68	35.64	50.11
1.50	0.35	6.89	23.68	73.80
1.75	0.29	7.81	9.83	83.63
2.00	0.25	9.34	16.36	100.00

TOTAL WEIGHT = 9.346M

GRAVEL = 0.00% SAND = 100.00% SILT = 0.00%
CLAY = 0.00%

CUMULATIVE FREQUENCY
ARITHMETICSTATISTICAL PARAMETERS

GRAPHICAL METHOD (FOLK AND WARD, 1957)

MEAN = 1.34 PHI MEDIAN = 1.25 PHI

C = 0.66 PHI

D35 = 1.14 PHI D65 = 1.41 PHI

SORTING = 0.35 WELL SORTED

SKEWNESS = 0.29 FINE SKEWED

KURTOSIS = 0.99 MESOKURTIC

MOMENT METHOD

MEAN = 1.32 PHI

SORTING = 0.33

SKEWNESS = 0.36

KURTOSIS = 2.26

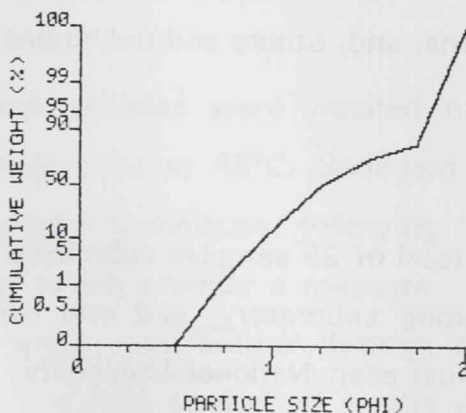
CUMULATIVE FREQUENCY
PROBABILITY

Figure 3.8 A sample of the output from the Rapid Sediment Analyser used in the analysis.

Results were given as Conventional Ages or as percent of Modern based on the Libby half-life of 5568 years, with correction for isotope fractionation applied. The conventional radiocarbon ages were environmentally corrected for oceanic reservoir effect by deducting 450 ± 35 years, as recommended by Gillespie and Pollach (1979). The environmentally corrected ages are used in this thesis.

3.3.4 Maldives-wide data and study-site selection

The foregoing field and laboratory methods were used specifically for the investigation of Eta atoll. Prior to the decision to concentrate this study on Eta atoll, a rudimentary analysis of the morphometric characteristics of all atolls of the Maldives was made. The British Admiralty charts for the Indian Ocean, Maldives sheets 1 to 4 (Sheets 1011 and 1012, 1992) and (Sheets 1013 and 1014, 1993), at a scale of 1:300,000 were used for this purpose.

On all of the atolls in the Maldives, characteristics such as number and types of reef platforms (faros, patch reefs) that occur on the atoll rim and inside the lagoon, the number of islands in an atoll, and the number and proportion of passages to the perimeter of atoll rim reef were calculated. The outline of each atoll was digitized using MapInfo software, for calculating the perimeter, length and atoll area. The salient characteristics identified were then used to determine a suitable study site, which would be representative of the general features and aspects of reef platforms and islands in the Maldives. Eta was found to be a representative atoll (see chapter 4) and this was confirmed during a reconnaissance visit to several atolls in the Maldives in December 1995 and January 1996.

3.3.5 Eta atoll and study site characteristics

Location of islands

The location of islands and reef platforms in Eta atoll is referred with respect to quadrants in which they occur. Since the 73° Longitude meridian divides the atoll into almost equal halves, this axis was used with the $5^{\circ} 8.5'$ Latitude parallel, which is about half the north-south stretch of the atoll. Accordingly, northeast, southeast, southwest, and northwest quadrants were identified. The northeast and southeast quadrants form the eastern half of the atoll, and the northwest and southwest quadrants form the western half of the atoll, as shown in Figure 3.9.

Morphology and area

Morphological and area characteristics of islands and reef platforms of Eta atoll were made from a set of aerial photos of the atoll taken by the Royal Air Force in 1969 at a scale of 1:25,000. Of the 60 islands 53 vegetated islands were utilised here. These photographs were obtained from the Maldives Ministry of Fisheries and Agriculture. Plan data on reef-top characteristics such as island and reef platform area was measured using a polar planimeter. The average value from three consecutive readings for each feature was used.

The reef-top features defined from the photographs were:

- island (defined as the vegetated area);
- active sediment zone (or beach) extending from the vegetation line to a marked sediment tonal change on the inner reef flat;
- reef flat (area seawards from active sediment zone to reef crest). The area within the reef crest was defined as the reef platform area;
- reef slope: area seawards of the reef crest.

These definitions are indicated in Figure 3.10.

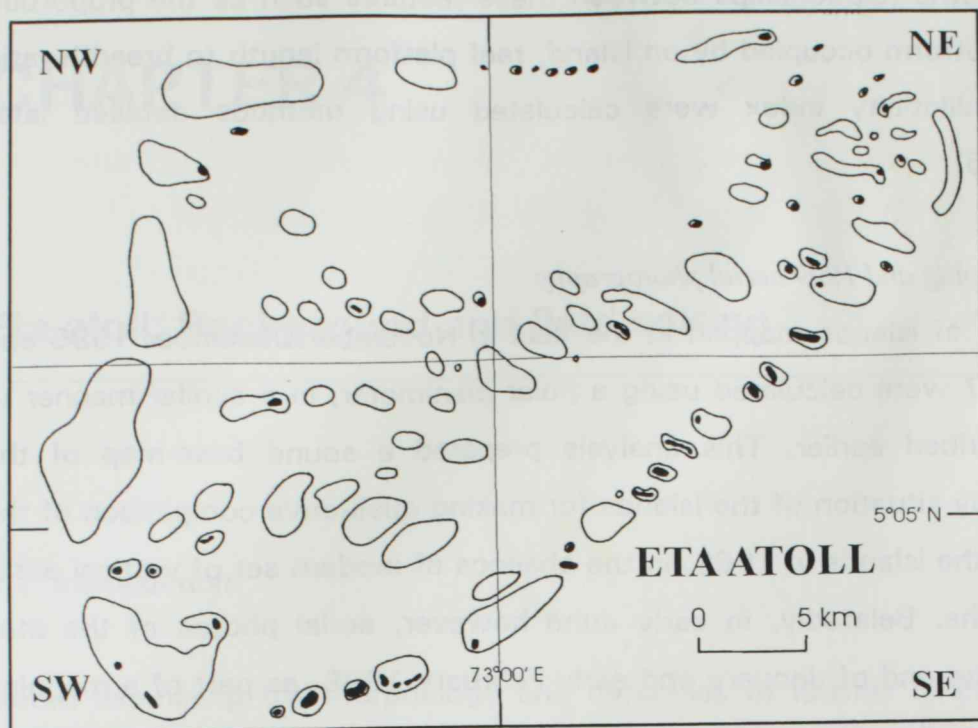


Figure 3.9 The quadrants of Eta atoll. References to these quadrants are made in the following chapters to indicate the location of a particular feature in the atoll.

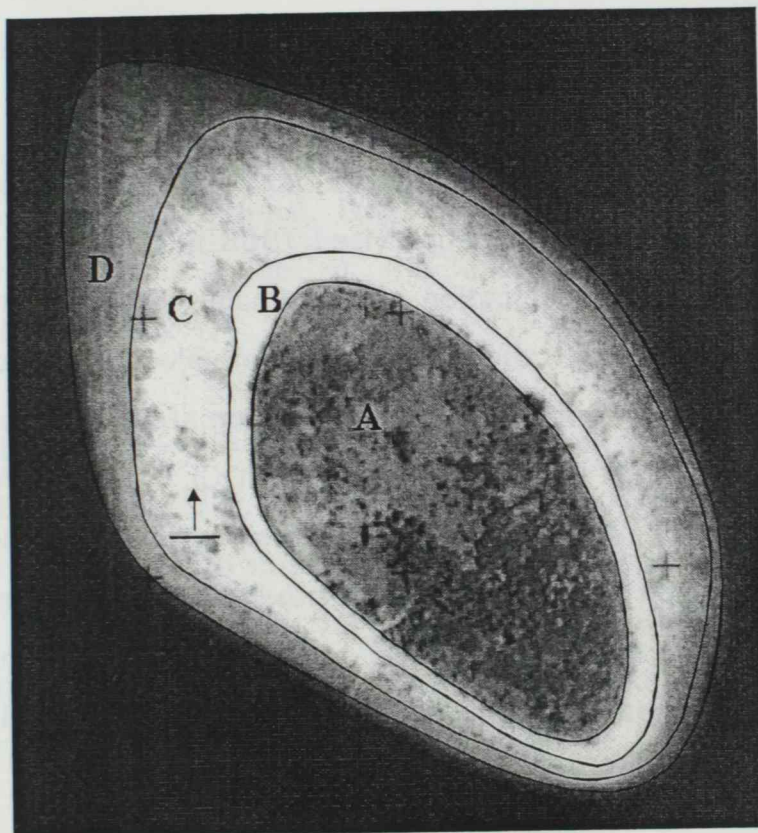


Figure 3.10 The definitions of reef-top morphologies as used in this study. A: island, B: active sediment zone (beach), C: reef flat, D: reef slope. The arrow indicates north, and the bar scale represents 50m.

Morphometric relationships between these features such as the proportion of reef platform occupied by an island, reef platform length to breadth ratio and an ellipticity index were calculated using methods detailed later (Chapter 5).

Island mapping and 1999 aerial photography

The areas of islands mapped in the field in November/December 1996 and April 1997 were calculated using a polar planimeter, in a similar manner to that described earlier. This analysis prepared a sound base-map of the present-day situation of the islands for making qualitative comparison of the status of the islands in 1969, in the absence of modern set of vertical aerial photographs. Belatedly, in early June however, aerial photos of the atoll taken at the end of January and early February 1999, as part of a mapping project by the Government of Maldives became available. With the availability of the photos, much effort has been made to incorporate data from this new resource into the thesis even at this late stage.

Vegetation classification

Information about the spectral signature values for the vegetation types identified for Eta atoll on the unsupervised 1988 SPOT image was used to perform a supervised classification of the image. Training areas for this purpose were selected from the labelled spectral values of the unsupervised classification. Based on a minimum of five training areas for each vegetation category, the Minimum Distance Classifier (MDC) in IDRISI for Windows was used to classify the image. The MDC assigns pixels to the class they are closest to in each band. This method produces best results for training areas with less perfect quality data. The supervised classification image can then display the location of the four vegetation types identified for the islands.

The methods described above have been used to obtain the results presented in Chapters 4, 5, 6, 7, and 8.

CHAPTER 4

Eta atoll: Background and field setting

4.1 Introduction

Before examining the morphology and dynamics of islands in Eta atoll in detail, this chapter describes the broad geological background of the Maldives, and proposes a classification of atolls, reef platforms and islands that is appropriate for the country. It then discusses the latitudinal variation in atoll, reef platform and island characteristics and their relationships in order to determine whether or not some of the generalisations made by other workers can be confirmed. Emphasis is initially on the more recent references rather than those of the earlier expeditions, which are summarised in Appendix 1.

Thus, the initial concern is with the Maldives as a whole and this provides a context for Eta atoll the focus of this study. The salient characteristics of Eta atoll and its setting are then described. It will be shown that the atoll has several features, including reef platform and island types that are characteristic of one group of atolls in the Maldives and justify the view that Eta atoll is representative of the 'open-type' of atolls.

4.2 Geological background of the Maldives

4.2.1 Volcanic foundation and carbonate banks

The Maldives is one of the three groups of atolls on the nearly 3000 km long Laccadive-Chagos Ridge, which marks the eastern limit of the Central Indian Basin (Schlich 1982). According to Kidd and Davies (1978) the Ridge was formed before India joined the rest of Asia, from a hot spot originating near present day R'eunion Island. The volcanics of the ridge which are believed to have been formed subaerially, as basalt flows, are now at depths of at least 2000m below sea level, and date to 57.2 million years (Late Palaeocene) (Duncan and Hargraves 1990; Aubert and Droxler 1992).

Shallow carbonate deposition on the submarine ridge began in early Eocene times (~ 50 million years) (Aubert and Droxler 1992), when much of the western Indian Ocean remained shallow and the ridge was within easy colonisation depths for corals (Kidd and Davies 1978). Sea level has fluctuated on the carbonate banks of the Maldives. Aubert and Droxler (1992) suggest that in the mid-Oligocene (30 my ago), the largest Palaeogene drop was recorded exposing shallow banks, which resulted in the development of a distinct karst relief. Local channelling and drowning events in the late Pliocene-Pleistocene (Aubert 1994), then caused segmentation of the complex into individual carbonate banks, resulting in prototypes of the reefal physiographies that we see today. At Ocean Drilling Programme Site 716, a long continuous carbonate-rich sequence recovered from a shallow basin in the Maldives, close to Eta atoll indicates a Late Quaternary sedimentation rate of 3cm per 1000 years based on oxygen isotope stratigraphy and biostratigraphic datums (Cullen and Droxler 1990).

In the most recent glacial period sea level fell from its last interglacial high (about 120,000 years ago) to its lowest level (about 120m below present level) approximately 20,000 years ago. At this time the reef structures were subjected to the most recent phase of subaerial exposure and karst erosion. Terraces or cave-like features near Alifushi (δ atoll), at depths from 20 to 65m (Cousteau and Dirole' 1971), provide some evidence of this exposure and suggest an episodic movement in sea level rather than a continuous fall and subsequent rise. More recently Anderson (1998) has identified submarine terraces around Maldivian atolls which suggest a sea level of about 130m below present at the last glacial maximum.

These geological studies indicate that successive exposure and submergence of carbonate banks has moulded the basic physical structure of the Maldives upon which the present-day atolls and related features have developed.

4.2.2 Atoll and island formation

Although he did not visit the Maldives Darwin (1842), primarily based on surveys of Moresby, suggested that the islands first appeared as a barrier reef and that erosion combined with subsidence of the carbonate bank separated and eventually deepened the channels dividing the atolls. On the other hand, Gardiner (1903) believed that deep sea erosion formed the foundations for coral colonisation. The reef lagoons were seen to have originated by a combination of more rapid reef growth on the deepwater edges of original banks together with submarine solution and accelerated erosion of the central part. Following his visit, Agassiz (1902) proposed the growth of reefs on pre-existing minor elevations.

Daly (1910) viewed the flatness of the atoll lagoon floors in the Maldives as resulting from wave planation because of low sea level and the succession

of reef growth with changes in sea level. Hass (1962) argued that porous reef framework can collapse under its own weight (behind the seaward advancing reef rim), to produce the distinct 'basin-shape' evident in the atolls of the Maldives. Since the deepest point on the oceanic geoid occurs under the Maldives (Figure 4.1), Nunn (1994) is of the opinion that the atolls may not have formed in accordance with the Darwinian subsidence model but by reefs growing on submarine banks, with sea level falls and geoid movements.

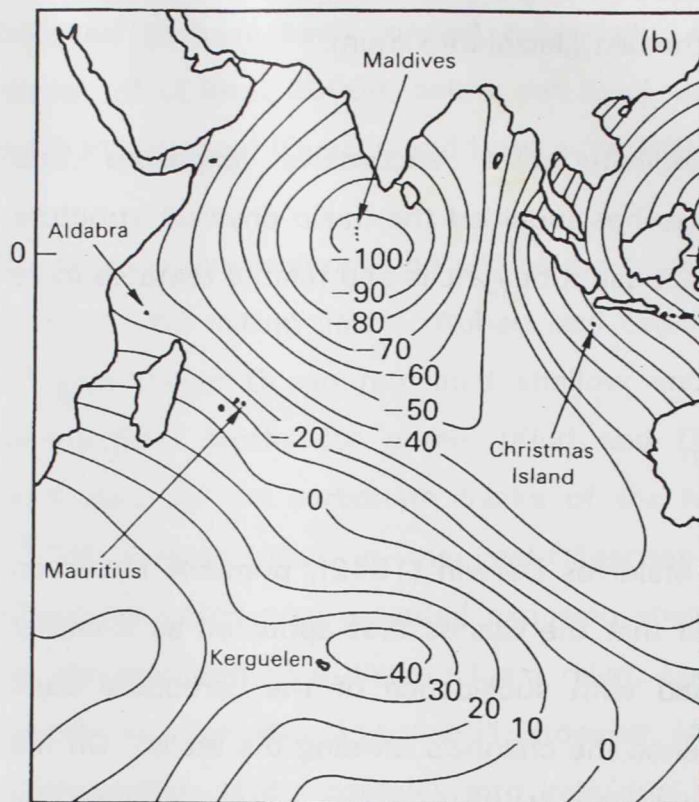


Figure 4.1 The modern surface of the oceanic geoid in the Indian Ocean. Ocean geoid heights are in metres calculated with respect to the best fitting ellipsoid. Globally, the deepest point of the oceanic geoid lies over the Maldives. (Source: Nunn 1994)

Purdy and Bertram (1992) cite examples from the Maldives to emphasise the importance of karst-produced relief against growth-produced relief, in shaping atoll morphology. On the other hand, Ladd (1977) thought the major factor controlling the distribution of atolls in the deep ocean (referring to Suvadiva (ϕ) in the Maldives) is submarine volcanism, a process that he believed has provided the numerous isolated cones, later to become atolls.

From evidence in the Maldives, Purdy and Bertram (1992) supported the importance of antecedent relief, (as stressed by Hoffmeister and Ladd (1944), particularly in explaining small reefs in mobile areas, where large scale Darwinian subsidence has probably not occurred (Steers and Stoddart 1977). However, Darwin (1842, p.78) indicated that reefs in certain situations may be converted into an atoll without passing through the intermediate form of a barrier-reef.

From this analysis it appears that the present day atoll morphology of the Maldives originated from the reef deposition-karst erosion cycles, occasioned primarily by glacially induced sea level changes since the Plio-Pleistocene. More recently, the present-day islands in the Maldives have formed since sea level reached its present level, after the last deglaciation, and only in the last 3000 years according to Woodroffe (1993).

In summary then, the atolls of the Maldives did not originate in a strictly Darwinian sequence of fringing reef, barrier reef to atoll through stages by subsidence. However, subsidence did occur, and this accounts for the enormous carbonate sedimentary cappings on the initial, now ancient volcanic ridge in the region. At the same time sea level fluctuations and erosion combined with subaerial solution, acted on the antecedent relief. Therefore, the present-day atolls at a first order level are revised imprints of an antecedent topography and morphology, that is the result of long term geological subsidence and sea level changes.

4.3 Characteristics of atolls, reef platforms and islands

The islands of the Maldives occur on reef platforms associated with 26 atolls. Atolls here are taken to mean emergent reefs or islands forming distinct entities, surrounded by relatively deeper waters (channels or straits) that separate one atoll from another. A broad classification of the atolls,

reef platforms and islands of relevance in the Maldives is presented in the next section.

4.3.1 Classification of atolls

Three broad geographical groupings of atoll are evident along the length of the Maldivian archipelago. First, the northern-most atolls are characterised by a relative absence of faros and patch reefs especially in the atoll lagoon, but they also contain islands both in the lagoon and on the atoll periphery. Second, atolls of the central (or the double chain) part of the archipelago are characterised by the presence of numerous faros, patch reefs as well as islands in the lagoon, and on the atoll rim. Third, a greater continuity of the peripheral reefs and relative absence of islands within the lagoon mark atolls to the south of the double chain. The proportion of passages on the atoll rim is much less in the south and the peripheral reef platforms usually support multiple islands. On a finer scale, three types of atolls and reefs can be identified for the Maldives: 1) open atolls, 2) closed atolls, and 3) 'table' reefs. These are shown in the photo of Ari (Ξ) Rasdhoo (ν) and Thoddoo (μ) from central western Maldives (Figure 4.2), taken from Space Shuttle in 1993.

- 1) *Open atolls* are characterised by an annular string of reef platforms and islands broken by broad and deep passages, which permit waves to penetrate into the lagoons. Faros and patch reef platforms sometimes surmounted by islands are common in the lagoon. The peripheral reefs of the atoll support either single or multiple islands. Thirteen of the 26 atolls in the Maldives fall into this group, including Eta atoll, the subject of this study. It is the open atolls that are uniquely Maldivian and the ones that gave Fosberg (1957) the 'impression of dissimilarity with the Pacific atolls'.

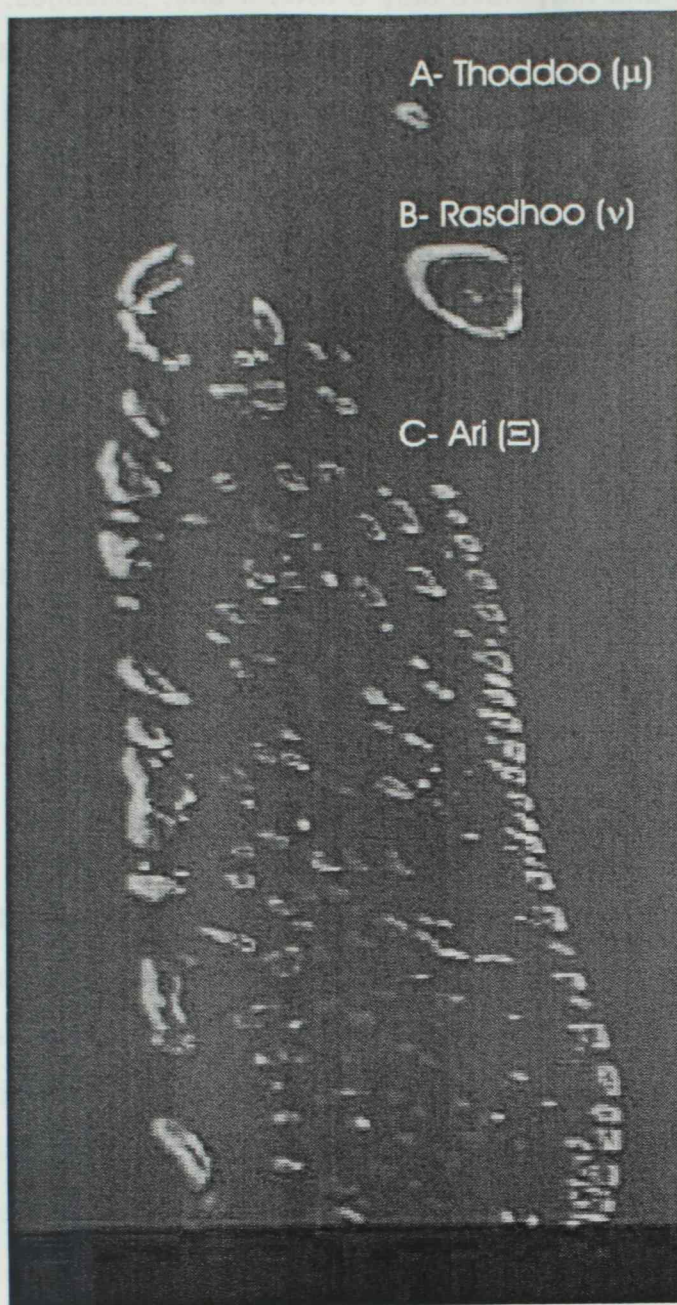


Figure 4.2 Three types of atolls that occur in the Maldives. This group of atolls which occur to the south of Eta atoll, shows the three distinct types:

- A- 'Table' reef (Thoddoo [μ]),
- B- Closed atoll (Rasdhoo [v]),
- C- Open atoll (Ari [Ξ])

This photo was taken by astronauts out of the windows of Space Shuttle.

Date: 1993-04-14, Time: 03:46:24 GMT, Alt: 160 nautical miles.

*Source: <http://earthrise.earthkam.ucsd.edu/cgi-bin/er/quick?r=56646&5>
(8/12/99)*

- 2) *Closed atolls* are characterised by greater continuity of the atoll rim, which circumscribes the lagoon and may have only a few, if any, passages. Patch reefs, faros, and islands are not common in the lagoons of these atolls. An example is Goidhoo Atoll (K), immediately to the south of Eta, and Addu Atoll (Ψ), the southernmost atoll in the Maldives. These are the 'typical' Pacific atolls.
- 3) *Table reefs* are not atolls in the strictest sense in that they do not have a lagoon around which islands occur on reefs. Rather, they are isolated, single reef platforms that arise from the deep surrounding sea. Islands on these reefs may occupy much of the reef platform. The four 'table reefs', Alifushi/Ehthigili (δ), Kaashidhoo (ι) Thoddoo (μ), and Fuahmulaku (χ) are the smallest in size of all the 'atolls' in the Maldives and they are dispersed from north to south.

4.3.2 Classification of reef platforms

A classification of reef platforms appropriate for the Maldives and for the study site is shown in Figure 4.3. The primary division is made between reef platforms that are clearly exposed or are clearly submerged at low water. Reefs and faros that occur about sea level are capable of supporting islands, while reef platforms which lie below sea level, including knolls, are not. Davies *et. al.* (1971) with reference to Addu Atoll (Ψ) indicated that patch reef platforms are ...*capped with wave-breaking coral*. While knolls are defined as ...*failing to reach the surface* (p.250). At a second order level, the location of reef platforms can be used to distinguish them. The three types are *lagoonal*, if the reef platform occurs within the atoll lagoon; *peripheral*, if it occurs on the atoll rim, and *oceanic* if it is located outside of an atoll. These reefs or faros may have islands, which can consist of a single island or multiple islands.

REEF PLATFORMS

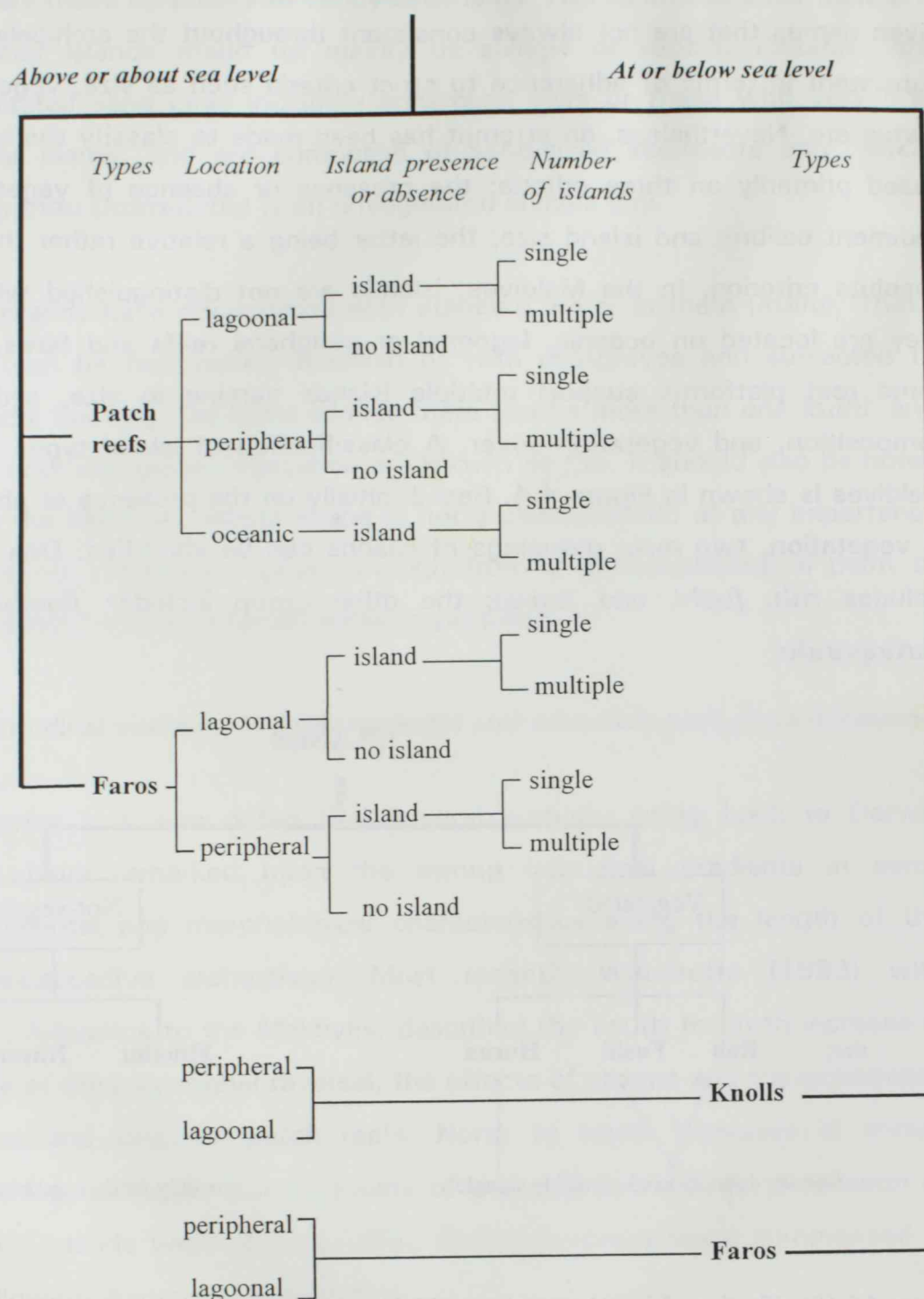


Figure 4.3. Classification of reef platforms in the Maldives. Reef platforms are initially distinguished with relation to sea level. They are further differentiated on their location, and whether or not they carry an island or more than one island.

4.3.3. Classification of islands

In the Maldives several types of islands are locally distinguished and are given names that are not always consistent throughout the archipelago or consistent in terms of adherence to strict criteria such as size, vegetation status etc. Nevertheless, an attempt has been made to classify the islands based primarily on three criteria: the presence or absence of vegetation; sediment calibre; and island size; the latter being a relative rather than an absolute criterion. In the Maldives, islands are not distinguished whether they are located on oceanic, lagoonal or peripheral reefs and faros. Also some reef platforms support multiple islands varying in size, sediment composition, and vegetation cover. A classification of island types in the Maldives is shown in Figure 4.4. Based initially on the presence or absence of vegetation, two main groupings of islands can be identified. One group includes *rah*, *fushi*, and *huraa*; the other group includes *finolhu* and *huraagandu*.

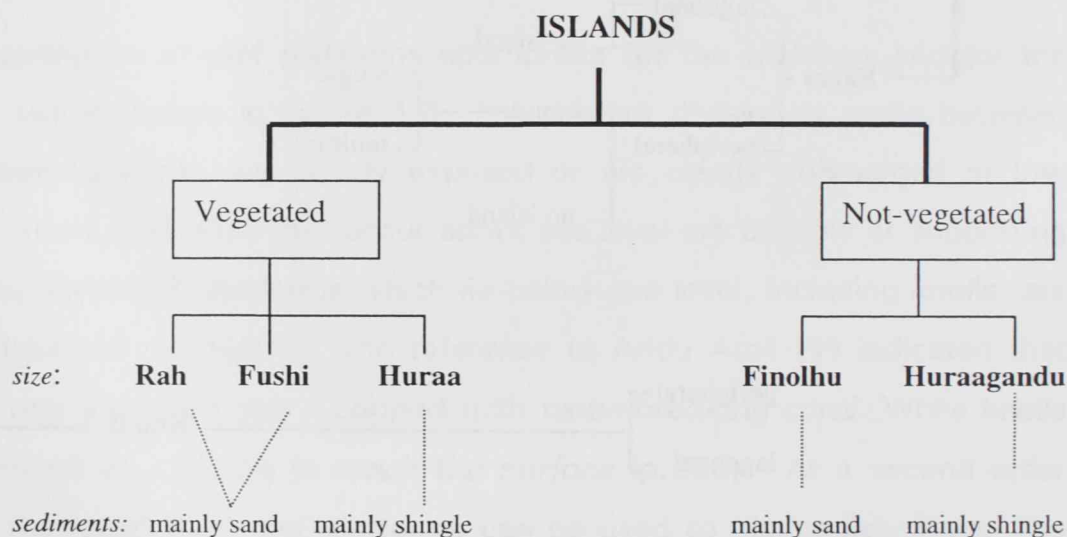


Figure 4.4 Classification of island types in the Maldives using local names. Note for vegetated islands no distinction is made on the grounds of sediment calibre between *rah* and *fushi*. The terms apply equally to islands made up of sand, shingle or a mixture.

Rah, the largest or the most 'mature' of the islands is followed by *fushi* which are distinguished on the basis of their size or vegetation cover. Both types are made up mainly of sandy sediments. *Huraa* on the other hand are vegetated islands made up mainly of shingle or rubble. *Finolhus* are unvegetated sand cays including ephemeral cays or those with very few vascular plants, and are composed of sand-sized sediments only, while *huraagandu* (*huraalette*) is an unvegetated shingle cay.

Some islands have depressions with standing water in them (*kulhi*). These *kulhis* can be freshwater, brackish or with mangroves and subjected to daily tidal flushing. On some islands there can be more than one *kulhi*, and *kulhis* with mangrove vegetation are known as *faa*. It should also be noted that in the Maldives, island shape is not a characteristic of any importance in terms of island description, though from a geomorphological point of view island shape is of fundamental importance.

4.4 Latitudinal variation in environmental and morphological characteristics

In Chapter 1 it was noted that several authors, going back to Darwin (1842) have remarked upon the strong latitudinal gradients in some environmental and morphological characteristics along the length of the Chagos-Laccadive archipelago. Most recently Woodroffe (1993) with specific reference to the Maldives, described the south to north increase in the role of the monsoonal reversal, the effects of storms and the occurrence of faros and lagoonal patch reefs. North to south increases in annual rainfall, lagoon depth, the continuity of the atoll rim and the proportion of rim with islands were also identified and both trends were summarised in the following diagram (Figure 4.5).

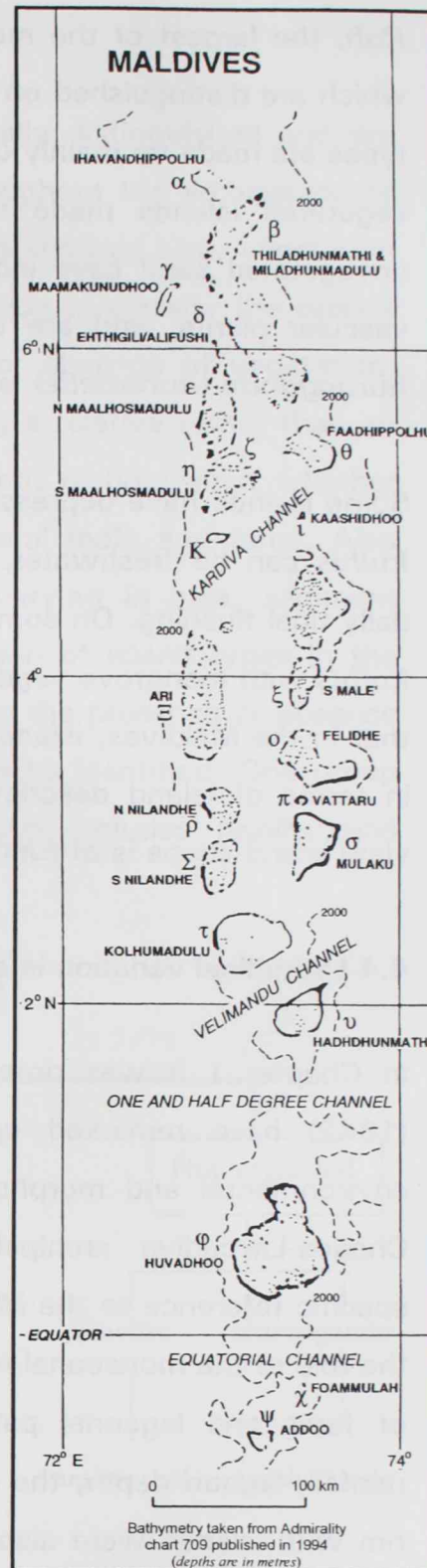
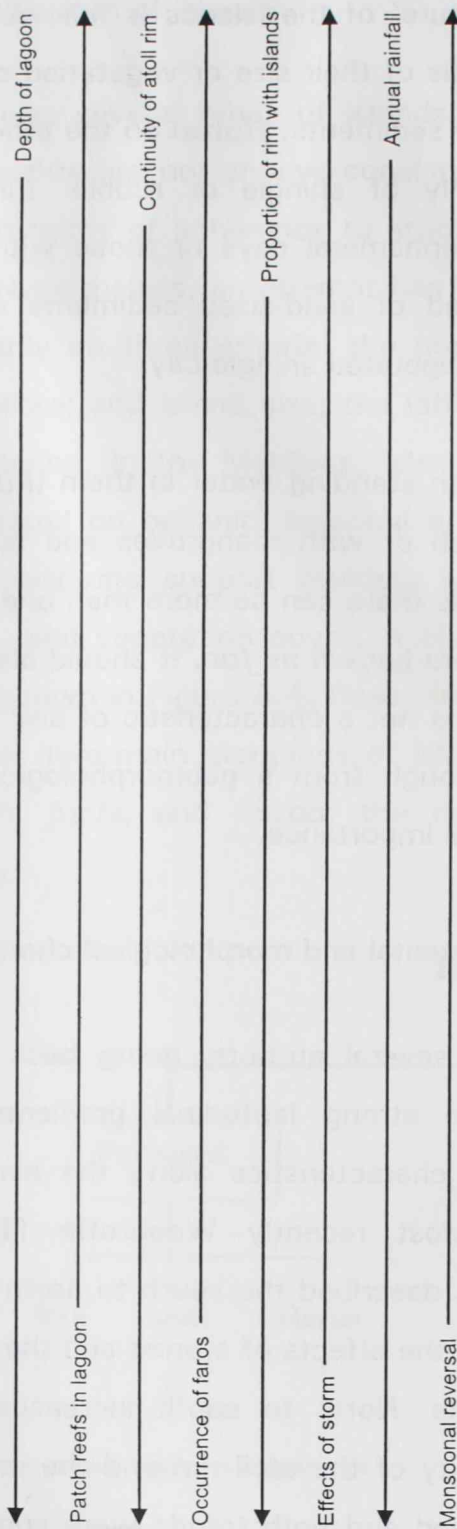


Figure 4. 5 The latitudinal variations in morphological and climatic trends through the Maldives (source: Woodroffe 1993). The figure shows that lagoon depths, continuity of atoll rim reef, the proportion of atoll rim reef with islands and the amount of rainfall increase towards the south. The number of patch reefs in lagoons, occurrence of faros and the effect of storms and monsoonal reversal increases from south to north.

A number of these latitudinal/morphological relationships are considered in this chapter. First to test the validity of some of the proposed trends and, second to establish how representative the study atoll (Eta) is of Maldivian atolls and islands in general. The techniques used for this analysis have been outlined in Chapter 3 and in each of the following figures the atolls are identified by the appropriate Greek letter with Eta (η) highlighted.

The analysis is based on a total of 2170 reef platforms of which 1046 (48.2%) contain islands. Oceanic reefs are not included in some of the analyses.

4.4.1 Reef platforms and islands

Figure 4.6 plots the total number of reef platforms divided into two groups, those on the margin of an atoll (peripheral) and those located within the lagoon (lagoonal). It shows that the southern atolls have a much greater number of lagoonal reef platforms with seven of the atolls in that area having over hundred reef platforms compared with only one atoll (North Maalhosmadulu (ϵ)) in the north having such a number. The figure also shows the number of reef platforms with one or more islands and those that do not have any islands at all. Islands are shown to be more frequent in the north both in lagoonal and atoll margin situations. On the other hand there is clear evidence that the total number of reef platforms within the lagoon is greatest in the southern half of the Maldives though proportionally fewer of them carry islands.

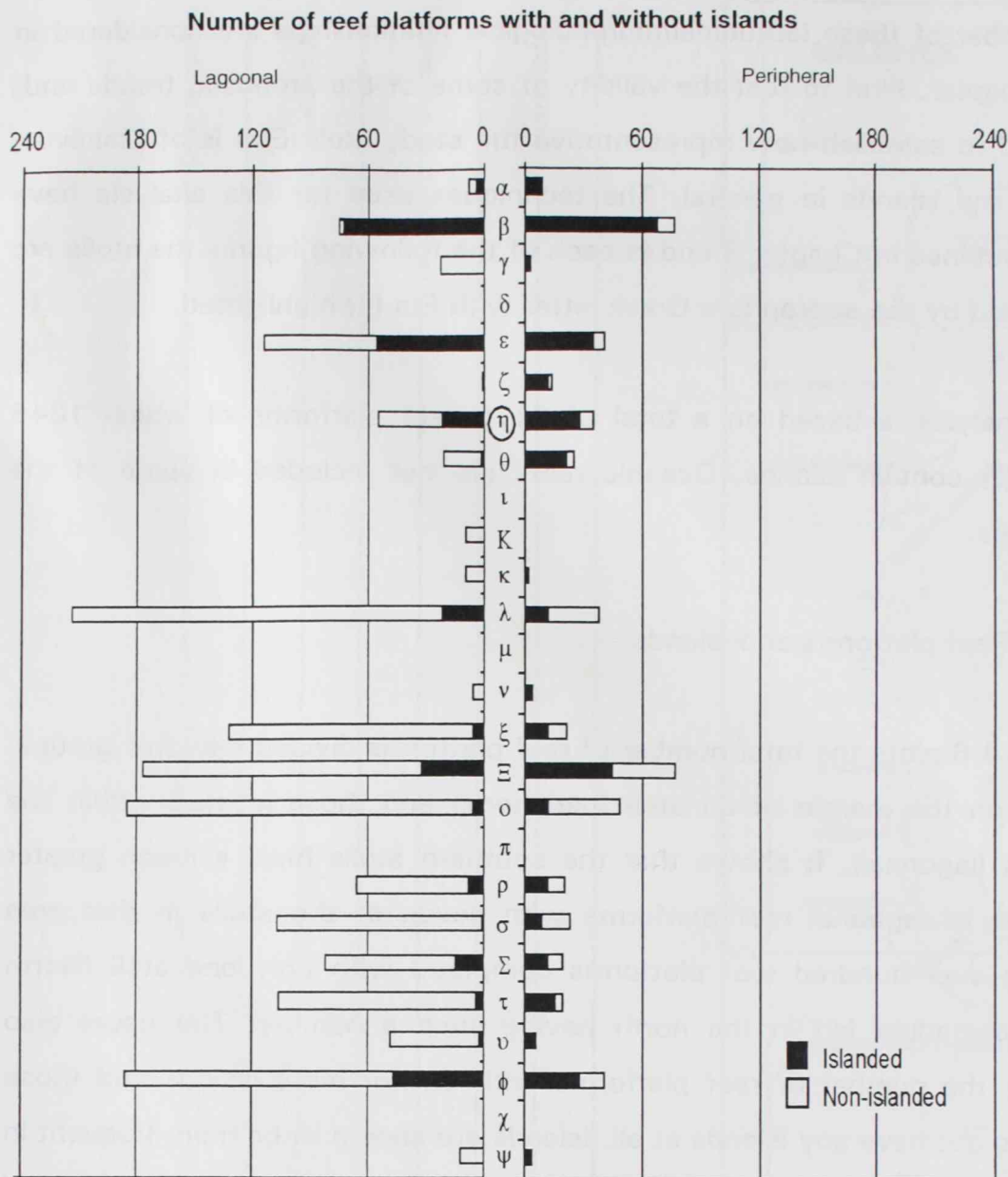


Figure 4.6 Number of reef platforms and those with islands ('islanded') and those without islands ('non-islanded'). Atolls are arranged in sequence from north to south using appropriate Greek letter identifier. Eta atoll is circled for ease of identification.

4.4.2 Islands

Figure 4.7 shows the number of reef platforms that have islands. No latitudinal trend is evident, though the two atolls with the largest numbers 141 and 91 Thiladhunmathi-Miladhunmadulu (β) and North Maalhosmadulu (ϵ) are in the north. There is however, a clear relationship with atoll type.

Ninety percent of the reef platforms with islands are found on open atolls, a not surprising relationship given that such atolls have broken rims with many peripheral reef platforms. Also plotted are reef platforms containing one island and more than one island (multiple islanded) the latter more common on peripheral reefs and rarely on lagoonal reefs. The number of reef platforms with more than one island does not show any latitudinal trend.

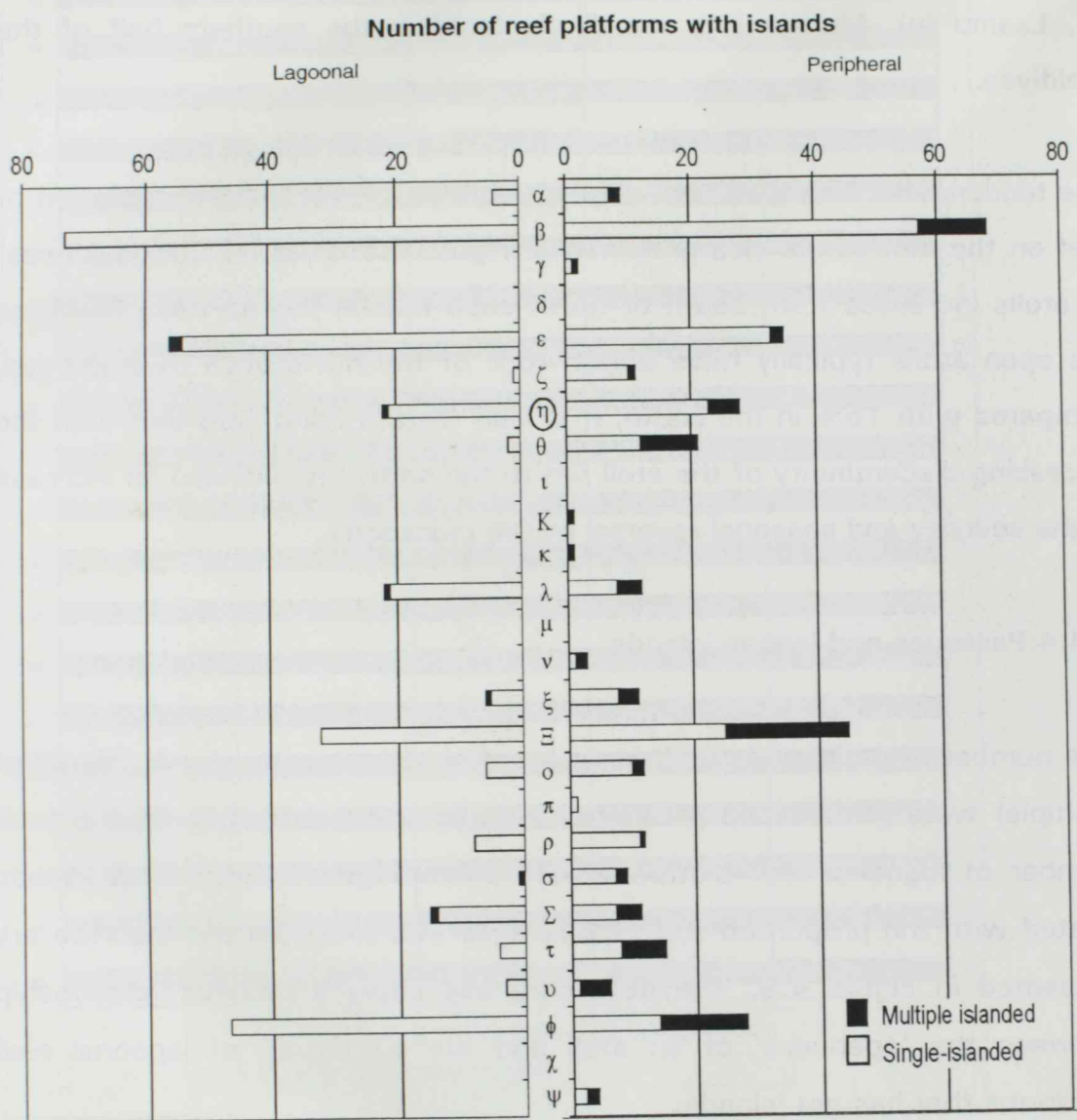


Figure 4.7 Number of reef platforms with islands subdivided into those with one island ('single-islanded') and those with more than one island ('multiple-islanded'). Islands on atoll rims and those within lagoons are shown separately. Eta atoll is circled for identification.

4.4.3 Atoll rim platforms and passages

The proportion of atoll rim made up of reef platforms and passages, (a measure of atoll openness), is shown in Figure 4.8, which for the sake of completeness also includes data from the table reefs and closed atolls. By definition (in this thesis) passages which occupy less than 10 per cent of the atoll rim are closed atolls and these together with the table reefs occur throughout the archipelago, though the largest closed atolls (Kolhumadulu (τ), Laamu (υ), Mulaku (σ)) are all clustered in the southern half of the Maldives.

The tendency for the open atolls in the south to have a greater proportion of reef on the atoll rim is clearly shown in Figure 4.8. That is, the 'openness' of atolls increases from south to north such that in the northern Maldives the open atolls typically have about 40% of the rim broken by passages, compared with 15% in the south. It is also worth noting here that with the increasing discontinuity of the atoll rim to the north there is also an increase in the severity and seasonal reversal of the monsoons.

4.4.4 Passages and lagoon islands

The number of peripheral and lagoonal reef platforms with islands (single or multiple) were plotted and presented in Figures 4.6 and 4.7. Of the total number of lagoonal reef platforms, the percentage of those with islands related with the proportion (%) of passages that make up the atoll rim are presented in Figure 4.9. The data generally imply a positive relationship between the 'openness' of an atoll and the proportion of lagoonal reef platforms that has got islands.

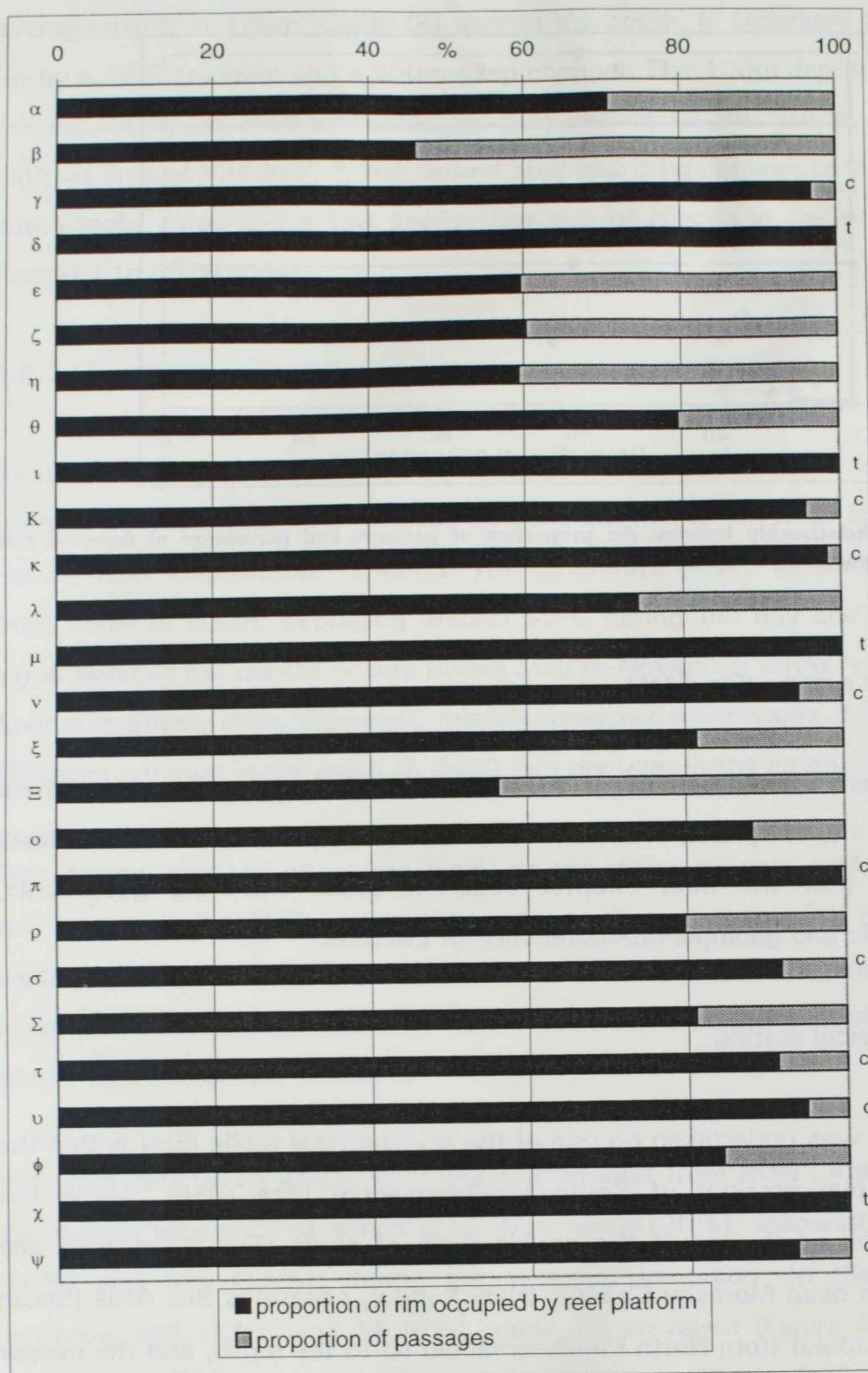


Figure 4.8 Latitudinal variation in the proportion of atoll rim occupied by reef and passage.
t = 'table reefs'; c = 'closed atolls'.

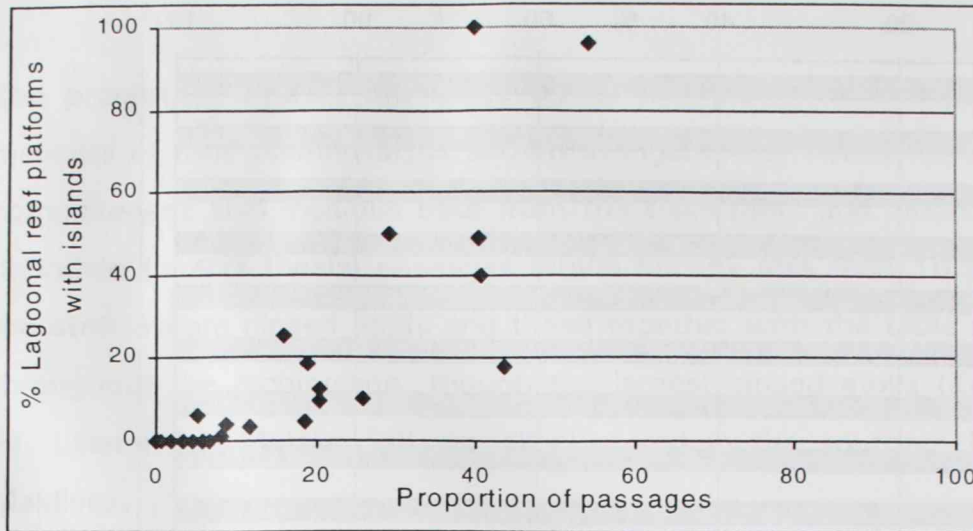


Figure 4.9 Relationship between the proportion of passages and percentage of lagoonal reef platforms occupied by islands.

4.5. Field setting (Eta Atoll)

The relevant characteristics of the field site (Eta atoll) are outlined here including the physical, climatic, and oceanographic information. Note however, that the next chapter deals in detail with the geographic, geomorphic and geologic characteristics of Eta atoll.

4.5.1 Physical setting

The study was undertaken on one of the geographical atolls (Eta) within the administrative precinct of South Maalhosmadulu (Baa Atoll), which lies towards the northwest of the double-chain of atolls. The 3-km wide and over 200m deep Moresby Channel (Hani Kandu), separates Baa Atoll (South Maalhosmadulu) from North Maalhosmadulu (ϵ) to the north, and the deeper (500m) Kaashidhoo Channel, passes to the east and south of the atoll. Within Baa Atoll (South Maalhosmadulu), three geographical atolls are distinguished. A pear-shaped smaller atoll to the north (ζ), is separated from the largest one (η) by a 900m wide channel (Kuda Kanduolhi), with an

average depth of 165m. Goidu (K) atoll to the south, is separated from Eta (η) by a 12.5 km wide and a 500m deep channel. The 100m depth contour, encompassing Eta atoll delineates the field setting for this study. Eta atoll with an area of 924 km², is the central atoll and it has numerous passages, patch reefs, faros and a few knolls. The size of islands in the atoll range from 0.1 to 45 hectares.

4.5.2 Climatic characteristics

As no climatic data is available for Eta atoll, data from Male' (70 km to the south), were analysed and utilised. The climate in the Maldives is hot and humid, with little diurnal variation. The temperatures are generally similar from north to south, averaging around 32°C during the day and 24°C by night. Most of the rainfall occurs during May to November while February to April is relatively drier. However, rainfall increases southwards, from about 1800mm per year in the north to 2400 mm per year in the south.

Two distinct seasons affect the Maldives and these are very evident in Eta atoll; the westerly (*Hulhagu*) and the easterly (*Iruvai*) season. Of these two seasons, the westerly generally has the strongest winds and stormy weather. It occurs between May and November and the easterly season occurs from December to March.

Interpretations of 19 years of meteorological data from Male', indicate that the highest frequency of winds occur from west (20%), followed by WNW (16%) and NW (11%), during the westerly monsoon. In the easterly monsoon, ENE (12%) and NE (9%) winds are prevalent (Figure 4.10). The average monthly wind and direction is shown in Figure 4.11, and that clearly shows the strong month to month variation in wind frequency by direction.

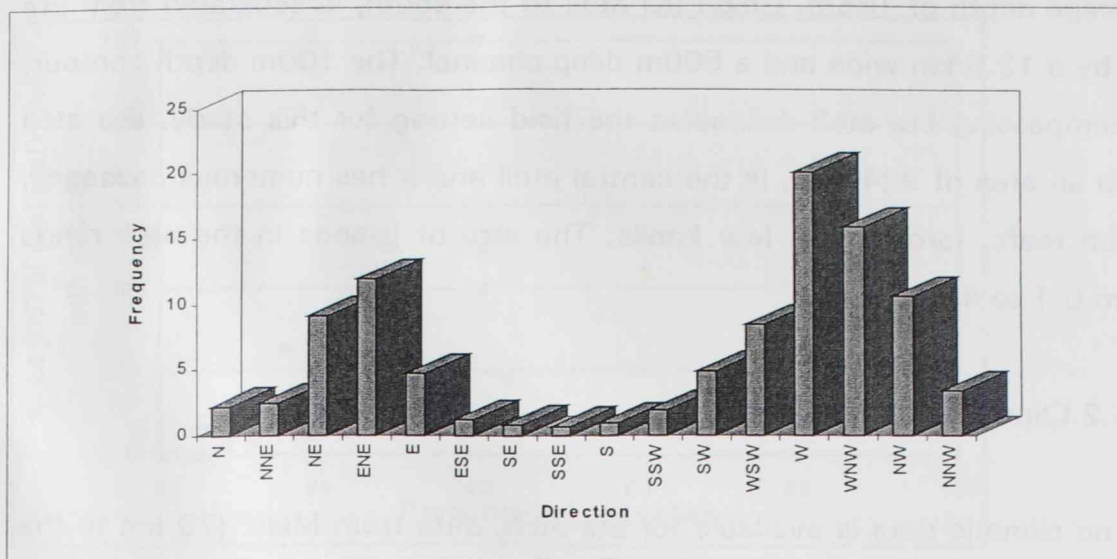


Figure 4.10 Average wind direction and frequency (1980-1998). The Figure shows the dominance of winds from two directions; easterly and westerly. The prevalence of westerly winds over the easterly winds affecting Maldives is also indicated.

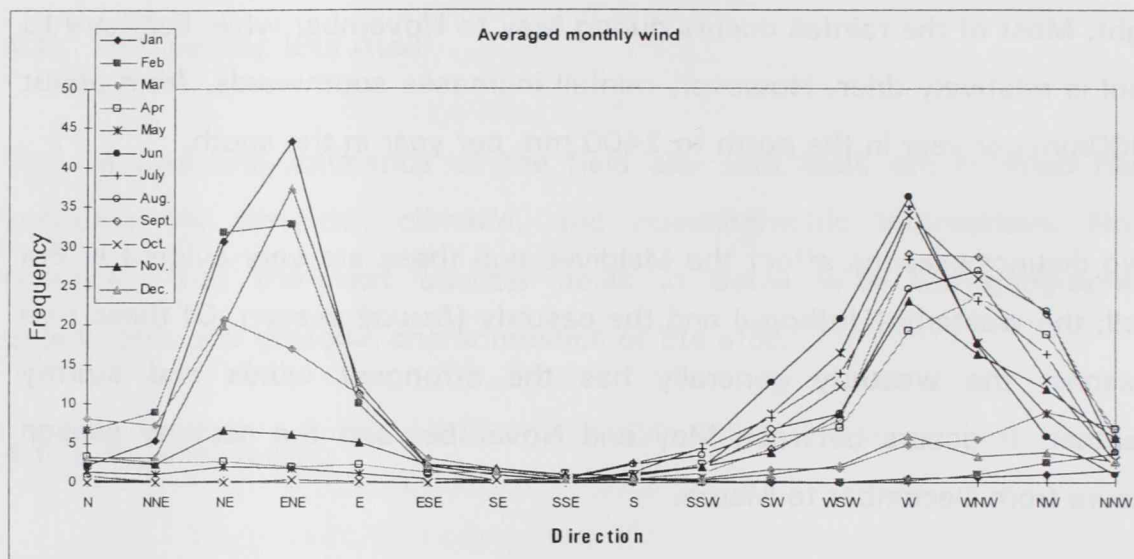


Figure 4.11 Average monthly wind direction and frequency (1980-1998). The dominance of easterly winds from December-March, and the westerly dominance from April-November is indicated.

Summary of wind conditions for the survey period and past averages:

18-year av. wind for Jan-March... 9.70km/hr
 18-year av. wind for April 6.93km/hr
 17-year av. wind for April-Oct..... 10.66km/hr
 17-year av. wind for Oct..... 10.98km/hr

1997 Jan-March av..... 9.50km/hr
 1997 April av..... 5.40km/hr
 1996 April-October av. 11.17km/hr
 1996 Oct. av..... 13.00km/hr

Though the Maldives is located well outside the cyclone belt, storms are not unknown and have been reported (Gardiner 1903; Maniku 1990), particularly in the north. Preu and Engelbrecht (1991) identified two main types of storms affecting the Maldives and consideration of their data, together with that relating specifically to Eta atoll is presented in Chapter 6.4.

4.5.3 Tides, waves currents and bathymetry

In the Maldives there is a semi-diurnal mixed tide, with a maximum range of 1.2m. Data from a field measurement programme around Male' by Lanka Hydraulic Institute Ltd. in September 1989 (MCPW *pers.com.*) also indicate that:

- meteorological tides show a normal distribution;
- there was no significant seiche activity;
- inside the atoll (Male'), wave climate is governed by locally generated waves of five seconds or less; and,
- significant wave heights outside the atoll for wind-waves reach 1.6m, and 2.0m for swells.

Details of the wave climate for the Maldives area for the period November 1986 to 1989 has been presented by Harangozo (1992). Significant wave height (H_s) data was extracted from the geophysical data record of the GEOSAT altimetric mission. For each day in the three year period all H_s data were obtained for a 20x20 degree box centred on Male'. The results (Figure 4.12) show the highest waves occur in the summer months, June to August. During this time wave heights are commonly over 2m high (and reached a maximum H_s of 4.2m). By comparison wave heights are generally less than 2m in the November to May period. Harangozo (1992) notes that the maximum deep water wave height in the record was calculated $H_{10} = 5.33\text{m}$.

These seasonal variations in wave climate have been confirmed by Young (1999) who also notes that in the Indian Ocean equatorial region immediately south of the Maldives, there is a strong background southerly swell (H_s 2 to 3m) generated by winds in the Southern Ocean between Australia and South Africa. Maximum wave heights are reached between May and August in the southern Maldives. In addition, analysis of recent tide gauge data from Hulhule' indicate a fluctuation of about ± 10 cm in MSL between 1991 and 2000 (Source: [ftp://ilikai.soest.hawaii.edu/woce/gifd/m0108w.gif](http://ilikai.soest.hawaii.edu/woce/gifd/m0108w.gif) (1/11/2000)) (see Appendix 1 p.A7 for figure)

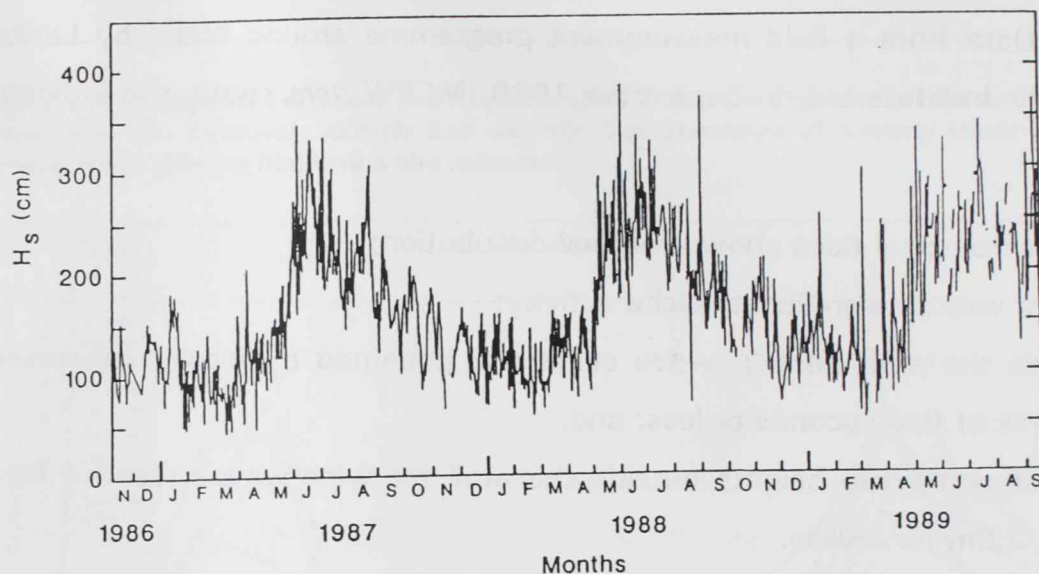


Figure 4.12 Daily time series of area averaged significant wave height (cm) based on altimetric data from GEOSAT for a 20 by 20 degree box centred on Male'. A peak in the significant wave height is evident from June through to August (Source: Harangozo 1992, p. 97).

The bathymetry of Eta atoll based on the Admiralty Chart (Figure 4.13) indicates that the atoll is of intermediate depth, compared to other atolls in the chain. The deepest point in the atoll is 62m, and occurs in a sinous north-south constricted basin in the southwest of the atoll. A much larger deep expanse of water devoid of any reefs is found in the northern part of the atoll with depths greater than 40m extending parallel with eastern rim of the atoll. On Figure 4.13 dashed lines are reef platforms (patch reefs and faros) that reach or are close to sea level, between which the passage depths are between 30-40m.

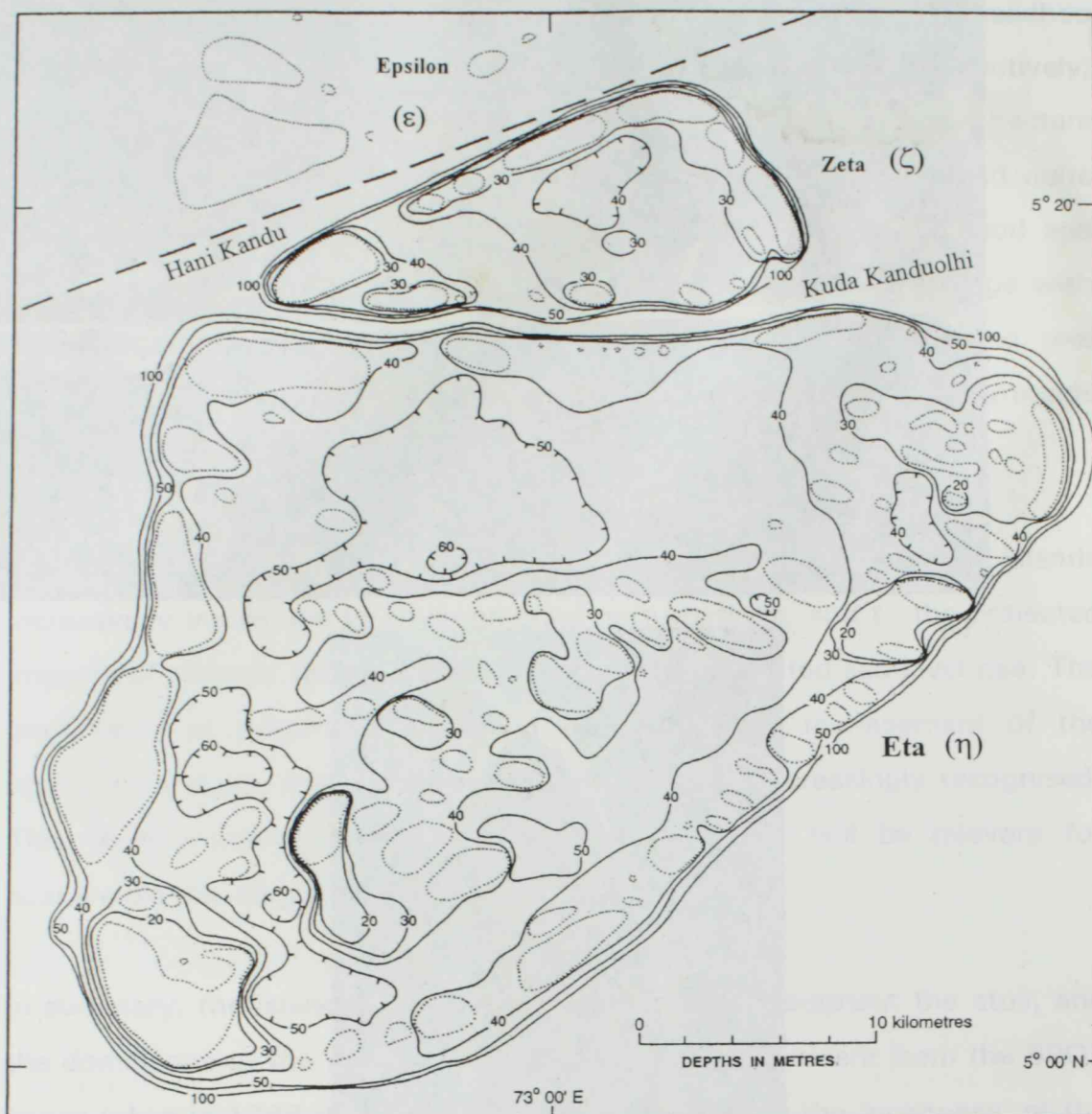


Figure 4.13 The bathymetry of the study site showing the boundary between Epsilon (ε) atoll to the north and Zeta (ζ) atoll. The bathymetry of Eta atoll shows the 100m contour that separates the study site from the other atolls. Thirty-three passages occur on Eta atoll, many of which are between 40-50m in depth. The passages on the southeastern side of the atoll are slightly shallower than elsewhere.

4.5.4 Contemporary status of the islands of Eta atoll

This thesis is primarily concerned with the uninhabited islands of Eta atoll and the 'natural' processes that have shaped them. In addition, there are nine inhabited islands plus five resort islands. Settlements are not confined to the largest islands, but are located more for access to the open sea and fishing grounds. With an estimated population of 9,394 for 1997 (Ministry



(a)



(b)

photo:MCPW 1999

Figure 4.14 Anthropogenic impacts on island and reef systems.

(a) settlement of Eydhafushi, the atoll capital of Eeta atoll, and

(b) the recently developed tourist resort of Fonimagoodhoo.

**B=buildings, C= construction of jetties etc., D=dredging of reef flat,
P=opening reef passages, R=reclamation.**

of Planning and National Development, Maldives, *pers.com.*), Thulhaadhoo and Eydhafushi have the largest populations (2274 and 2603 respectively) and are very densely populated, with 219 and 90 persons per hectare respectively. Up until now, the uninhabited islands have been used quite sustainably, in that they were mainly visited for collecting firewood and coconuts. However, in recent times that status has begun to change with activities such as harbour developments, reclamation and opening reef passages. Two examples of the extent to which islands and their surrounds can be modified are shown in Figure 4.14.

The consequences of these and other human impacts make the islands increasingly vulnerable to environmental perturbations, and to the projected impacts of climatic changes and, in particular accelerated sea level rise. The importance of longer-term planning for sustainable management of the resources and the islands themselves is becoming increasingly recognised. This study intends to identify several aspects that will be relevant for sustainable planning and management of the islands.

In summary, the islands of Eta atoll are scattered throughout the atoll, and the dominance of the sea over the area of islands is evident from the SPOT image taken in 1988 (Figure 4.15). That image shows the 'openness' of the atoll and the nature and extent of reef platforms, including the faros (ring-shaped reefs), and the dominance of islands on patch reefs. The arrangement and the alignment of the reef platforms are also clear. These patterns are likely to be reflective of the antecedent topography as well as the influence of the dominant current and wave directions, which may also influence the specific characteristics of the islands described in the next chapter.

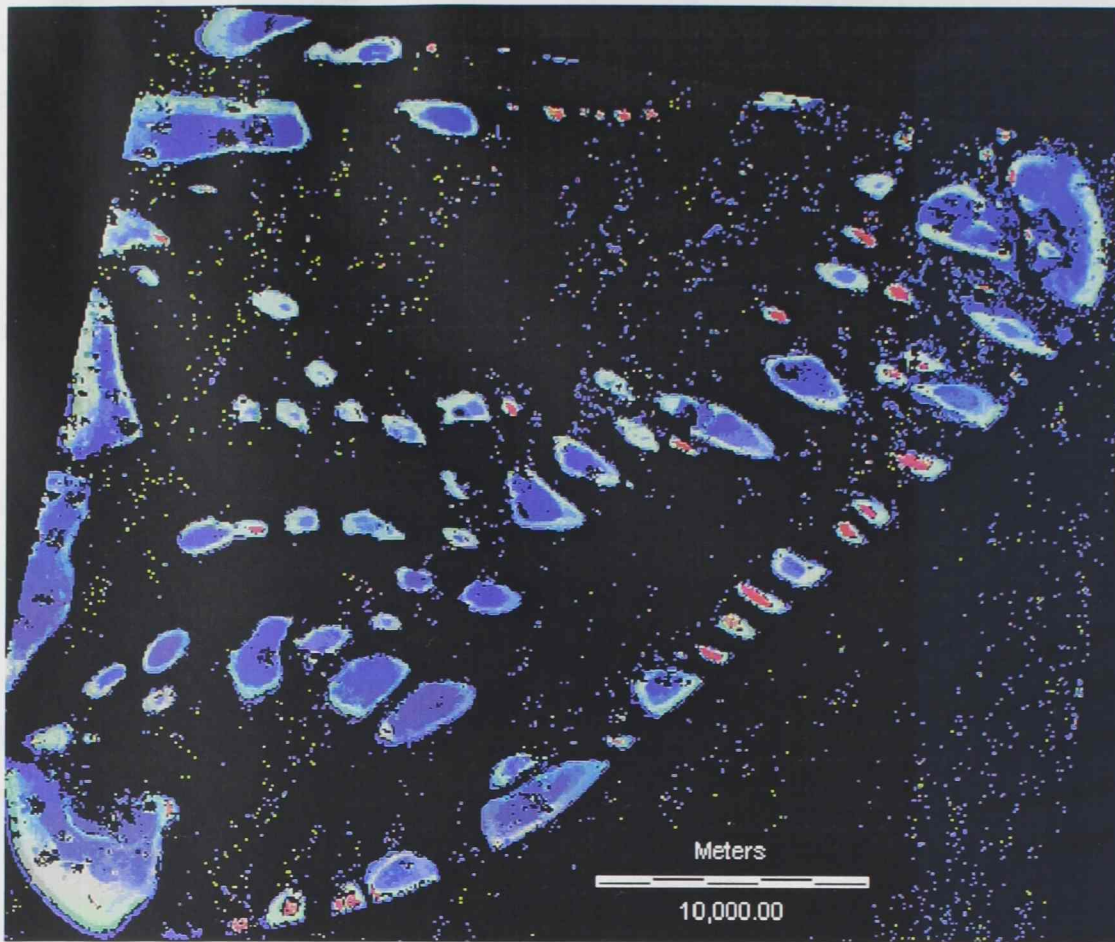


Figure 4.15 SPOT image of Eta atoll showing the different types of reef platforms and those which have islands on them. This composite image of Eta atoll taken in 1988 clearly shows the vegetated areas of islands in red, and the shallow reef flat areas in white and light blue. The shades of blue extending to deep blue indicate the increasing depth of faros and lagoons. The 'openness' of the atoll and the nature of distribution of the islands throughout the atoll is also very clear from this image.

CHAPTER 5

Islands of Eta atoll - Geographic, geomorphic and geologic characteristics

5.1 Introduction

The geographic, geomorphic and geologic characteristics of the islands of Eta atoll are described in the first part of this chapter. Examination of these characteristics is based on survey and mapping data collected in the field and on analysis of hydrographic charts and aerial photographs of the islands taken in 1969. Techniques have been described in Chapter 3.

The second part considers the general relationships between these characteristics and their spatial patterns as well as providing a quantitative classification of islands based on cluster analysis. The names and location of islands on Eta atoll are given in Figure 5.0.

5.2 Geographic characteristics

The geographic characteristics, which will be considered below, include;

- island and reef platform size,
- proportion of reef platforms occupied by island(s),
- position of island(s) on reef platforms, and
- island and reef platform orientations.

Table 5.1 summarises these characteristics utilising the quadrants of the atoll as shown in Figure 3.9.

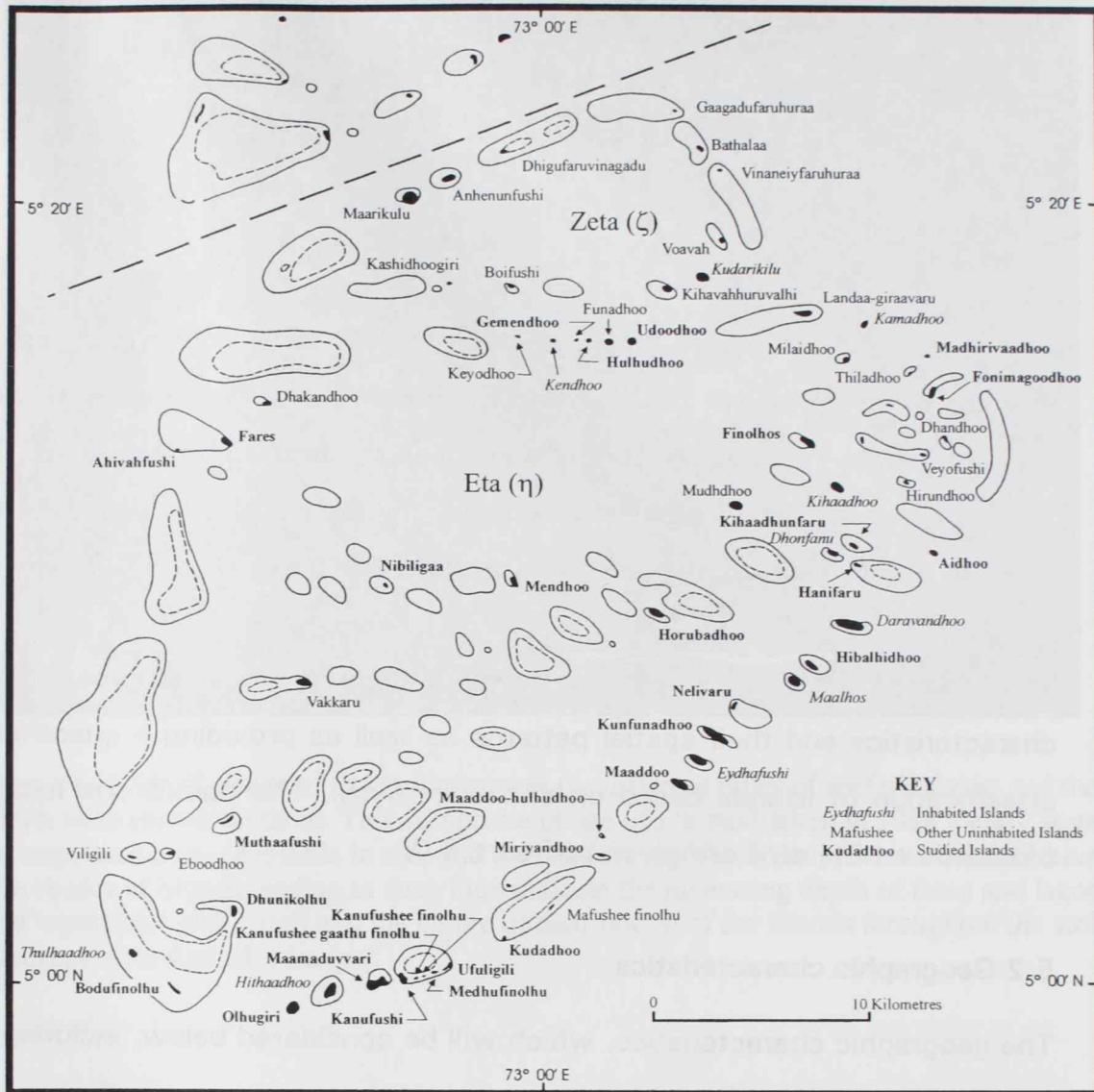


Figure 5.0. The islands of Eta atoll. The figure shows the islands that are studied and other inhabited and uninhabited islands of Eta and Zeta atolls. (A list of islands in Eta atoll and the activities undertaken on them with regards to this study was presented in Chapter 3).

Table 5.1 Selected characteristics of islands in the four quadrants of Eta atoll.

ISLAND	Island area (hectares)	% of reef platform occupied by islands	Island orientation	Island position on reef platform	Island Ellipticity Index
Northeast quadrant					
Aidhoo	2	34.7	NW-SE	W	2.1
Dhandhoo	2	19.8	NW-SE	SW	1.8
Dharavandhoo	45.5	48.9	NW-SE	W	2.7
Dhonfanu	12.6	26.4	NW-SE	NE	3.1
Finolhos	20.5	46.0	NW-SE	W	3.0
Fonimagoodhoo	7.2	6.9	N-S	SW	3.0
Funadhoo	7.8	44.7	E-W	E	1.2
Gemendhoo	1.2	34.6	NWSE	C	1.5
Hanifaru	1	0.3	NW-SE	W	4.5
Hirundhoo	4.1	38.4	NW-SE	W	2.7
Horubadhoo	12	51.3	NW-SE	C	3.3
Hulhudhoo	2.2	44.3	0	C	1.1
Kamadhoo	16.8	50.8	NE-SW	W	1.1
Kendhoo	13.7	61.6	E-W	E	1.7
Kihaadhoo	26.4	65.0	NW-SE	W	1.6
Kihaadhunfaru	8.2	12.7	NW-SE	SE	2.6
Landaa-giraavaru	14.5	4.6	E-W	E	3.8
Madhirivaadhoo	4	35.2	E-W	C	1.6
Milaidhoo	3	10.3	N-S	C	1.2
Mudhdhoo	16	47.4	NW-SE	E	1.9
Thiladhoo	2.7	18.7	0	S	1.1
Udoodhoo	9.3	51.1	0	C	1.0
Veyofushi	3.2	2.4	NW-SE	E	1.7
Southeast quadrant					
Eydhafushi	22.2	38.5	NW-SE	W	1.7
Hibalhidhoo	14.3	21.4	NW-SE	SW	2.8
Kunfunadhoo	35	42.1	NW-SE	SW	3.9
Maaddoo	18.8	51.5	NW-SE	SW	3.9
Maaddoo-hulhudhoo	1.6	37.7	NW-SE	C	1.4
Maalhos	23.2	54.6	NW-SE	W	1.5
Miriyandhoo	4.8	16.6	E-W	W	2.4
Nelivaru	0.1	0.1	N-S	NW	

Table 5.1 Continued

ISLAND	Island area (hectares)	% of reef platform area occupied by island	Island orientation	Island position on reef platform	Island Ellipticity Index
Northwest quadrant					
Ahivahfushi	0.1	0.1	N-S	SW	1.7
Dhakandhoo	4.8	46.7	E-W	E	1.7
Fares	10.2	3.5	NW-SE	NE	2.9
Keyodhoo	1.7	47.0	NW-SE	E	1.3
Mendhoo	10.5	25.8	NW-SE	E	1.9
Nibiligaa	0.5	1.0	NW-SE	E	8.3
Southwest quadrant					
Bodufinolhu	2.5	0.1	NW-SE	S	12.5
Dhunikelhu	11.3	0.5	N-S	NE	2.4
Emboodhoo	2.8	21.8	E-W	N	3.0
Hithaadhoo	25.2	18.7	NE-SW	SE	1.8
Kanufushee	0.1	0.1	NE-SW	SE	3.2
Finolhu					
Kanufushee	0.1	0.1	E-W	SE	2.7
Gaathu Finolhu					
Kanufushi	7.2	2.6	NW-SE	SW	2.9
Kudadhoo	0.6	0.1	N-S	SW	2.2
Maamaduvvari	29.6	38.0	NE-SW	S	2.7
Medhufinolhu	0.1	0.1	NE-SW	SE	4.3
Muthaafushi	3	4.3	NE-SW	N	8.4
Olhugiri	20	71.0	E-W	C	1.4
Thulhaadhoo	4.97	0.2	NW-SE	W	1.6
Ufuligili	0.5	0.2	NE-SW	E	8.3
Vakkaru	11.8	4.8	E-W	E	3.0
Viligili	1.9	2.1	E-W	W	2.2

Notes: **Island orientations**; N-S=north-south, E-W=east-west, NW-SE=northwest-southeast, NE-SW=northeast-southwest, 0=no specific orientation.

Island position on reef platform; N=north, E=east, S=south, W=west, NW=northwest, NE=northeast, SE=southeast, SW=southwest, C=center.

5.2.1 Island and reef platform size

Island and reef platform areas were calculated by planimeter using the 1969 aerial photographs. The area of islands range from 45.5 hectares (0.45km^2) to 0.1 hectares (0.001km^2). Figure 5.1 shows the distribution of island sizes for ten classes. The mean size of the islands is 9.72 hectares but as evident from the figure, the modal class is from 1 to 5 hectares. Of the 53 islands 31 have areas less than the mean value, of which, eight islands are less than one hectare in size. Areas of individual islands graphically shown

in Figure 5.2 illustrates the range of sizes and the lack of any significant size clustering, with the exception of the <5 hectares class.

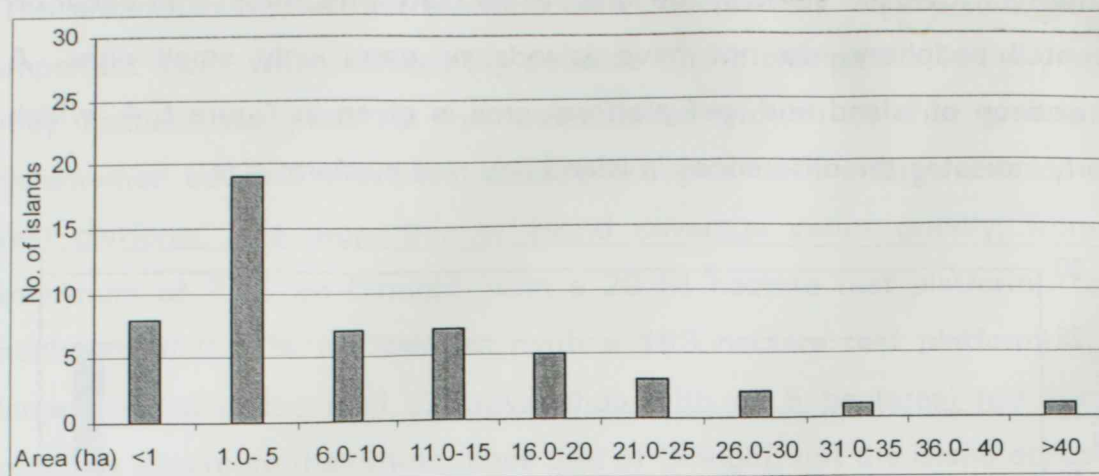


Figure 5.1 Number of islands in 10 size classes for Eta atoll.

Note: values falling between 5-6, 10-11, etc. are allocated to the lower size class.

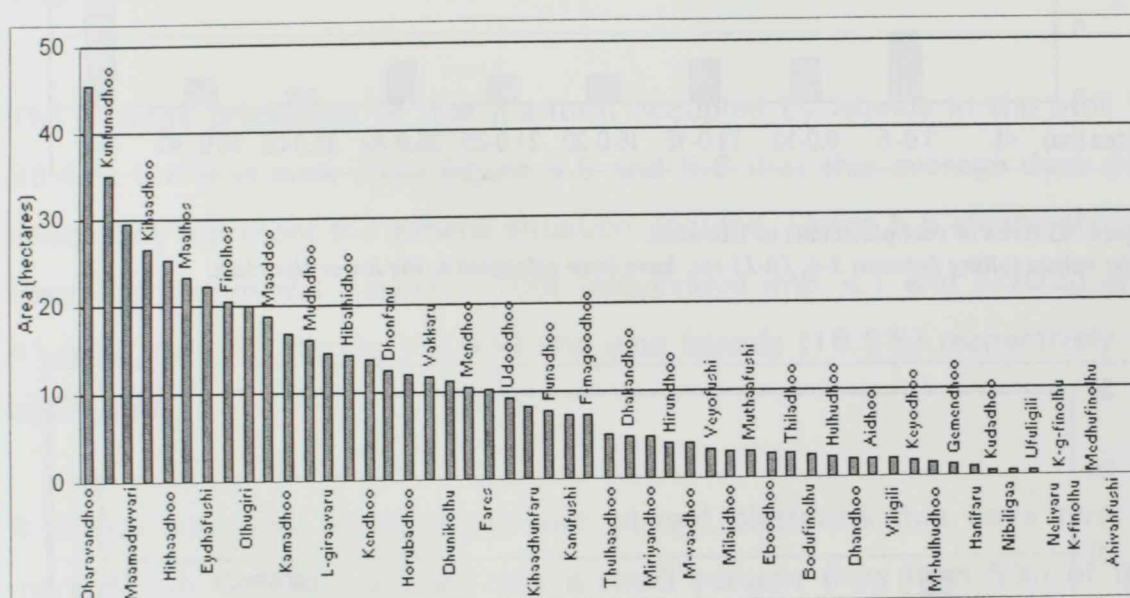


Figure 5.2 Area of islands in Eta atoll shown in decreasing value from left to right.

The area of individual reef platforms on which islands are located in the atoll range from 2137 hectares (2.14 km²) to 3.4 hectares (0.034 km²). Figure 5.3 shows the number of reef platforms in different area classes in the atoll. The modal area of reef platforms is over 40 hectares, yet only one island has an area more than 40 hectares and the mean island area is just under 10 hectares. It is also interesting to note that the smallest eight

islands ($<1\text{ha}$) in the atoll occur on reef platforms that are more than 50 hectares. The largest islands ($>27\text{ha}$) are found only on peripheral reef platforms. However, some of the largest reef platforms (faros) that occur on the atoll periphery, do not have islands or carry only small ones. A comparison of island and reef platform area is given in Figure 5.4, which clearly indicates the differences in island and reef platform size.

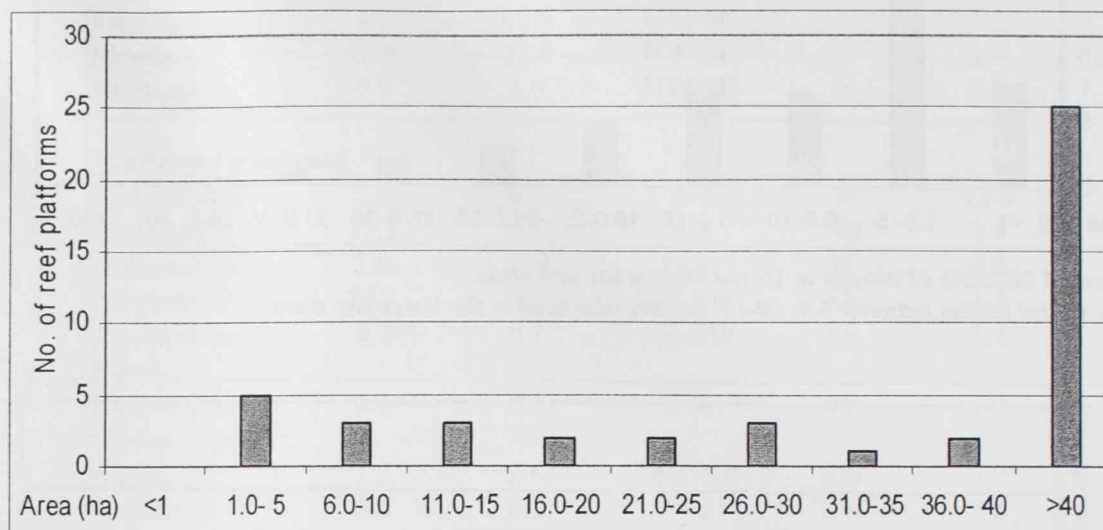


Figure 5.3 Area of reef platforms in Eta atoll.

Note: values falling between 5-6, 10-11 etc. have been allocated to the lower size class.

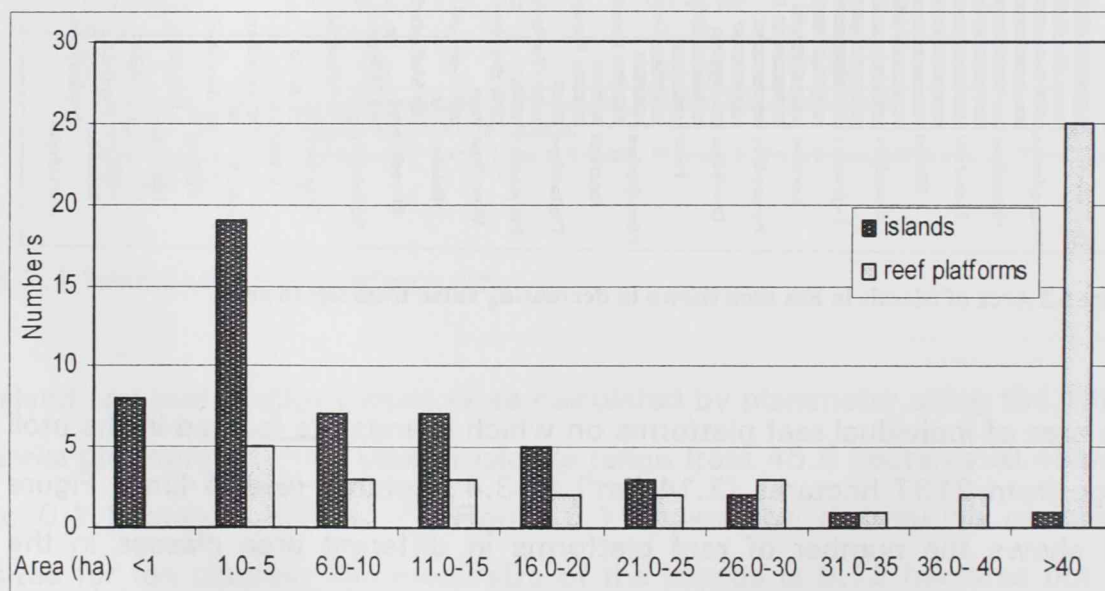


Figure 5.4 Comparison of island and reef platform areas in Eta atoll.

Note: values falling between 5-6, 10-11 etc. have been allocated to the lower size class

5.2.2 Proportion of reef platform area occupied by island(s)

The proportion of the reef platform area occupied by islands may be an important index when considering possible future changes to islands, as it may indicate the potential for future island growth or that growth is constrained because the island already occupies such a large area of the reef platform. The proportion of island coverage varies greatly, from a maximum of 71% on Olhugiri (with a 28.14 hectare reef platform), to a minimum of 0.07% on Nelivaru (with a 153 hectare reef platform). The largest island in the atoll (Dharavandhoo with 45.5 hectares) has a reef platform area more than three times that of Olhugiri, but the island occupies about half (49%) of its reef platform. Table 5.2 and Figure 5.5 show the proportion of reef area occupied by islands in decreasing order.

The average proportion of reef platform occupied by islands in the atoll is 28.4%, but it is clear from Figure 5.5 and 5.6 that this average does not adequately represent the general situation. Instead, Figure 5.6 clearly shows there are two modal classes <10% (subdivided into <1 and 1-10%) and 41-50% with 21 islands (39.6%) and nine islands (16.9%) respectively in each class.

It is also important to point out that all reef platforms that have two or more islands on them occupy only a small percent (less than 5%) of the platform. Moreover, eight of the 10 reef platforms with the lowest island cover are faros. On the other hand, eight islands in the atoll occupy more than 50% of the reef platform area. The location of the reef platform (peripheral or lagoonal) and its nature (faro or patch reef) appear to be significant influences on the proportion of reef platform occupied by island(s).

Table 5.2 Proportion of reef platform occupied by islands. The number of additional islands occurring on the same reef platform is indicated by (+)

Reef platform	% occupied
Olhugiri	71.00
Kihaadhoo	64.98
Kendhoo	61.65
Maalhos	54.59
Maaddoo	51.47
Horubadhoo	51.30
Udoodhoo	51.09
Kamadhoo	50.77
Dharavandhoo	48.87
Mudhdhoo	47.38
Keyodhoo	47.00
Dhakandhoo	46.86
Finolhos	46.00
Funadhoo	44.70
Hulhudhoo	44.26
Kunfunadhoo	42.07
Eydhafushi	38.53
Hirundhoo	38.42
Maamaduvvari	37.98
Maaddoo-hulhudhoo	37.74
Madhirivaadhoo	35.18
Aidhoo	34.75
Gemendhoo	34.57

Reef platform	% occupied
Dhonfanu	26.43
Mendhoo	25.78
Eboodhoo	21.82
Hibalhidhoo	21.45
Dhandhoo	19.84
Hithaadhoo	18.75
Thiladhoo	18.74
Miriyandhoo	16.57
Kihaadhunfaru	12.75
Milaidhoo	10.26
Fonimagoodhoo	6.95
Vakkaru	4.76
Landaa-giraavaru	4.60
Muthaafushi	4.32
Fares +	3.52
Kanufushi +++++	3.02
Veyofushi	2.37
Viligili	2.11
Nibiligaa	1.00
Bodufinolhu ++	0.88
Hanifaru	0.30
Kudadhoo	0.10
Nelivaru	0.07

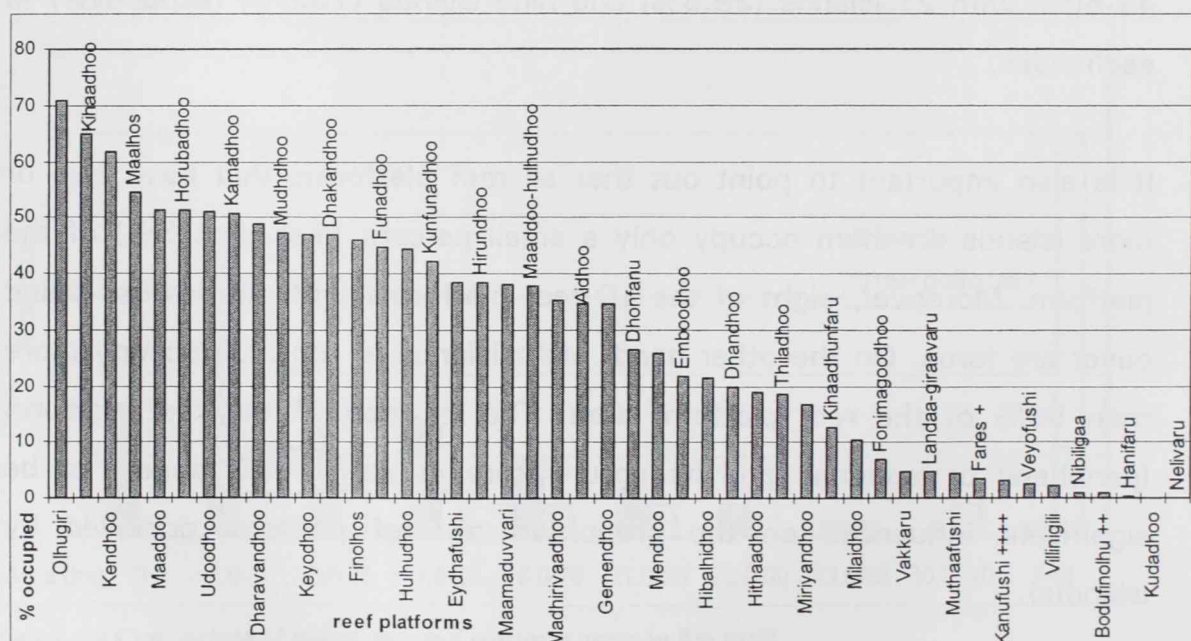


Figure 5.5 Proportion of reef platform occupied by islands (based on 1969 aerial photographs).
Note: (+) indicates the number of additional islands on specified reef platforms.

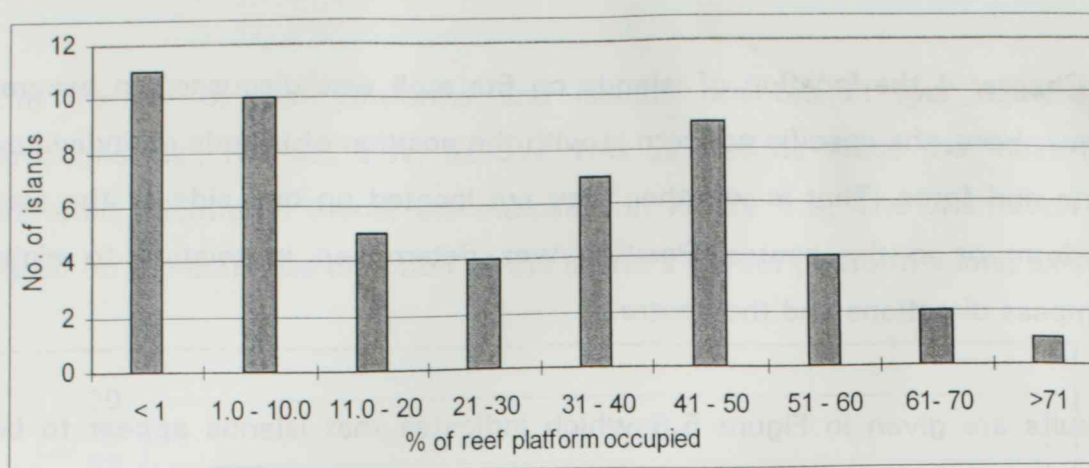
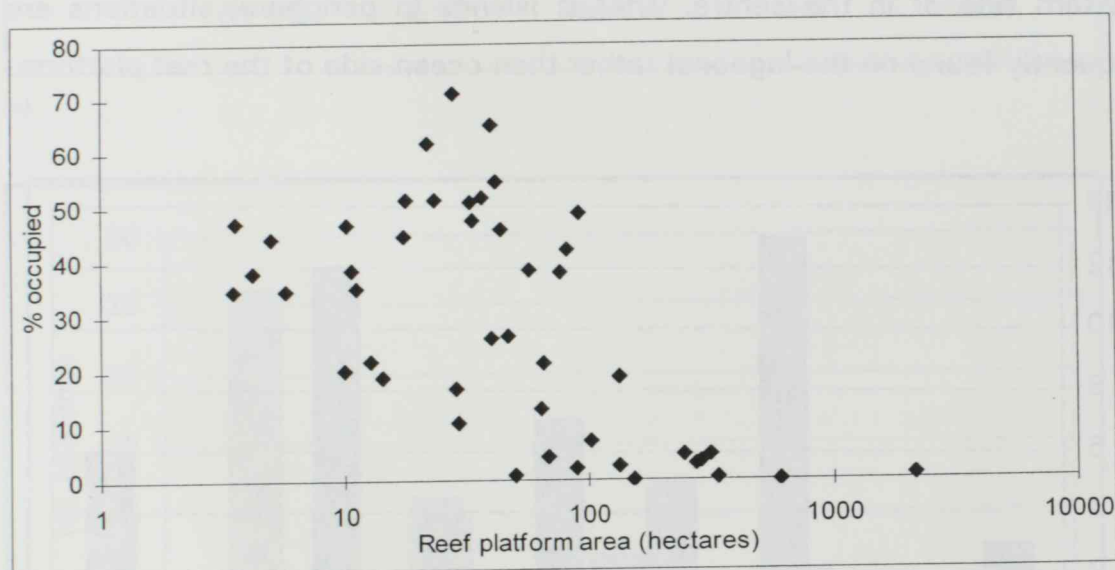


Figure 5.6 Frequency distribution of proportion of reef platform occupied by islands based on nine class intervals. *Note: values falling between 10-11, 20-21 etc. have been allocated to the lower % class.*

Figure 5.7 shows the relationship between reef platform area and the proportion occupied by islands.



5.2.3 Position of islands on reef platforms

In Chapter 4 the location of islands on Eta atoll was discussed in general terms. Here, the specific concern is with the position of islands on individual reefs and faros. That is whether they are located on one side of the reef platform or in the centre. Position was determined in relation to eight compass directions and the centre.

Results are given in Figure 5.8 which indicates that islands appear to be preferentially positioned either towards the east of their reef platforms (13 out of 53 islands), or to the west (12). Six islands occur about the center of the reef platforms, of which five occur in the eastern half of the atoll. With reference to Table 5.1 it is evident that islands in the western half of the atoll are generally located towards the eastern side on their reef platforms, whereas, many islands in the eastern half of the atoll are found towards the western side or in the centre. That is islands in peripheral situations are frequently found on the lagoonal rather than ocean-side of the reef platform.

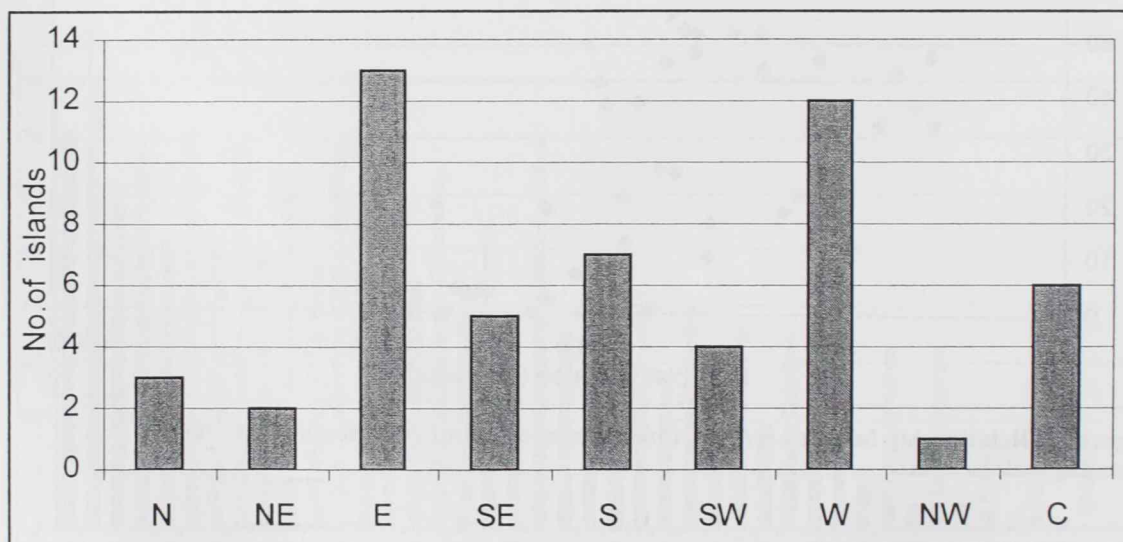
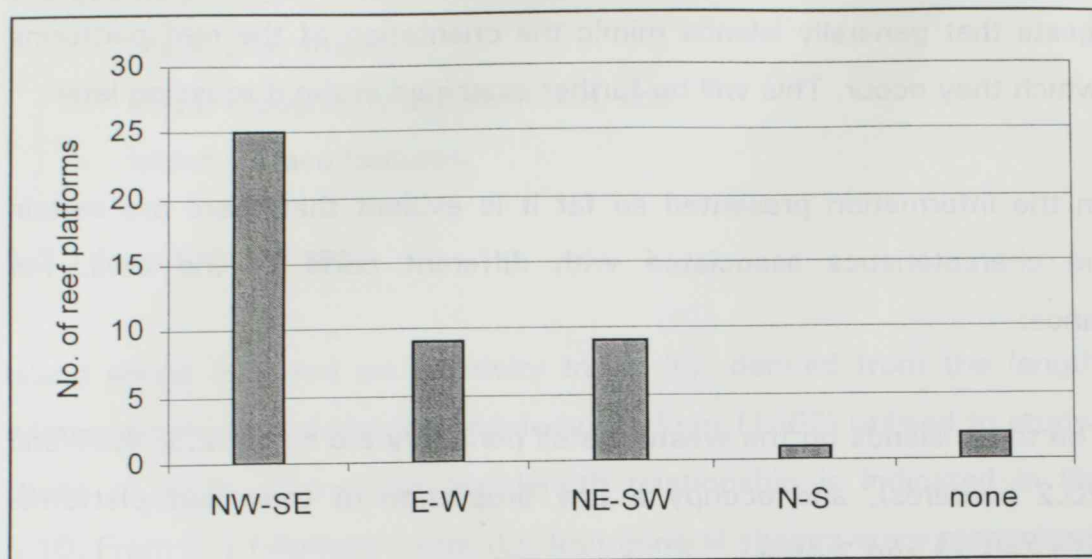


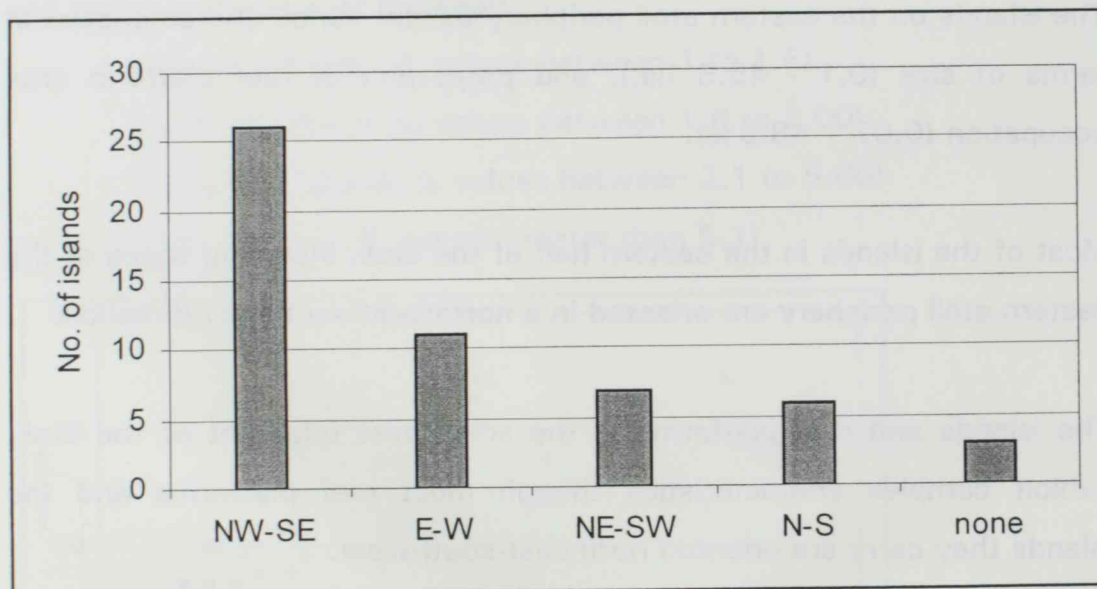
Figure 5.8 Position of islands on reef platforms in Eta atoll. N=north, NE= north-east, E= east, SE= south-east, S=south, SW=south-west, W=west, NW=north-west, C=center.

5.2.4 Orientation of reef platforms and islands

The number of reef platforms and islands oriented in four compass-directions viz.; NW-SE, E-W, NE-SW, N-S as well as those that have no preferred orientation (none) are indicated in Figure 5.9. The orientation is based on the compass-direction of the island's or reef platform's long axis.



(a)



(b)

Figure 5.9 Orientation of (a) reef platforms and (b) islands in Eta atoll.

About half (26 of 53) of the islands, including some of the largest and also the smallest are oriented in a northwest-southeasterly direction. Most of these islands occur in the eastern half of the atoll. Islands oriented in an east-west direction accounts for about a fifth of the islands. In addition, six islands are oriented in a north-south direction. Four islands do not have any preferential orientation, that is, they are located in the centre of the reef platform. Comparison of the orientation of islands and their reef platforms suggests that generally islands mimic the orientation of the reef platforms on which they occur. This will be further examined in the discussion later.

From the information presented so far it is evident that there are certain island characteristics associated with different parts of the atoll. For instance:

- The three islands on the western atoll periphery are small (2.5, 4.97 and 10.2 hectares), and occupy a tiny proportion of their reef platforms (0.12, 0.23 and 3.45%).
- The islands on the eastern atoll periphery exhibit varied characteristics in terms of size (0.1 - 45.5 ha.), and proportion of reef platform area occupation (0.07 - 48.9%).
- Most of the islands in the eastern half of the atoll, including those of the eastern atoll periphery are oriented in a northwest-southeast direction.
- The islands and reef platforms in the southwest quadrant of the atoll, exhibit complex characteristics though most reef platforms and the islands they carry are oriented northeast-southwest.
- The highest proportion of platform occupied by an island in the atoll (71%) occurs on the second smallest reef platform on the southern atoll periphery in the southwest quadrant.

- The lowest proportion of reef platform area occupied by islands occurs on faros in the southwest quadrant. Most multiple-islanded reef platforms occur in this quadrant too.

5.3 Geomorphological characteristics of islands

The geomorphological characteristics considered here include;

- island plan shape
- island topography and elevation, and
- island surface features.

5.3.1 Island plan shape

Island shape is based on Ellipticity Index (I_e), derived from the length to width ratio, based on the methodology Stoddart (1965) utilised to study the shape of atolls. The width and length relationship is indicated in Figure 5.10. From this Ellipticity Index (I_e), four general shapes were recognised for 52 islands in Eta atoll (and excludes Nelivaru which lacks any vegetation and varies in shape over the year);

- 'circular' islands (I_e values between 1 to 1.5)
- 'elliptical' islands (I_e values between 1.6 to 2.00)
- 'elongated' islands (I_e values between 2.1 to 5.00)
- 'linear' islands (I_e values greater than 5.1).

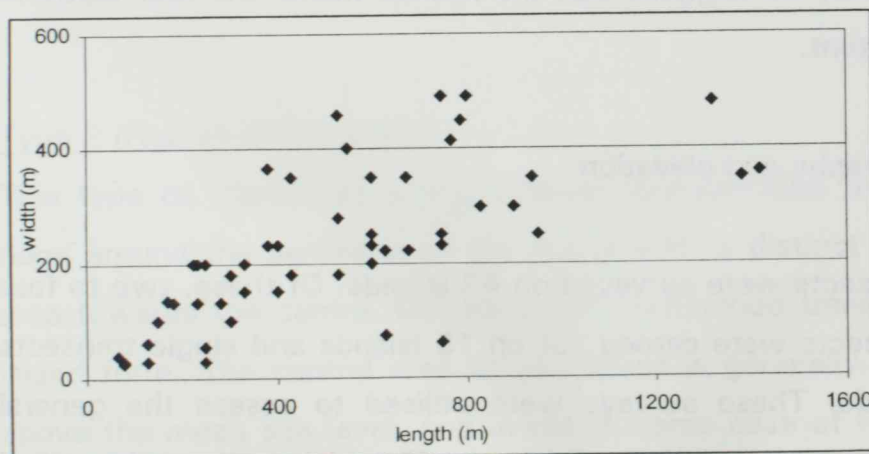


Figure 5.10 Relationship between width and length of the islands in Eta atoll.

The Ellipticity Index for the islands of the atoll range from 1.04 to 12.5, and the mean Index value is 2.84. On the basis of the Index, the majority of islands (48.1%) in the atoll are elongated in shape, followed by elliptical shape (23.1%), and circular (21.1%). Only four islands are linear (7.7%) in shape. Figure 5.11 shows the number of islands in each class shape for the islands in Eta atoll.

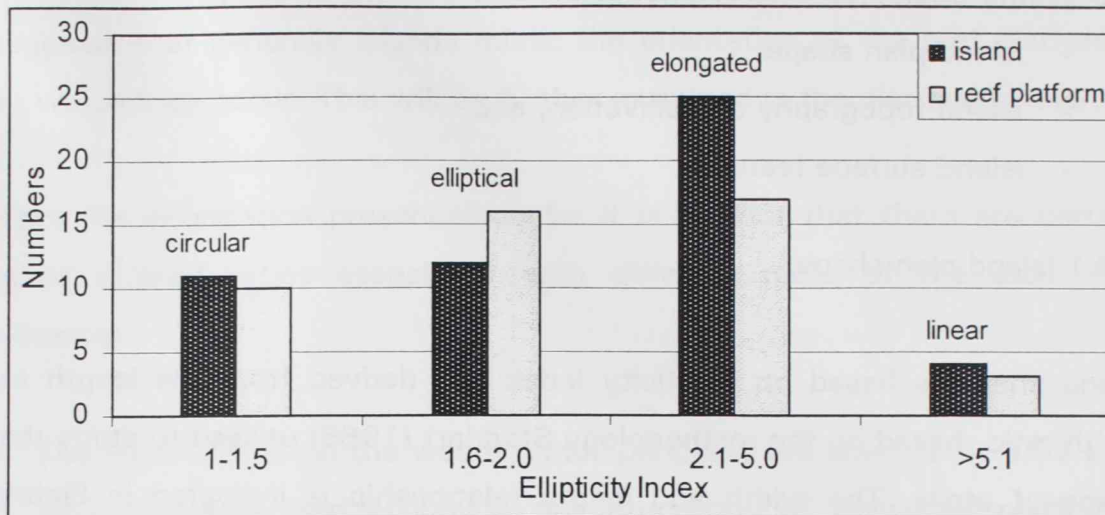


Figure 5.11 The number of islands and reef platforms in each shape class based on Ellipticity Index.

Similar to the islands, the largest number of reef platforms in the atoll have an elongated shape (Figure 5.11) closely followed by reef platforms with an elliptical shape. However, more circular islands occur than reef platforms of similar shape. While these data do not show individual island and reef platforms results they do suggest that the islands mimic the reef platform shapes to some extent.

5.3.2 Island topography and elevation

Topographical transects were surveyed on 43 islands. Of these, two to four topographical transects were carried out on 15 islands and single transects on 28 other islands. These surveys were utilised to assess the general surface form and maximum height of islands. The highest point identified

was 3.19m on Funadhoo, but the average maximum height of the islands is 1.96m above mean sea level. Highest points on islands usually occur on either lagoonward or seaward ridges at island margins.

Three types of island surface forms (topography) were distinguished for the islands in Eta atoll.

Type 1 (Figure 5.12)

Dome-shaped islands with simple convex ridge-form include the smallest of the islands and particularly those with little or no vegetation (*finolhu*). In some cases these islands have low ridge-swale topography (e.g. Nelivaru), or a broad ridge surmounted by a distinct crest as illustrated in Figure 5.12.

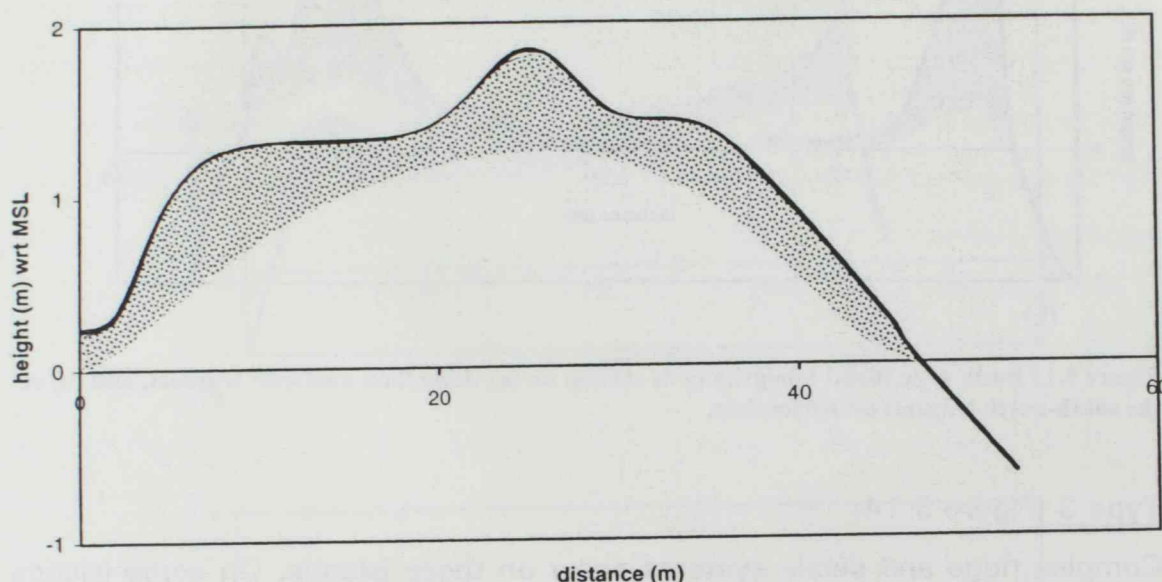


Figure 5.12 Veyofushee Finolhu cross-island transect (north to south), showing the simple convex form.

Type 2 (Figures 5.13a and b)

This type of island has a basin-shape, characterised by a relatively high ridge around the perimeter of the island with a distinct depression or low area towards the centre. Udoodhoo and Hirundhoo transects illustrate this island form. The central area of the island is generally less than a metre above the mean sea level, and in the extreme case of Hirundhoo much of the 'base' area is at mean sea level.

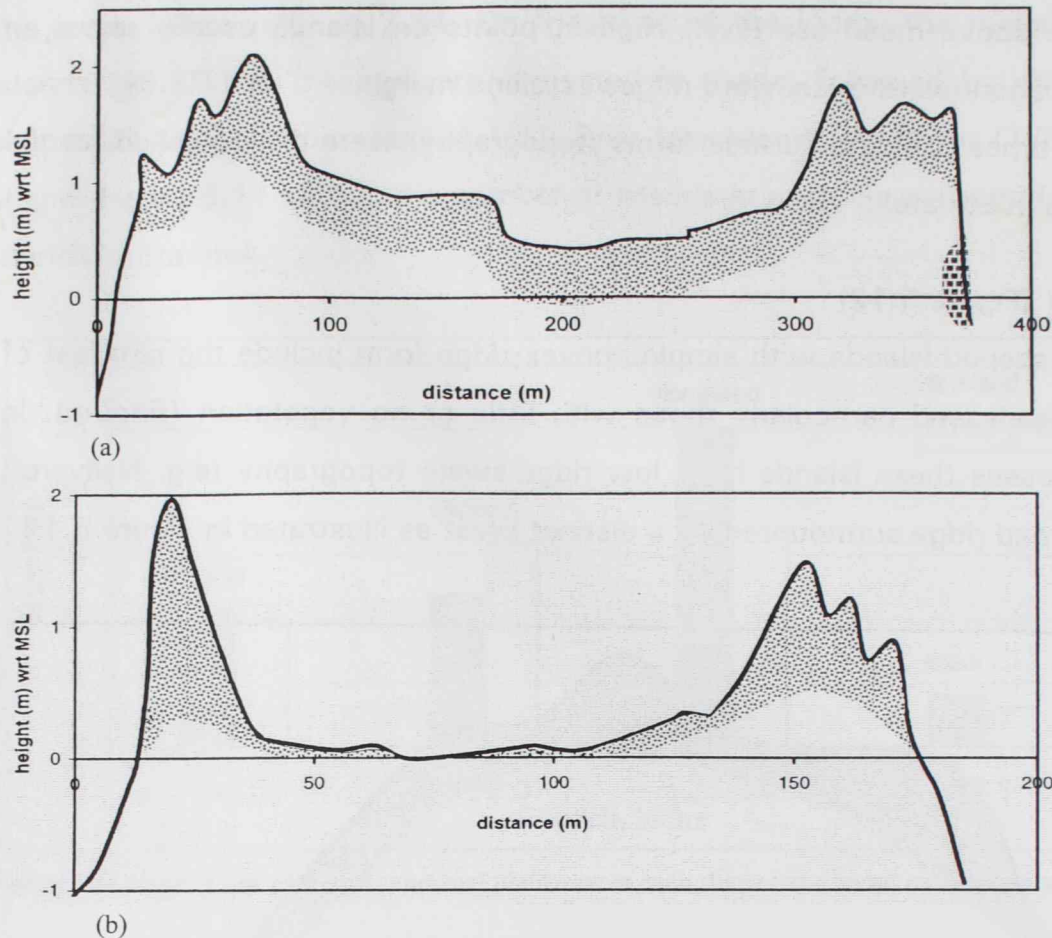
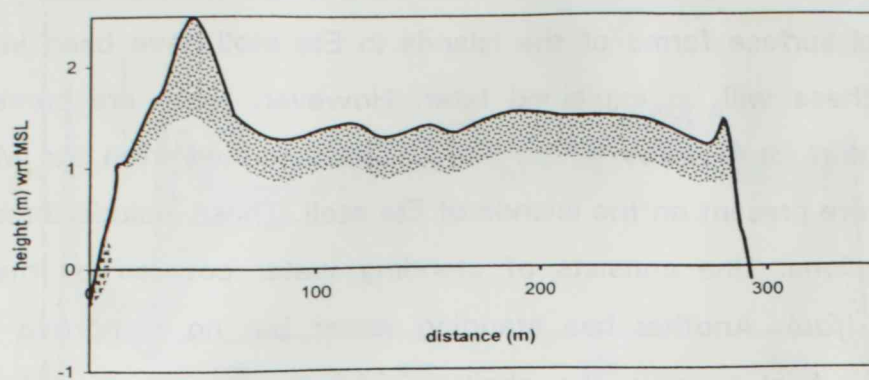


Figure 5.13 Basin-type island topography as evident on (a) Udoodhoo west-east transect, and (b) on the south-north transect on Hirundhoo.

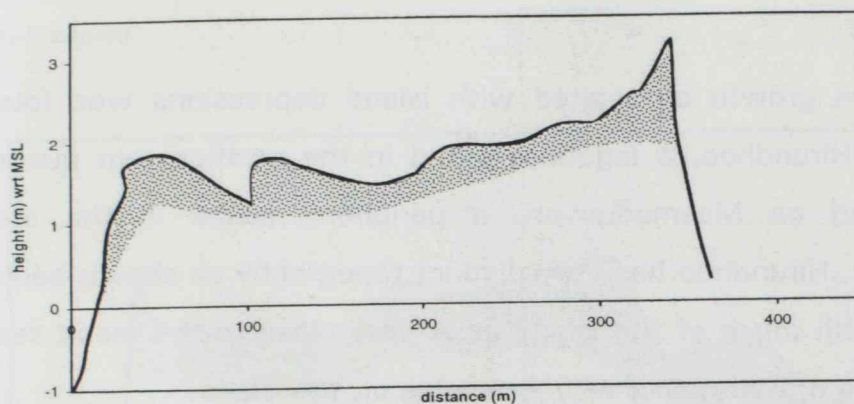
Type 3 (Figure 5.14)

Complex ridge and swale systems occur on these islands. On some islands prominent ridge(s) occur on one side of the island, with either near-uniform topography continuing away from the high ridge as on Mendhoo (Figure 5.14a), or lowering gradually towards the opposite shore giving a distinctly asymmetrical profile as in the case of Funadhoo (Figure 5.14b), though in this case there are some marked undulations towards the northern shore.

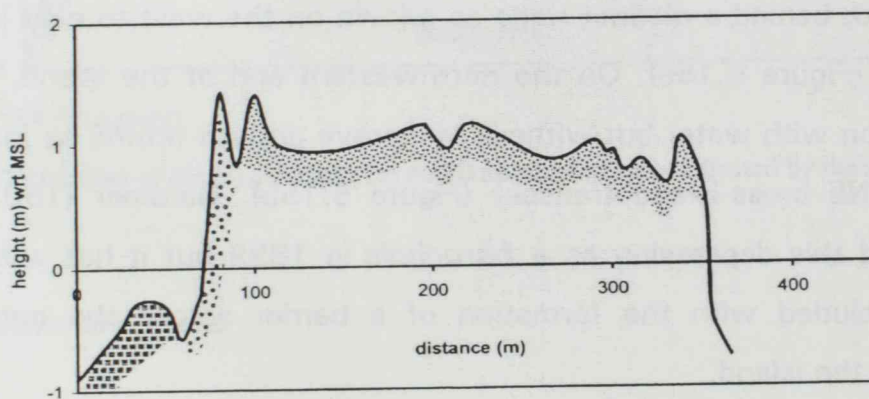
More than one peripheral ridge can occur, an example being on the southern side of Maamaduvvari where there is a double-ridge form (Figure 5.14c). The position of the prominent ridge(s) on the lagoonside, seaward side or passage-side is not uniform throughout the atoll.



(a)



(b)



(c)

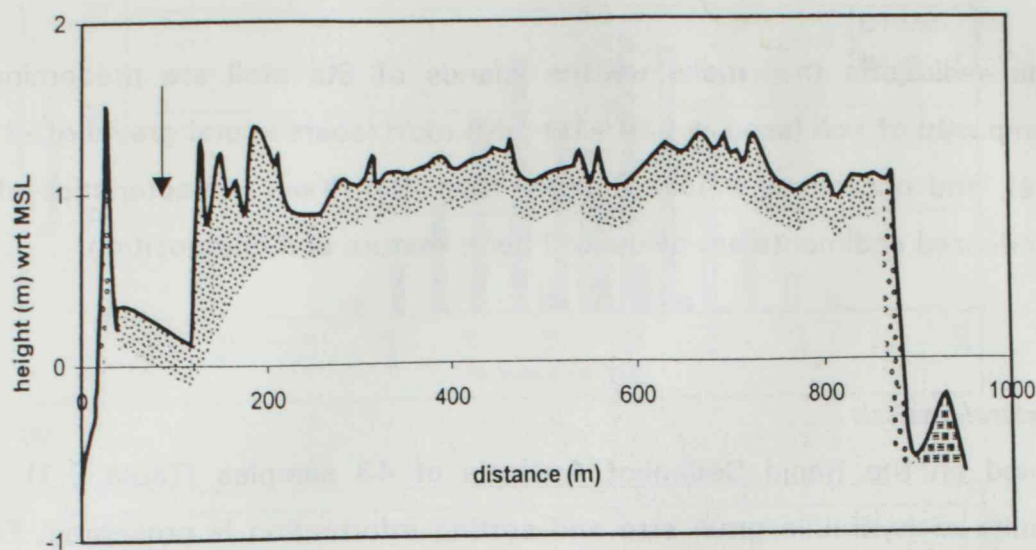
Figure 5.14 Complex island topography. (a) A single high ridge on the southwestern side of Mendhoo (SW-NE), (b) asymmetrical form on Funadhoo (S-N), and (c) undulating island surface form with two prominent ridges on Maamaduvvari (S-N).

5.3.3 Island surface features

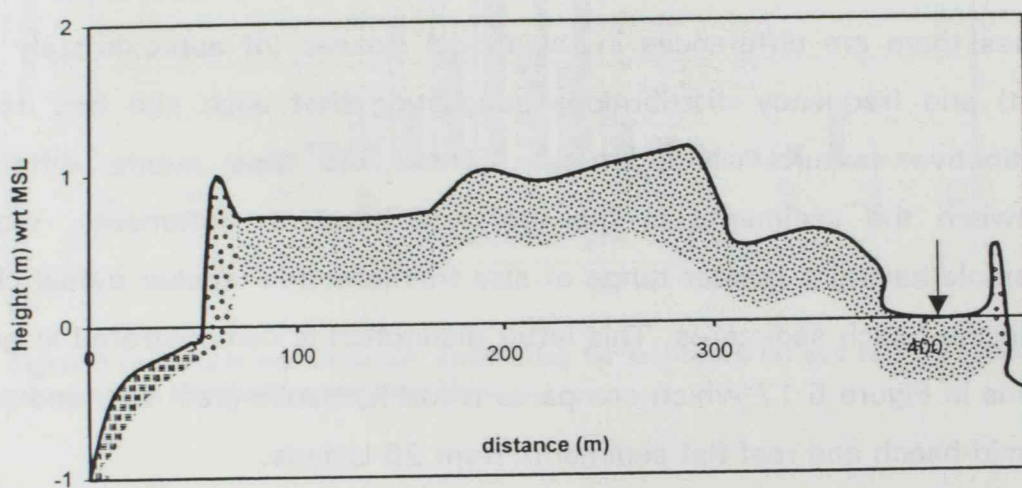
The general surface forms of the islands in Eta atoll have been indicated here and these will be explained later. However, there are some other prominent surface features which have been described from the Maldives and which are present on the islands of Eta atoll. These include three pond-like depressions. One consists of standing water covered by mangrove vegetation (*faa*). Another has standing water but no mangrove growth (*kulhi*). The final type is the shallow tidal depression or embayment, opening onto the leeward shore of an island, and termed *barachois* (Gardiner 1903).

Mangrove growth associated with island depressions was found on two islands, Hirundhoo, a lagoonal island in the northeastern quadrant of the atoll, and on Maamaduvvari, a peripheral island in the southwestern quadrant. Hirundhoo has very distinct topography as shown earlier in Figure 5.13b with much of the island at or very close to the mean sea level, and mangrove growth being very extensive on the island.

On Maamaduvvari, the mangrove area (*faa*) occurs on the western side of the island, behind a distinct ridge as shown on the west to east lengthwise transect (Figure 5.15a). On the northwestern end of the island, there is a depression with water but without mangrove growth (*kulhi*) as indicated by the SW-NE cross-island transect (Figure 5.15b). Gardiner (1903) initially described this depression as a *barachois* in 1899 but it has subsequently been occluded with the formation of a barrier across the northwestern 'horn' of the island.



(a) (W-E transect)



(b) (SW-NE transect)

Figure 5.15 The location of *faa* (a) and *kulhi* (b) on Maamaduvvari are indicated by the arrows.

5.4 Sediments and rocks

Two types of geological materials occur on and around the islands. The first type is the unconsolidated sediments, which are found on reef flats, beaches and forms the bulk of the island accumulations. The other is lithified material forming beachrock, cay sandstone, phosphatic rock, and conglomerate.

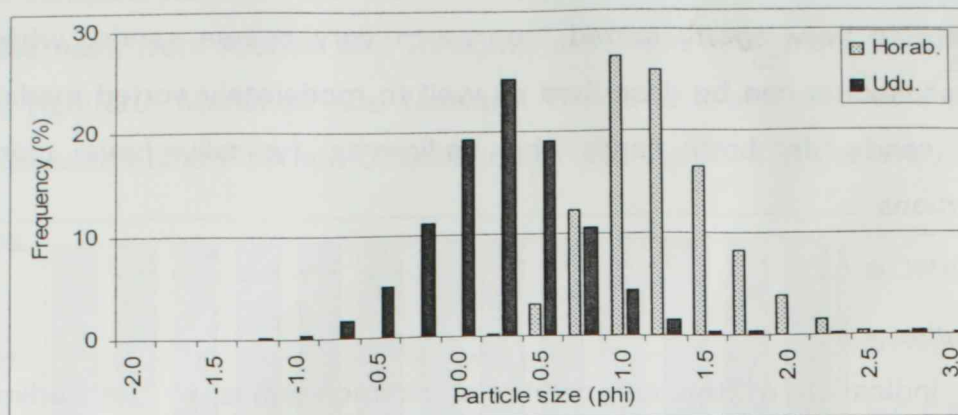
5.4.1 Island sediments

The sediments that make up the islands of Eta atoll are predominantly composed of *veli* (sand + 4 to -1ϕ) with *akiri* (coarse coral gravel of -2 to -7ϕ), and occasional boulders (more than -8ϕ). Two characteristics of the sand-sized sediments are discussed here; texture and composition.

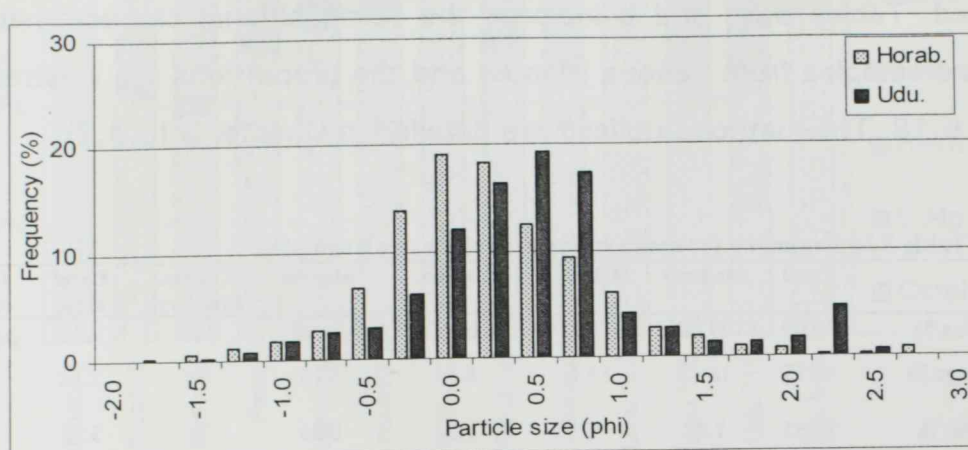
Textural analysis

Based on the Rapid Sediment Analysis of 43 samples (Table 3.1), brief results of hydraulic grain size and sorting information is presented. Figure 5.16 shows examples of grain size distribution for a reef and a mid-beach sediment sample from two islands, Horubadhoo and Udoodhoo. In both cases there are differences in the modal classes (of approximately 1 phi unit) and frequency distributions suggesting that each site has its own distinctive textural characteristics. There are also subtle differences between the sediments in the reef and beach environments, the reef example having a greater range of size fractions and weaker modal classes than the beach sediments. This latter distinction is demonstrated in general terms in Figure 5.17 which compares mean hydraulic grain size and sorting of mid-beach and reef flat sediments from 26 islands.

The mean grain sizes of the reef sediments vary widely from -1ϕ to just over 2ϕ , and there is a broad range of sorting values (0.25 - 1.9). In comparison, the beach sediments are better sorted (0.25 - 0.75) and bulk of the samples have mean grain size values within a limited range (0.4 - 1.7ϕ). These results suggest that size-sorting take place during entrainment and transportation from reef to island shore.



(a)



(b)

Figure 5.16 Particle size frequency distribution for mid-beach (a) and reef (b) sediment samples from Horubadhoo and Udoodhoo.

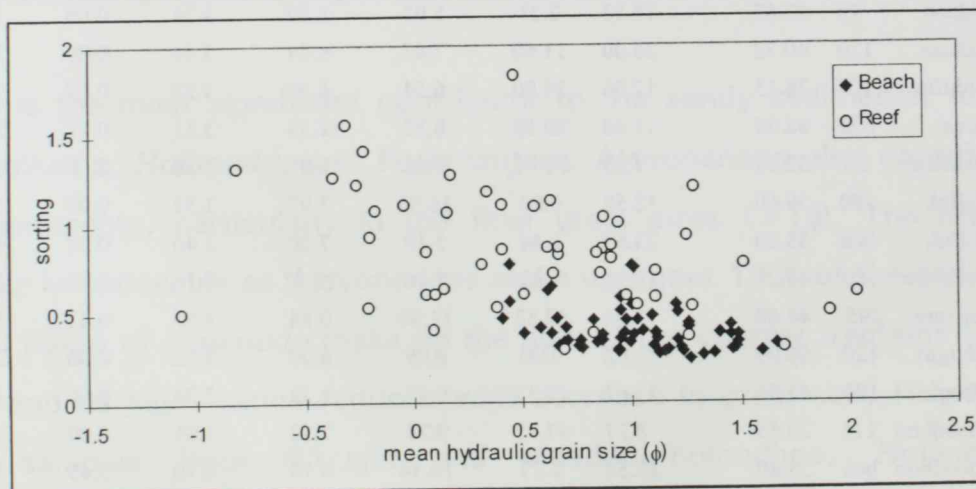


Figure 5.17 Mean grain-size and sorting of beach and reef sediments.

Texturally the reef platforms sands of Eta atoll can be described as moderate to very poorly sorted, coarse to very coarse sands, while the beach sediments can be described as well to moderately sorted medium to coarse sands. In both cases the sediments typically have unimodal distributions.

Composition

For an indication of the compositional characteristics of the sediments, eleven core samples and two beach samples from nine islands were analysed. Tables 5.3a and b indicate the compositional characteristics of the sand samples from various islands, and the proportions are illustrated in Figure 5.18. The methods utilised are detailed in Chapter 3 (3.3.2).

Table 5.3a Summary for compositional analysis of all samples.

	Coral	Molluscs	Halmda.	Forams.	Alcyons	Crustns. Echi. Bryo	Coral algae	Oth. & unknws.
Max.%	66.09	25.00	47.37	16.56	10.47	3.45	7.16	5.96
Avge.%	48.72	16.15	13.5	8.54	5.13	0.6	1.32	3.43
Min %	20.55	7.85	0	5.01	0.84	0	3.93	1.55

Table 5.3b Compositional analysis of selected sediment samples.

Sample	depth*	Coral	Molluscs	Halmda.	Forams	Alcyons	Crustns. Echi. Bryo.	Coral algae	Oth. & unknws.
Aidhoo	75	62.67	18.11	2.23	5.01	5.29	3.34	0.00	3.34
Aidhoo	120	40.72	25.00	11.60	7.47	6.44	5.41	0.00	3.35
Bodufin.	125	38.13	17.86	26.80	6.54	4.58	3.27	0.65	2.18
Fares	200	48.35	13.40	20.58	8.35	2.33	3.11	0.19	3.69
Hanifaru	98	52.19	7.85	21.71	7.62	1.85	5.31	0.69	2.77
M-Hul.	80	59.60	12.58	0.00	16.56	3.97	1.32	0.00	5.96
M-Hul.	bch	53.60	23.63	1.44	5.19	7.20	3.46	0.58	4.90
Mendhoo	160	48.21	15.98	6.89	7.16	10.47	7.16	1.10	3.03
Nelivaru	295	44.68	17.54	17.33	11.90	0.84	3.55	0.42	3.76
Olhugiri	120	66.09	13.62	0.00	6.09	6.09	5.22	0.00	2.90
Olhugiri	180	42.83	23.62	18.32	9.49	1.32	2.21	0.66	1.55
Udoodhoo	115	20.55	8.27	47.37	9.27	7.52	3.01	0.00	4.01
Udoodhoo	bch	55.80	12.54	1.25	10.34	8.78	4.70	3.45	3.13

Halmda= Halimeda, Foram= Foraminifera, , Crustns.=Crustaceans,
Echi. = Echinoids, Bryo.=Bryozoa, Alcyons= Alcyonarians, Oth. &unknws..= Others and unknown;
bch= beach sample, Bodufin= Bodufinolhu, M-Hul=Maaddoo-hulhudhoo.

*Depths are given in cm from surface.

These samples include ones that are from different depths of islands (two samples each from Aidhoo and Olhugiri), a sample each from Bodufinolhu, Fares, Hanifar, Mendhoo and Nelivar. One beach and one core sample from Maaddoo-hulhudhoo and Udoodhoo are also included in the analysis.

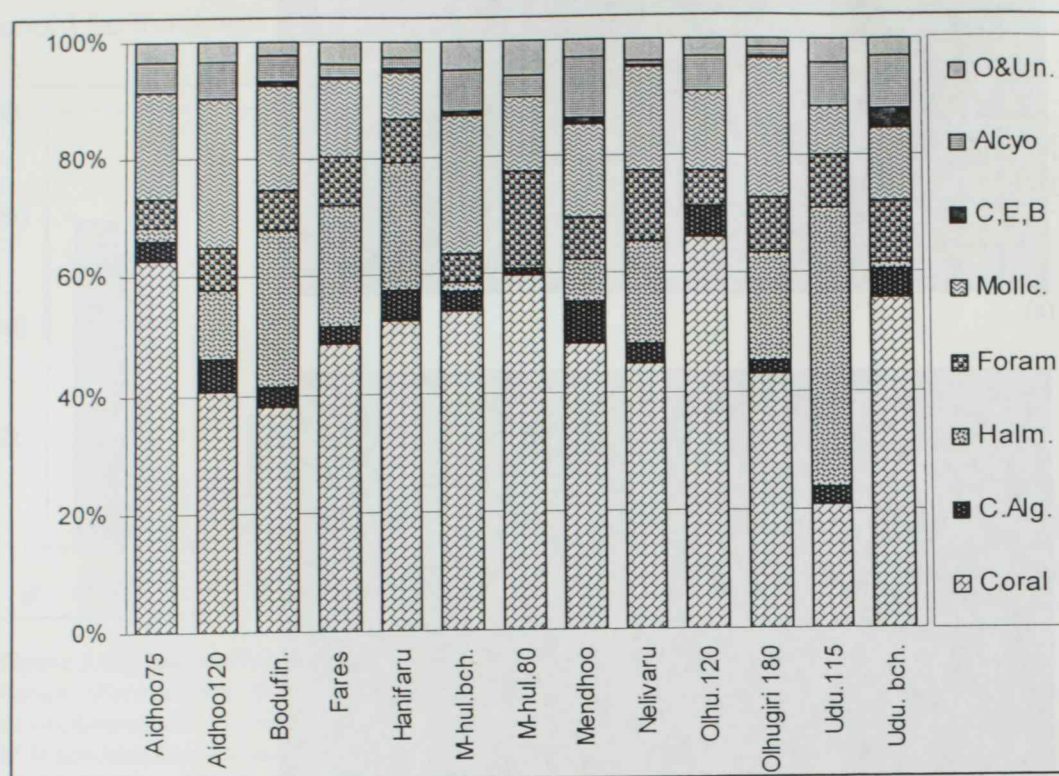


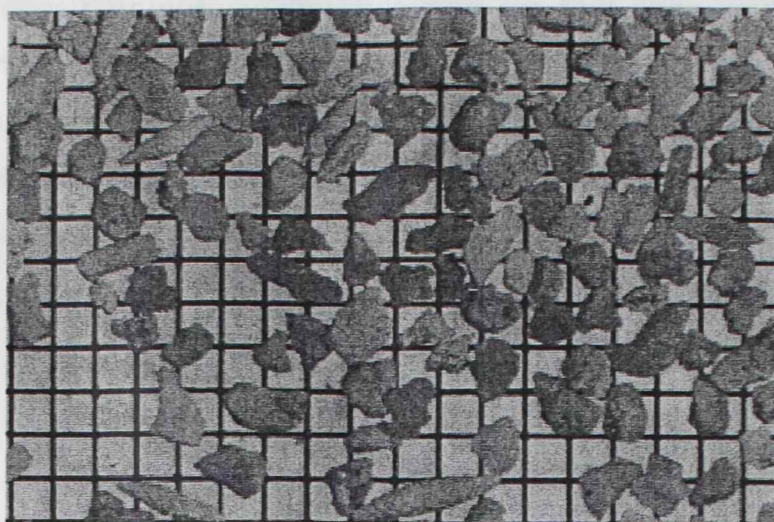
Figure 5.18 Compositional characteristics of the nine sediment samples. The figure indicates the significance of coral in making up the sediments on islands and beaches.

Samples; M-hul.bch = Maaddoo-hulhudhoo beach, Bodufin. = Bodufinolhu.,

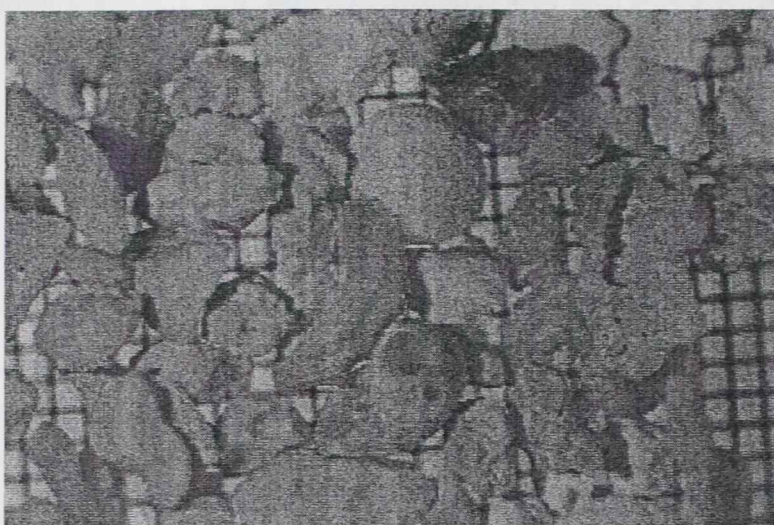
Olhu. = Olhugiri, Udu = Udoodhoo, bch. = beach.

Organisms; O&un = Others and unknowns, Alcyo = Alcyonarians, C = Crustaceans, E = Echinoids, B = Bryozoa, foram = Foraminifera, Halm. = Halimeda, C.Alg. = Coraline algae.

Coral is the most significant contributor to the sandy sediments, followed by molluscs, *Halimeda*, and *Foraminifera*. Alcyonarians also contribute to the sediments, particularly in the finer grain sizes ($>1\phi$). The Mendhoo sample is noticeable as Alcyonarians make up about 10% of the sediments. Often flakes of *Halimeda* make up the bulk of the coarser fractions (-1 to 0ϕ), and its significance reduces with decrease in grain size. However, in two samples from Olhugiri and Maaddoo-hulhudhoo, *Halimeda* is completely absent. The composition of two sediment samples is shown in Figure 5.19.



(a)



(b)

Figure 5.19 Composition of an island sediment sample from Udoodhoo. The composition of sediments in the (a) finer and (b) coarser ranges. The scale indicated by the grid is 0.1mm.

The results of compositional analysis indicate that on average Foraminifera (*Marginopora* and *Amphistegina*) contribute between 5 to 16% to the sediments. Their presence also becomes significant with decrease in grain size, which may be a function of their resistance to breakage. Molluscan particles contribute to sediments in all size fractions. Small, yet intact gastropods were identified even at 2ϕ (0.25mm) size.

Insufficient data are available to determine whether or not the composition of present-day beach sands and island sands differ. In two instances,

differences in the composition of the beach and island sediment samples for Maaddoo-hulhudhoo and Udoodhoo are presented in Figures 5.20 and 5.21. The reasons for the observed differences are not immediately obvious, though temporal changes in reefal sediment and transportation regimes could be involved.

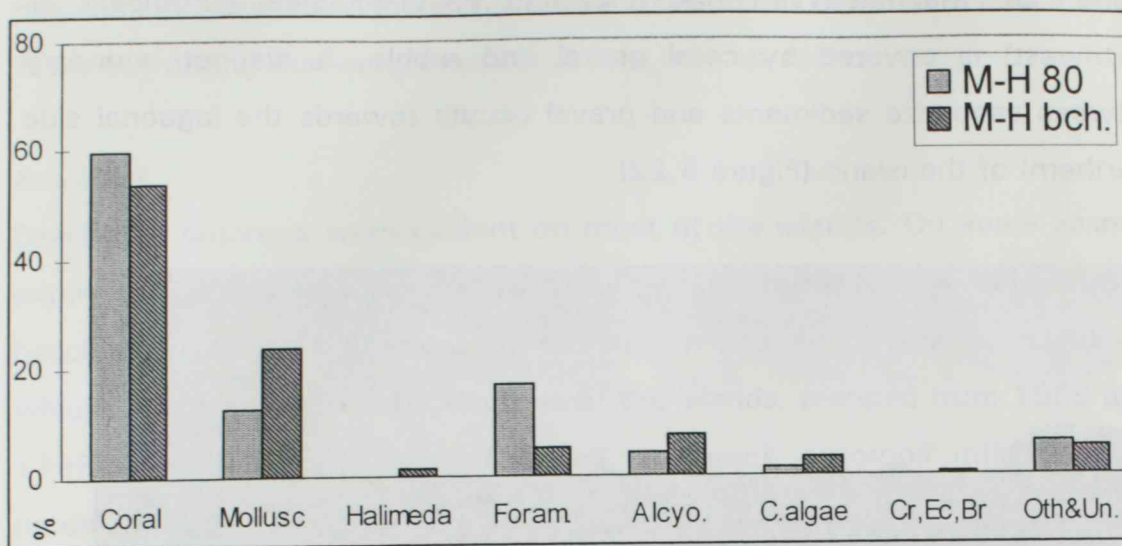


Figure 5.20 Composition of island and beach sediment samples from Maaddoo-hulhudhoo.

Foram. = Foraminifera, *Alcyo.* = Alcyonarians, *C.algae* = Coralline algae, *Cr.* = Crustaceans,

Ec = Echinoids, *Br.* = Bryozans. *Oth&Un.* = Others and unknowns

M-H 80 = Maaddoo-hulhudhoo sample from 80cm below surface

M-H bch. = Maaddoo-hulhudhoo beach sample.

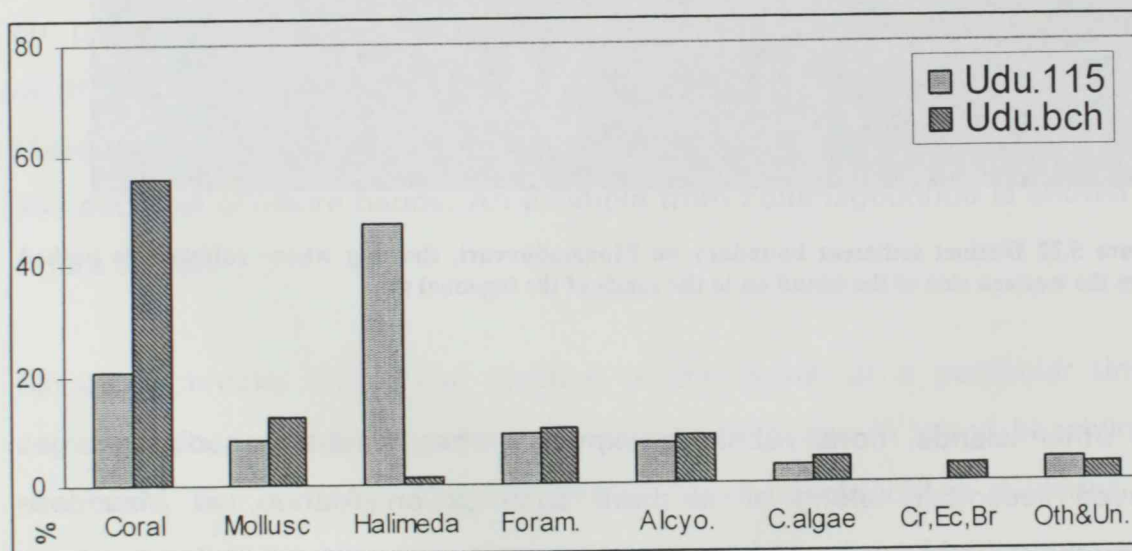


Figure 5.21 Composition of island and beach sediment samples from Udoodhoo

Foram. = Foraminifera, *Alcyo.* = Alcyonarians, *C.algae* = Coralline algae, *Cr.* = Crustaceans,

Ec = Echinoids, *Br.* = Bryozans. *Oth&Un.* = Others and unknowns

Udu.115 = Udoodhoo island sample from 115cm below surface

Udu. bch = Udoodhoo beach sample.

Gravel and coarse sediments

In addition to sand coarser sediments or related materials found on the islands include; coral gravel and rubble, broken beachrock, and lithified gravel. Two islands (Viligili and Ufuligili) are predominantly made up of coral gravel ($> -2\phi$) while on Olhugiri gravel is exposed around much of the island. On Maamaduvvari, most of the seaward side (southeast to northwest) is covered by coral gravel and rubble. A distinct boundary between sand-size sediments and gravel occurs towards the lagoonal side (northern) of the island (Figure 5.22).

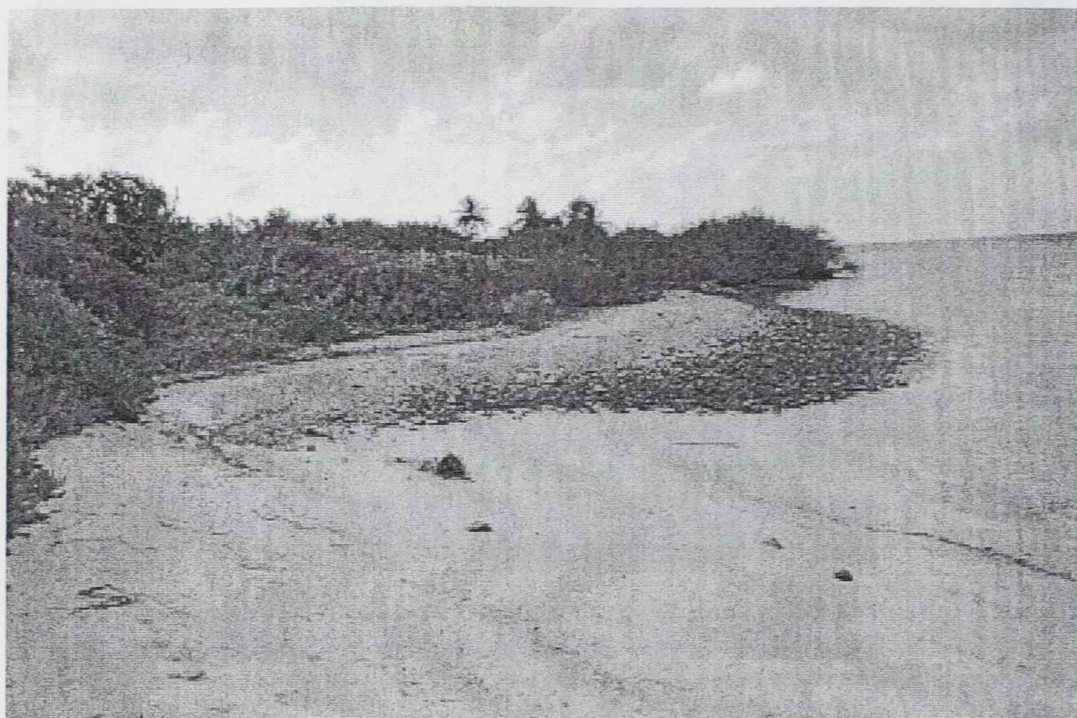


Figure 5.22 Distinct sediment boundary on Maamaduvvari, showing where rubble gets pushed from the western side of the island on to the sands of the lagoonal side.

On other islands, coral rubble is exposed when sand-size sediments get moved seasonally along or offshore such as on Aidhoo, or Maaddoo-hulhudhoo. Details of this seasonal process are presented in the next chapter.

5.4.2 Lithified rocks

Four types of lithified rocks occur on or around the islands of Eta atoll; beachrock, beach conglomerate, cay sandstone, and phosphatic rock. The conditions under which these can form were reviewed in Chapter 2. The presence or absence of these rocks on the islands of Eta atoll is indicated in Table 5.4 noting that conglomerate occurs only on Aidhoo.

Beachrock

Beachrock outcrops were evident on most of the islands. On some islands extensive outcrops of beachrock occur around much of the present-day beach. An excellent example of this is on Udoodhoo (see Appendix 3, which shows the significant features of the islands, mapped from 1969 and 1999 aerial photos). Such extensive beachrock outcrops influence the processes that take place on the beach area, under present conditions. Figure 5.23a shows an exposure of beachrock occurring on present-day Bodufinolhu with two distinct parts to it.

On some islands beachrock outcrops appear to have a preferential location on particular sides. Distinct 'trains' of beachrock are evident on the southern side of Aidhoo, northern side of Fares, southeastern side of Maaddoo (see Appendix 3). Some outcrops are detached from the island, and occur as offshore bands. An example from Fonimagoodhoo is shown in Figure 5.23b.

Since beachrocks record the position of the beach at a particular time, current exposures can be used to investigate changes in island beachlines over time. For instance, Gardiner (1903) used beachrock as evidence of erosion on the islands in Eta atoll, and in other areas of the Maldives.

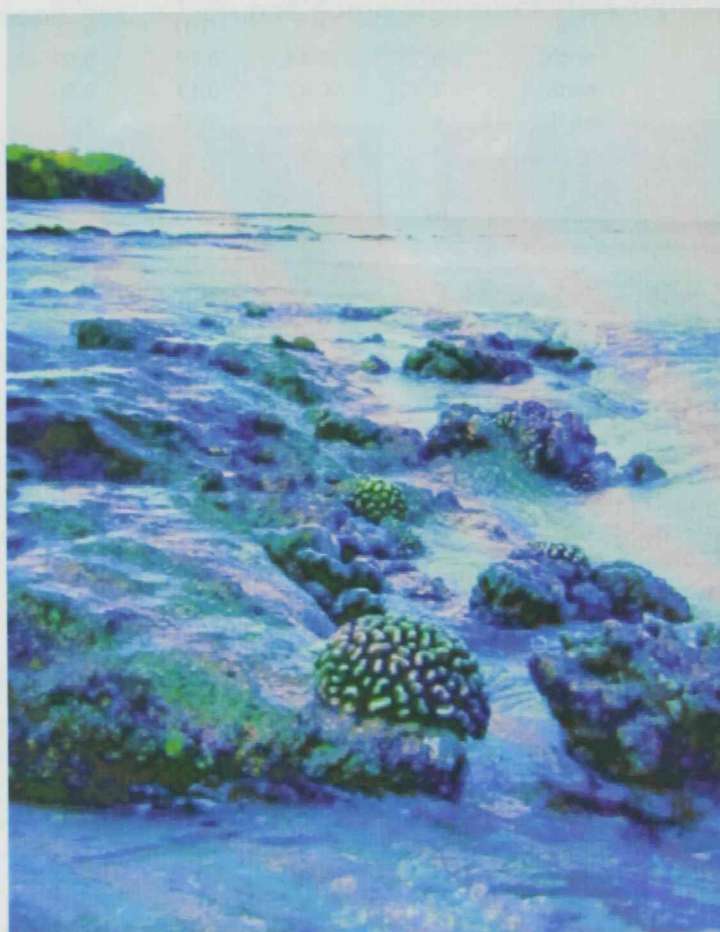
Table 5.4 Status of lithified rocks on the islands.

ISLAND	Beachrock	Cay sandstone	Phosphatic rock
Ahivahfushi	X	?	?
Aidhoo	X	X	0
Bodufinolhu	X	0	0
Dhakandhoo			
Dhandhoo			
Dharavandhoo			
Dhonfanu			
Dhunikolhu	X	?	?
Emboodhoo			
Eydhafushi			
Fares	X	X	0
Finolhos	X	?	?
Fonimagoodhoo	X	?	?
Funadhoo	X	?	?
Gemendhoo	X	X	0
Hanifaru	0	0	0
Hibalhidhoo	X	0	0
Hirundhoo			
Hithaadhoo			
Horubadhoo	X	?	?
Hulhudhoo	X	?	?
Kamadhoo			
Kanufushee Finolhu	0	?	?
Kanufushee Gaathu Finolhu	0	?	?
Kanufushi	X	?	?
Kendhoo			
Keyodhoo			
Kihaadhoo			
Kihaadhunfaru	0	?	?
Kudadhoo	X	?	?
Kunfunadhoo	X	X	0
Landaa-giraavaru			
Maaddoo	X	X	0
Maaddoo-hulhudhoo	X	X	1
Maalhos			
Maamaduvvari	X	X	0
Madhirivaadhoo	X	?	?
Medhufinolhu	0	?	?
Mendhoo	X	X	0
Milaidhoo			
Miriyandhoo	X	?	?
Mudhdhoo	X	?	?
Muthaafushi	X	0	0
Nelivaru	0	0	0
Nibiligaa	0	0	0
Olhugiri	X	X	0
Thiladhoo			
Thulhaadhoo			
Udoodhoo	X	X	0
Ufuligili	X	?	?
Vakkaru	X	?	?
Veyofushi			
Viligili			
Numbers	27	10	1

Note: ' ? ' indicates where subsurface was not investigated



(a)



(b)

Figure 5.23 Beachrock outcrops on (a) the present beach of Bodufinolhu and (b) offshore on Fonimagoodhoo.

Note one of several live corals on seaward face of beachrock, as indicated by the arrow.

Islands that lack beachrocks are usually sand cays (*finolhus*), like Nelivaru and Nibiligaa, or islands with very active sedimentation, such as Hanifaru. However, in some cases beachrock may be obscured beneath the overlying unconsolidated sands and is only exposed infrequently. Table 5.5 gives an indication of the location, the exposed upper and lower limits, and the slope (dip) of beachrock outcrops on selected islands of Eta atoll. The distance column represents the width of the exposed outcrop between its highest and lowest points.

Table 5.5 Selected parameters of beachrocks on selected islands.

Island	occurrence	distance (m)	lower limit*	upper limit**	Min. range (m)	slope°
Bodufinolhu	west	10	-0.16	0.34	0.5	2.3
Fares	NE	5	-0.3	-0.07	0.23	2.3
Fares	north	6	-0.48	0.17	0.65	6.3
Funadhoo	north	7	-0.43	0.13	0.56	4.6
Gemendhoo	south	4	-0.65	-0.35	0.3	4.6
Hulhudhoo	south	3	-0.22	0.52	0.3	5.7
Kanufushi	NE	9	-0.34	0.18	0.52	3.4
Kanufushi	SW	10	-0.92	0.13	1.05	6.3
Maaddoo	east	3	-0.27	0.5	0.77	15
Mendhoo	west	4	-0.31	0.03	0.34	5.2
Mendhoo	north	4	-0.52	-0.28	0.24	3.4
Miriyandhoo	north	7	-0.47	0.27	0.74	6.3
Mudhdhoo	north	12	-0.27	0.74	1.01	4.6
Udoodhoo	south	3	-0.21	0.26	0.47	9.2
Vakkaru	south	10	-0.56	0.56	1.12	6.3

*Evident lower limit of beachrock in metres, with reference to mean sea level

** Upper limit of beachrock, with reference to mean sea level

Min. range= Minimum vertical range of beachrock between upper and lower limits.

The highest elevations and greatest ranges for beachrock is indicated on Vakkaru and Kanufushi. The elevation range of beachrock outcrop on Vakkaru is at least 1.12m extending from 0.56m below the mean sea level (MSL) to 0.56m above MSL. On Kanufushi this range is 1.05m, from 0.92m below MSL to 0.13m above MSL. However, the maximum elevation of beachrock occurrence is on Mudhdhoo (0.74m). Both Vakkaru and Mudhdhoo are lagoonal islands, whereas Kanufushi is located on a large faro.

In addition, broken beachrock occurs on the southern side of Funadhoo and Gemendhoo. Figure 5.24 shows beachrock fragments in the upper part of the development on Funadhoo, while the consolidated layer is evident below that.

Beach conglomerate

Lithified gravel as a form of beach conglomerate is not common on Eta atoll though it does occur on the southern side of Aidhoo (Figure 5.25). This particular formation differs from typically described conglomerate platforms in that it is a narrow (1m-wide) band of about 10m length, with a seaward dip. Gravel pieces between 3.2-12.8cm (-5 to -7ϕ) are incorporated in the lithified development, which has some characteristics typical of beachrock.



Figure 5.24

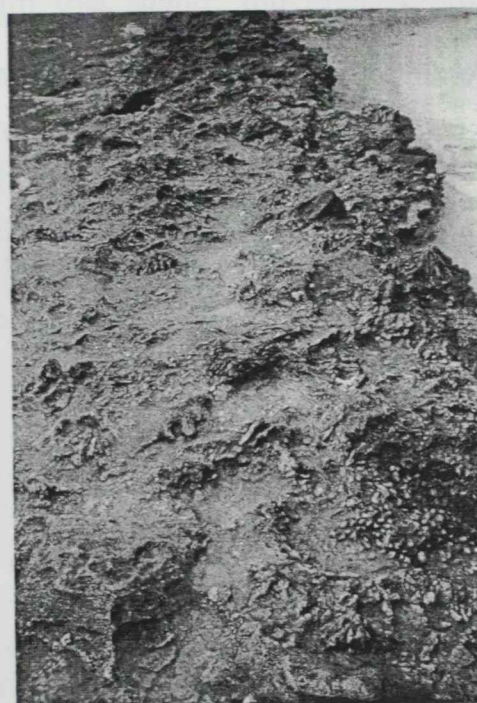


Figure 5.25

Figure 5.24 Broken and consolidated beachrock outcrops on the southern side of Funadhoo.

Figure 5.25 Conglomerate beach on the southern side of Aidhoo. Variations in the size of material forming the development and the dip is evident.

Cay sandstone

Cay sandstone occurs on many peripheral islands (Aidhoo, Maaddoo, Maaddoo-hulhudhoo, Maamaduvvari, Olhugiri, Fares, Gemendhoo and Udoodhoo), but was not observed on Bodufinolhu, Hanifaru, Hibalhidhoo and Nelivaru. Of the three lagoonal islands investigated, cay sandstone was only found on Mendhoo. On some islands like Aidhoo, Maaddoo or Maaddoo-hulhudhoo extensive cay sandstone developments occur throughout the island (see Appendix 4 which shows the soil profiles on the islands). Later it is suggested that the presence or absence of cay sandstone is in part a function of island age (Chapter 8).

Figure 5.26 shows exposed cay sandstone on Maaddoo. On other islands such developments were restricted either to the centre or to one side of the island. For instance, no cay sandstone was encountered in corings done on the northwestern transect (Transect A) of Mendhoo, while extensive and extremely hard layers were encountered on corings carried out on the other two transects towards the south of the island.



Figure 5.26 Exposed cay sandstone on the eastern side of Maaddoo.

The cay sandstone layers are generally 7 to 8cm thick, and while some could be cored through with hand-auger, others such as those encountered throughout Maaddoo-hulhudhoo, parts of Maddoo, and Mendhoo were not. Where it was possible to core through Maaddoo-hulhudhoo, the rock was found to be 13cm thick. Coastal exposures of cay sandstone on Maaddoo indicate that it occurs in layers, and despite an overlying dark soil the rock itself remained relatively unstained (as Figure 5.26 shows).

Phosphatic rock

Phosphatic rock results from the interaction of guano (seabird excrement) water, litter and sediments on reef islands. Only one outcrop of phosphatic rock was encountered on the islands investigated; this at the eastern end of Maddoo-hulhudhoo (Figure 5.27). This site has relevance for the chronological development of islands on the atoll in that the oldest radiocarbon dates are from samples from this island; the implications of which will be discussed later (Chapter 8).



Figure 5.27 Exposed phosphatic rock outcrop on Maaddoo-hulhudhoo as indicate by the arrow.

Thus far this chapter has examined some of the geographic, geomorphological and geological characteristics of the islands in Eta atoll, but the relationship between the various characteristics have not been explored except in the most cursory manner. Some of these relationships will now be considered with a view to identifying and subdividing the islands into groups possessing common characteristics and relationships, and also to see if there is some consistent spatial pattern in the distribution of island groupings around the atoll.

5.5 Spatial patterns of island and reef platform characteristics and relationships

5.5.1 Island position, orientation and shape

Earlier it was indicated that most of the islands in the eastern half of the atoll occur towards the west on their reef platforms, while the islands in the western half of the atoll are set in more easterly positions. These positions are consistent with exposure to the monsoonal conditions in that during the easterly monsoon (*Iruvai*) wind and wave action will have a greater impact on the reefs along the eastern side of the atoll and that the zone of convergence of waves diffracted through the passages and refracted across reef platforms, will tend to be located towards the lee (west) of the reef platform. Given these circumstances, islands can be expected to be located towards the west of the reef platforms.

On the other hand, islands on the western side of the atoll are particularly exposed to the westerly monsoon (*Hulhagu*) and in this case islands are generally positioned on the eastern part of the reef platform. Similar positions are also common for islands in the centre of the atoll and along the northern margin suggesting that waves from the western direction penetrate into the lagoon and through Kuda Kandulhi channel. In the extreme south of the atoll the preferred position of the islands is towards

the south east of the reef platform which likely results from exposure to a combination of westerly waves and southerly swells.

The general relationship between island position and exposure is more complicated when reef platforms are in close proximity to one another. This occurs in the northeast of Eta atoll where there is little consistency in the position of islands on reef platforms. For instance, Dhonfanu is set more to the north on its reef platform and Kihaadhunfaru to the south; the first reflecting protection, and the second more exposure to the north- easterly seas.

In summary, the factors that influence the position of islands (seasonal wind and wave action, reef platform location, and diffraction and refraction) are also important in determining the orientation and shape of islands. In detail however, the alignment, geometry and nature of the reef platform itself also influences island orientation and shape.

For instance, Figure 5.28 shows the close relationship between the orientation of the majority of reef platforms and the islands on them. Islands that do not reflect the orientation of the underlying reef platform are generally those that occupy a very small proportion of the reef platform or occur on faros. Examples include islands such as Kanufushi, Kudadhoo, or Nelivaru. These islands also do not have similar plan shapes to the underlying reef platforms. In most instances however island shape often mimics the geometry of the underlying reef platform. Shape is one of the factors used in the categorisation of the islands (using cluster analysis), towards the end of this chapter.

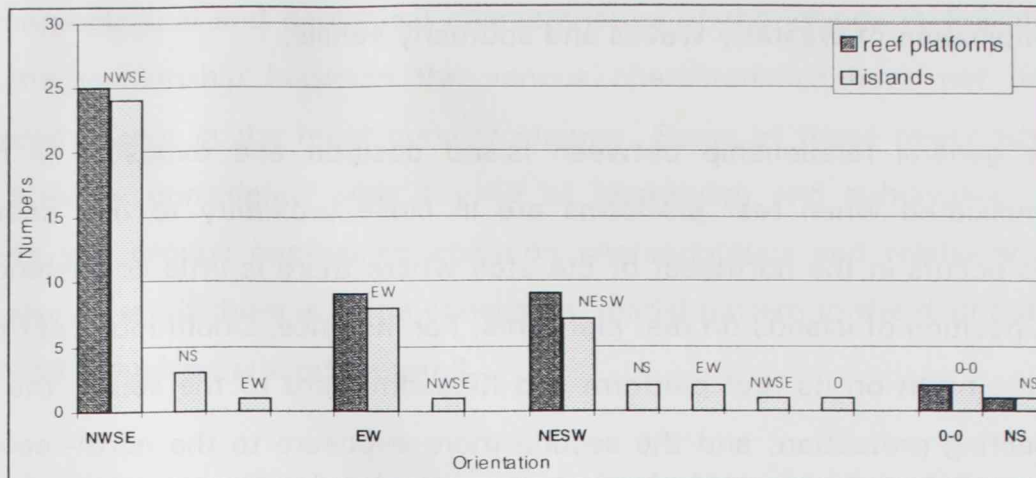


Figure 5.28 Orientations of reef platforms and islands on them. The bold lettering denotes the orientation of the reef platforms and the smaller lettering on top indicates the orientation of islands associated with each particular reef platform.

NWSE=northwest-southeast, NS=north-south, EW=east-west, NESW=northeast-southwest, 0-0= no orientation.

5.5.2 Island size and elevation

In addition to island position, orientation and shape, island size (absolute or as a proportion of reef platform occupation) and elevation are important aspects when considering the past and future developments of reef islands.

In Eta atoll islands range in size from < 1 ha to 45.5 ha. Four of the five largest islands (> 25 ha) are located on the southeastern periphery of the atoll, while there is no particular spatial pattern to the distribution of the nine smallest islands (< 1 ha), which occur both on the periphery as well as inside the atoll. These small islands generally occupy a tiny proportion of the underlying reef platform.

Similar to the position and orientation of islands, the proportion of reef platform area occupied by an island is also influenced by the interaction of reef platform characteristics and wave and current activity. According to Stoddart and Steers (1977) there appears to be no simple relationship between the size of a cay and the size of the underlying reef. However, in

Eta atoll generally the largest reef platforms have a small proportion occupied by islands. Indeed, three of the four largest reef platforms (faros) all of which occur on the western rim of the atoll have no islands at all. The reverse is also evident; that is, small reef platforms proportionately support a large island area. Table 5.2 indicates that the islands occupy between 71% to 0.07% of the reef platform in Eta atoll.

Figure 5.7 presented earlier in this chapter clearly shows that on the smallest reef platforms (<10ha) islands occupy between 35-50% of the possible area, while on all except one of the largest reef platforms (>100ha), islands cover less than 10% of the possible area. Reef platforms between these two values have much greater variation in island occupation, though two distinct groups are evident on Figure 5.7; one group has a mean value of about 50% occupation; the other about 15%.

Unlike most of the other island characteristics, which vary around the atoll, variation in the maximum island elevation is much less and this variable made little difference in the cluster analysis (see section 5.6). Figure 5.29 shows the maximum heights on islands, and they typically occur between 1.5 to 2.5m above MSL (average 1.9m). Two islands have maximum elevations above three metres and these are located on the northern central periphery of the atoll. Highest elevations generally occur on ridges on present island margins suggesting that exposure to wave action increases with island enlargement.

Although maximum heights between islands do not vary much, higher elevation values occur on islands with different characteristics. For instance, the third highest elevation value is shown to occur on Mendhoo, which is located in the centre of the atoll. The maximum heights of the *finolhus* are relatively high in comparison to many other islands that are located on the atoll periphery or occupy a much higher proportion of the reef platform. The lowest value (0.91m) is indicated for Hulhudhoo, and

although it is located on the northern atoll periphery, it is nestled between two other islands in close proximity. Nibiligaa is another *finolhu* occupying 1% of the reef platform and located close to the centre of the atoll, but has a maximum height of 1.69m. These facts suggest that in addition to location and the proportion of reef platform occupied, local wave energy is also significant in inducing sedimentation at high levels on islands.

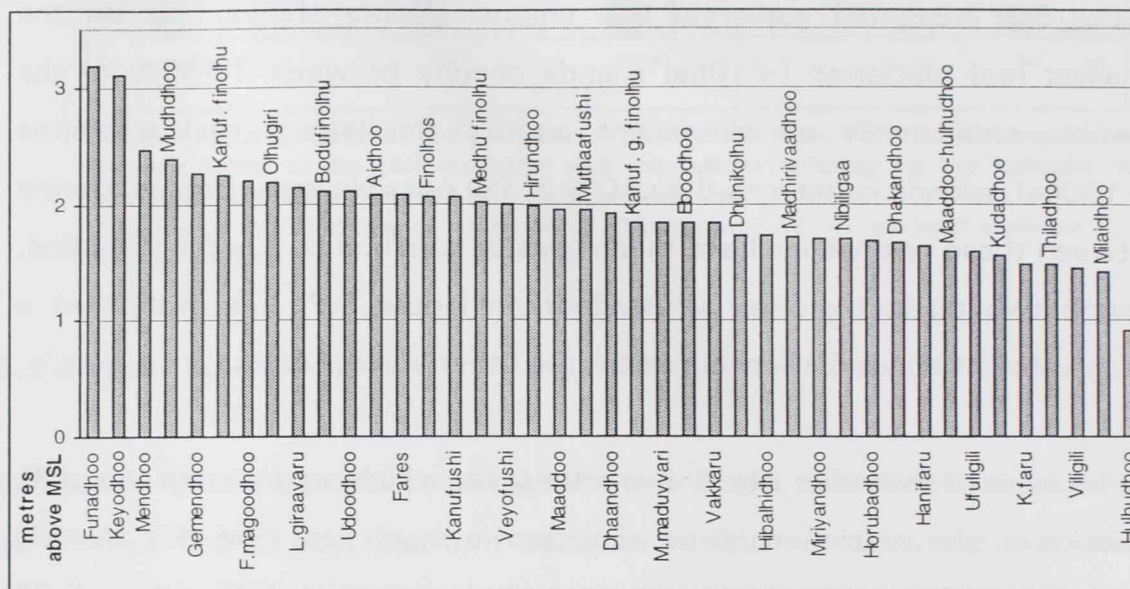


Figure 5.29 Distribution of maximum height of islands.

Kanuf.finolhu=Kanufushee Finolhu, *F.magoodhoo*=Fonimagoodhoo, *L.giraavaru*=Landaa-giraavaru, *Kanuf.g.fin*=Kanufushee Gaathu Finolhu, *M.maduvvari*=Maamaduvvari.

Closely related with elevation is island surface form or topography. Three different island surface forms of Eta atoll have been identified and these were illustrated earlier in this chapter. Similar to maximum heights on islands, there appears to be no obvious spatial pattern to the distribution of the surface forms around the atoll though both aspects are significant in the context of this thesis. First, as a component in the chronology of island development, and second in assessing the vulnerability of the islands to possible increased sea level, and other environmental perturbations.

5.6 Categorising islands in Eta atoll

Having examined some of the salient characteristics of the islands on Eta atoll in a qualitative way, an attempt is now made to categorise groups of islands in a more objective way. Such categorisation can also be used to see if there is any consistent spatial pattern of island groupings around the atoll. Cluster analysis was performed for 52 islands, the basic input data being given in Table 5.6. Nelivaru was not included in this analysis as it lacks any vegetation and its shape varies significantly with changes in the seasonal wave and current conditions over the year.

5.6.1 Methodology

Selected physical attributes of islands (length, width, ellipticity index, and area) were analysed for the writer by Dr. P. Kench, using K-means cluster analysis in the STATISTICA Version 5.0 statistical analysis software.

K-means cluster analysis allows the user to determine the number of output clusters. The analysis begins with the user-defined number of cases (islands) randomly assigned to each cluster. The cases (islands) are then moved between the clusters until the greatest possible distinction between clusters is achieved. The resultant clusters aim to minimise within-cluster variability while maximising between cluster variability.

The differences in means (of island attributes) between clusters are a measure of 'how different' the clusters are. Therefore, the clusters with similar mean values are more closely associated than clusters with very different mean values.

Table 5.6 Input data of the islands for the cluster analysis.

ISLAND	Length (m)	Width (m)	Ellipticity Index	Area (hectares)
Ahivahfushi	67	40	1.68	0.1
Aidhoo	280	130	2.15	2.0
Bodufinolhu	750	60	12.50	2.5
Dhakandhoo	400	230	1.74	4.8
Dhandhoo	230	130	1.77	2.0
Dharavandhoo	1320	480	2.75	45.5
Dhonfanu	680	220	3.09	12.6
Dhunikelhu	600	250	2.40	11.3
Emboodhoo	300	100	3.00	2.8
Eydhafushi	770	415	1.86	22.2
Fares	630	220	2.86	10.2
Finolhos	900	300	3.00	20.5
Fonimagoodhoo	600	200	3.00	7.2
Funadhoo	430	350	1.23	7.8
Gemendhoo	150	100	1.50	1.2
Hanifaru	250	56	4.46	1
Hibalhidhoo	830	300	2.77	14.3
Hirundhoo	400	150	2.67	4.1
Hithaadhoo	790	450	1.76	25.2
Horubadhoo	750	230	3.26	12
Hulhudhoo	224	200	1.12	2.2
Kamadhoo	530	460	1.15	16.8
Kanufushee Finolhu	80	25	3.20	0.1
Kanufushee Gaathu	80	30	2.67	0.1
Finolhu				
Kanufushi	530	180	2.94	7.2
Kendhoo	600	350	1.71	13.71
Keyodhoo	170	135	1.26	1.7
Kihaadhoo	800	490	1.63	26.4
Kihaadhunfaru	600	230	2.61	8.2
Kudadhoo	130	60	2.17	0.6
Kunfunadhoo	1420	360	3.94	35
Landaa-giraavaru	950	250	3.80	14.5
Maaddoo	1380	350	3.94	18.8
Maaddoo-hulhudhoo	180	130	1.38	1.6
Maalhos	750	490	1.53	23.2
Maamaduvvari	940	350	2.69	29.6
Madhirivaadhoo	330	200	1.65	4
Medhufinolhu	130	30	4.33	0.1
Mendhoo	530	280	1.89	10.5
Milaidhoo	250	200	1.25	3
Miriyandhoo	430	180	2.39	4.8
Mudhdhoo	675	350	1.93	16
Muthaafushi	630	75	8.40	3
Nelivaru				0.1
Nibiligaa	250	30	8.33	0.5
Olhugiri	550	400	1.38	20
Thiladhoo	230	200	1.15	2.7
Thulhaadhoo	380	230	1.65	4.97
Udoodhoo	380	365	1.04	9.3
Ufuligili	250	30	8.33	0.5
Vakkaru	750	250	3.00	11.8
Veyofushi	300	180	1.67	3.2
Viligili	330	150	2.20	1.9

5.6.2 Results

The results of the analysis show six identifiable clusters, as given in Table 5.7. Initially it was thought that island size, together with shape, would be an appropriate starting point for such categorisation, and in the event the addition of other variables such as island height, and proportion of reef occupation added little to the results.

Table 5.7 Cluster groups of islands based on length, width, ellipticity and area.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Bodufinolhu	Aidhoo	Funadhoo	Ahivahfushi	Dharavandhoo	Eydhafushi
Dhonfanu	Dhakandhoo	Kamadhoo	Dhandhoo	Kunfunadhoo	Finolhos
Dhunikolhu	Emboodhoo	Kendhoo	Gemendhoo	Maaddoo	Hibalhithoo
Fares	Hirundhoo	Mendhoo	Hanifaru		Hithaadhoo
Fonimagoodhoo	Hulhudhoo	Olhugini	Kanufushee Finolhu		Kihaadhoo
Horubadhoo	Madhirivaadhoo	Udoodhoo	Kanufushee Gaathu		Landaa-giraavaru
			Finolhu		
Kanufushi	Milaidhoo		Keyodhoo		Maalhos
Kihaadhunfaru	Miriyandhoo		Kudadhoo		Maamaduvvari
Mudhdhoo	Thiladhoo		Maaddoo-hulhudhoo		
Muthaafushi	Thulhaadhoo		Medhufinolhu		
Vakkaru	Veyofushi		Nibiligaa		
	Viligili		Ufuligili		

The descriptive statistics and the mean values from the cluster analysis is given in Table 5.8. The mean values for the four variables presented here allow for making comparisons between each of the six clusters.

Table 5.8 Descriptive statistics for the cluster groups.

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Length	654.1	321.2	503.3	163.9	1373.3	841.2
Width	205.9	179.2	367.5	66.3	396.7	380.6
Ellipticity	4.2	1.9	1.4	3.4	3.5	2.4
Area	9.3	3.4	13.0	0.8	33.1	22.0
No. of islands	11	12	6	12	3	8

Cluster 1:

These islands are of medium size, with nine of the 11 islands between 7 to 16 hectares. They are generally elongate in shape, and the group includes the two islands with the highest ellipticity indices in Eta atoll. The majority of the islands are oriented northwest-southeast, and except for three, they occupy less than 5% of the reef platform. There are two identifiable spatial groups of cluster 1 islands on the atoll. One group extends from Fonimagoodhoo in the northeastern corner, southwestwards towards the centre of the lagoon, while the second group includes the islands from Bodufinolhu in the extreme south, northwards along the inner (lagoonal) western margin of the atoll. Both groups are located immediately lagoonward of the cluster 2 islands.

Cluster 2:

The islands in this cluster are quite different to those in the previous cluster. They are generally elliptical in shape, with no preferred orientations, and are especially characterised by their small size (1.9 to 4.9 hectares). They include both lagoonal and peripheral islands in the exposed northeastern and western part of the atoll. While the proportion occupied by these islands vary from 2 to 44%. Eight of the twelve islands occupy 15-44% of the reef platforms, most of which are patch reefs.

Cluster 3

These six islands are of medium size (average of 13 ha) and low ellipticity values; four islands are circular while two are elliptical in shape. They form a single spatially discrete group, running in an east-west line along the northern margins of the atoll, immediately south of the Kuda Kandulhi channel. The one exception is Mendhoo, which is located in the very centre of the atoll. All of the islands tend to be centrally located on the reef platform, and except for Mendhoo, all islands more than 44% of the reef area. A further point is that cay sandstone and beachrocks were found on all the islands in this cluster.

Cluster 4:

This is the largest cluster with 12 islands. The group is characterised by islands that are very small (with mean area $< 1\text{ha}$) in area, and elongated in shape. Eight islands occupy a minute proportion of their reef platforms (under 0.3%), and in two instances there is more than one island on the same reef platform. Except for Nibiligaa, all of the islands are located on or close to the atoll periphery, though there is little pattern to the distribution. The majority of the islands in this cluster are associated with faros. The small average size of islands (0.8ha), low percentage of reef platform occupation, together with the faro location and the fact that five of the twelve islands lack any beachrock or cay sandstone, suggest that the islands in this cluster are likely to be quite unstable and subjected to rapid change.

Cluster 5:

This is the smallest cluster with only three islands included. The islands are distinguished by their large size and elongate shape and occur close by each other on the eastern atoll periphery. They also occupy a high proportion of the reef platform (42 to 51%), and are oriented northwest-southeast. Beachrocks were observed on all of them. The three islands in this group are closely allied with those in cluster 6.

Cluster 6

Islands included in this cluster are also large islands (14-29 hectares), and are typically elongated in shape. All islands except Kihaadhoo occur on the eastern atoll periphery, though Landaa-giraavaru is the northern most of all of the islands in Eta atoll. Apart from this island, all others occupy a substantial proportion of the reef platform. It is also evident that islands in this cluster have similarities with Cluster 5 in both the proportion of reef area occupied by the islands and size characteristics, as well in terms of their location on the atoll. Beachrock occurs on all of these islands.

The division of the islands into six clusters that have some internal homogeneity provides a valuable descriptive starting point for an assessment of the dynamics of the islands at several time scales. Moreover, the size-shape clusters also show a spatial coherence, which suggests a systematic geographical variation in some of the factors, which control island size and shape. The spatial patterns also suggest an even coarser grouping of islands is possible with cluster 1 and 2 forming one such group, 5 and 6 a second group, with clusters 3 and 4 left as separate groups.

5.7 Discussion and summary

Morphometry of islands

This analysis of morphometric and other properties of the islands in Eta atoll has confirmed some obvious points. First that the islands are small, with an average size of 9.72 hectares and half of the 53 islands being less than 5 hectares. Second, the islands are of low elevation with a average maximum elevation of 1.9m above MSL, and the highest elevation, typically associated with the marginal ridges, reaching just above 3m above MSL. More commonly island surfaces are between 0.75-1.25m above MSL. Clearly, these two characteristics by themselves imply a susceptibility particularly to climate change and sea level rise.

In terms of shape, the islands of Eta atoll are typically oval to circular with quite simple outlines. There are however, few linear islands, which are so characteristic of Pacific atolls. Indeed, of the four types of atoll islands described by Richmond (1993) for Central Pacific atolls, only Type I (analogous to simple sand cays, roughly symmetrical to oval in plan shape) is common in Eta atoll.

There are no Eta equivalents of the horseshoe- to boomerang-shaped islands that occur on reef bends (Type II) or the narrow, elongated and gently-curved to sinuous in plan-shaped islands (Type III) or the more complex island structures developed around emergent cemented rubble and reef flat deposits (Type IV), which are typical of Pacific atolls.

While the extreme linear and elongate island shapes are absent from Eta atoll, eleven of the islands have length:width ratios greater than 3:1. Moreover, seven of the 11 islands are <3 hectares in size.

Location of islands

On Eta atoll, the islands are not evenly distributed over the atoll. Islands are present on most of the reef platforms around the eastern side of the atoll from Keyodhoo in the centre north around to Olhugiri in the extreme south as well as several islands within the lagoon. On the western side of the atoll there are only a few islands and those that do occur there occupy a very small proportion of the reef platform on which they are located.

This east to west difference in pattern of island distribution was first recognised by Gardiner (1903, p.157) who argued that the absence of islands on the western side of the atoll was due to its exposure to the strong winds and seas associated with the westerly monsoon.

Two other factors could also be important. One is the large size of the reef platforms in the western half of the atoll, and the other is that the majority of the reef platforms in the western area are faros rather than patch reefs. The lack of islands on larger reef platforms has been noted elsewhere. For instance, on the Great Barrier Reef Hopley (1982, p.352) found that *Cays are least associated with large reefs probably because the wave refraction pattern does not produce the centripetal action required, but tends to spread sediment more evenly over the reef top.*

Position and number of islands on reef platforms

There is also a pattern to the position of islands on individual reef platforms over the atoll. Islands on peripheral reef platforms are generally located on the lagoonal side. Thus, around the eastern rim, from Kamadhoo in the northeast to Miriyandhoo in the southeast, islands are typically located on the western side of the reef platforms.

The few islands on the western rim, together with those in the north and middle of the atoll are generally located on the eastern half of the reef platforms or close to the centre (particularly islands along the Kuda Kaduolhi). Much more variable in position are the islands at the southern extremity of the atoll; though there is a tendency towards southeastern locations. These distributions are consistent with the seasonal variations in monsoonal conditions and a background southerly swell.

Most reef platforms on Eta atoll have only a single island. Multiple islands on the same reef platform are rare and then occur only on faro (Table 5.2). Such a situation is more akin to that on the Great Barrier Reef (Hopley 1982, p.341) than on typical Pacific atolls that commonly have several discrete islands, on the same reef platform. For example on Funafuti atoll there are nine separate islands on the same reef flat in the northeast of the atoll and 18 on the southern reef rim (McLean and Hosking 1991). The closed atolls of the Maldives also typically carry several islands on the same reef platform (for example Goidhu atoll (K), immediately south of Eta, has six islands on the same reef).

In many instances on Eta atoll island shape and orientation closely mimic that of the reef platform on which the island stands, a point recognised by Flood and Heatwole (1986) for coral cays of the Swain Reefs, southern Great Barrier Reef. They suggest that the shape and orientation of an island is controlled to a large degree by the wave refraction pattern of its reef.

Gourlay (1988) who has expanded on this notion (see Chapter 2) has also suggested that *cays on near circular reefs are generally unstable since the location of the focal zone [of wave refraction] readily shifts with wave direction and wave period*. On Eta atoll several of the reef platforms have circular outlines, and in the case of the 10 circular islands (I_e between 1 to 1.5) all occupy more than 35% of the available reef platform. This suggests that here circular islands may be more stable as a result of the island's adjusting to waves coming from two directions (with the changing monsoon), a factor that is explored in the next chapter.

CHAPTER 6

Short-term changes on the islands

6.1 Introduction

For the analysis of island change and development three time scales were identified in Chapter 1: short-term, medium-term and long-term and these are the subjects of the next three chapters.

Short-term changes refer to those that take place over hours to months and include seasonal variations. Morphodynamic changes at this time-scale usually affect the margins of the islands and generally involve erosion and/or accretion resulting either from episodic and irregular extra-tropical storm-wave or swell activity or from more regular seasonal changes in wind-wave climate. Such changes do not affect each island in the same way, and considerable inter-island differences can be expected.

6.2 Seasonal changes

A distinguishing feature of the Maldives archipelago is that the islands are subjected to the easterly (*Iruvai*) and westerly (*Hulhagu*) seasons. Easterly winds dominate from December to April and westerly winds prevail from May to November. During these times wave heights are typically 1 to 1.5m and 2 to 3m respectively (Harangozo 1992). Details were given in Chapter 4.5. This seasonal reversal in monsoonal winds over the year and its effect on the islands in the Indian Ocean has been acknowledged to be 'complicated' (Stoddart and Steers 1977 p.89). In this regard Gardiner

(1931, p.39) noted that *Sand is swept along a reef, removed from one place and accumulated in another, especially in seasons of alternating winds*. Furthermore, Woodroffe (1993) indicated that many islands in the Maldives contain spits at both ends that shift seasonally with the reversal of the monsoons.

Hence, this examination is limited to identifying the extent and patterns of seasonal erosion and accretion taking place on the islands of Eta atoll based on beach profile changes measured generally on the western and eastern sides of the islands. The methodology utilised for this investigation was outlined in Chapter 3, and the relevant climatic information presented in Chapter 4. Changes to beach profiles were examined on the western and eastern ends/sides of islands as it was assumed that major physical changes in island form in response to the seasonal changes would be most obviously expressed here. The location of beach profiles on selected islands is indicated in Figure 6.1 and the corresponding insets. In addition, the location of the island with respect to the atoll is also indicated. Profile locations on 13 other islands were shown in Figure 3.5.

Beach profiles were surveyed on forty-two (42) islands in the atoll, towards the end of *Hulhagu* (westerly season), from 18 to 28 October 1996. Due to unexpected constraints to the fieldwork programme, it was only possible to resurvey beach profiles on twenty-seven (27) of the same islands, at the end of *Iruvai* (easterly season), which was undertaken between 1 to 12 April 1997, but not in the following season. It is believed that results from these twenty-seven islands, chosen with consideration to island size, orientation, location and shape, are sufficiently representative of the situation in the atoll to generalise about the changes, which are presented and discussed here for selected islands. Field observations suggested that island shape and size are two of the important variables in terms of seasonal impacts, and shape has been used to subdivide the islands in the following analysis.

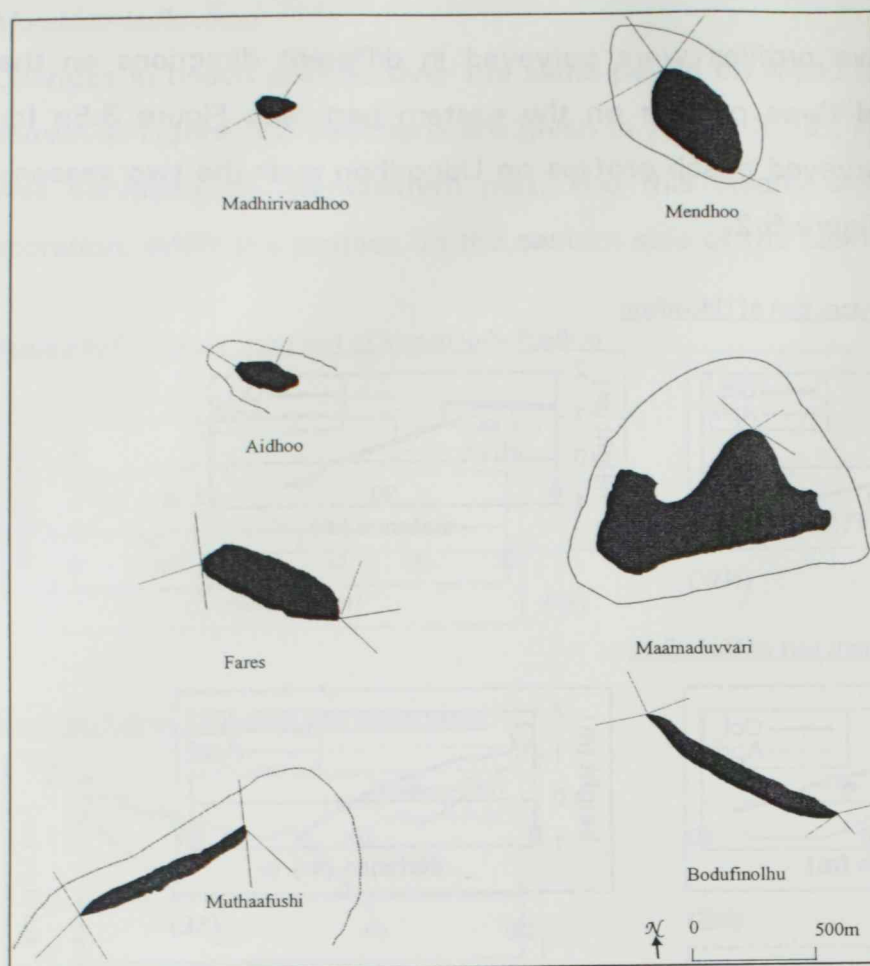


Figure 6.1 Location of beach profiles on selected islands

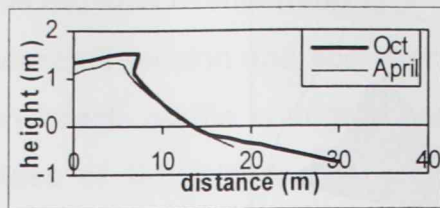
6.2.1 Circular islands

Three circular islands, of different sizes, Udoodhoo (1.04 l_e , 9.3 ha) and without any specific orientation, Maaddoo-hulhudhoo (1.38 l_e , 1.6 ha) and slightly oriented northwest-southeast, and Olhugiri (1.38 l_e , 20 ha), and oriented slightly east-west, are considered here. Udoodhoo occupies 51% of the reef platform, and occurs on the northern periphery of the atoll, in the NE quadrant, while Maaddoo-hulhudhoo occupies 37.74% of the reef platform, occurs close to the atoll periphery in the SE quadrant (Figure 3.10). Olhugiri has the highest proportion of reef platform occupation in the atoll (71%) and occurs on the southern atoll periphery.

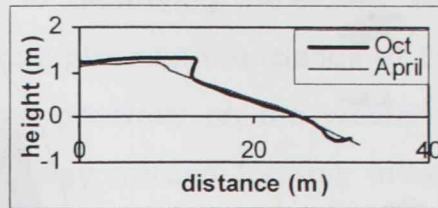
Udoodhoo

On Udoodhoo, two profiles were surveyed in different directions on the western side, and three profiles on the eastern part (see Figure 3.5e for locations). The surveyed beach profiles on Udoodhoo over the two seasons are presented in Figure 6.2.

Beach profiles on the western part of Udoodhoo

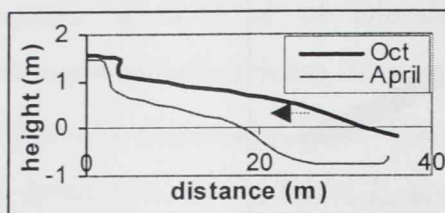


(NW)

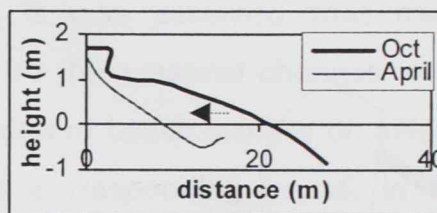


(SW)

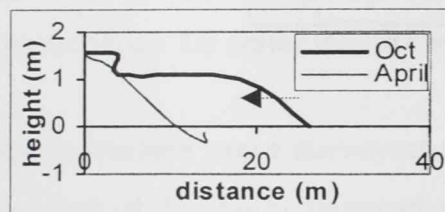
Beach profiles on the eastern part of Udoodhoo



(NE)



(SE)



(E)

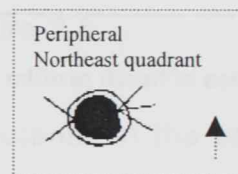


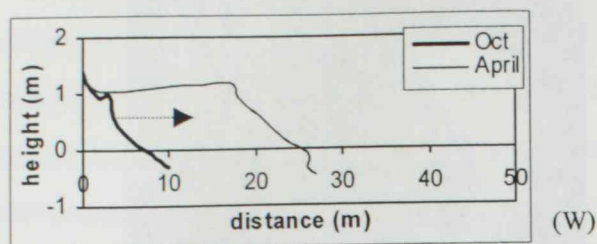
Figure 6.2 Beach profile changes on the western (top) and eastern (bottom) parts of Udoodhoo. Erosion is indicated by the arrow (between October and April).

Udoodhoo beach profiles indicate that between the survey periods no significant change took place on the western side, while on the eastern side, a retreat of beach between 10-15m at MSL is evident from the figure, and indicated by the arrows. This suggests that the erosion products from the eastern part of the island did not get transferred around to the western side of the island, but rather were moved immediately offshore or alongshore to the northern and southern parts of the island.

Maaddoo-hulhudhoo

Changes in beach profiles over the same period on Maaddoo-hulhudhoo are shown in Figure 6.3 (locations are given in Figure 3.5d). Only one transect was surveyed on the western part, and this clearly showed substantial accretion, while the profiles on the eastern side of the island show erosion.

Beach profile on the western part of Maaddoo-hulhudhoo



Beach profiles on the eastern part of the island

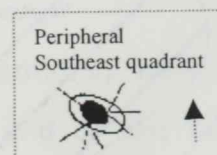
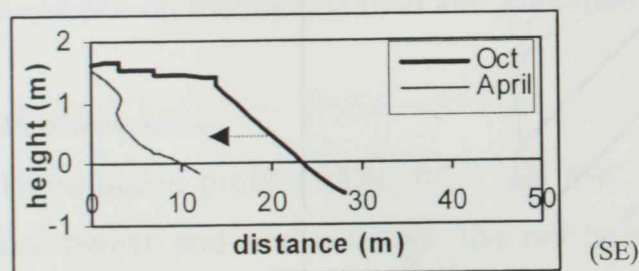
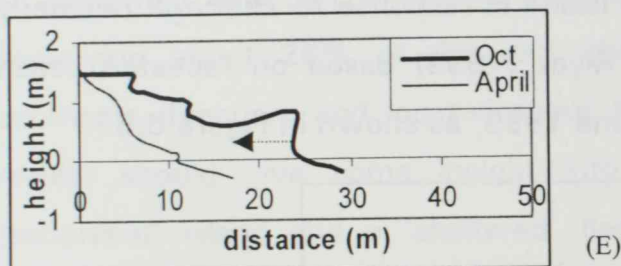
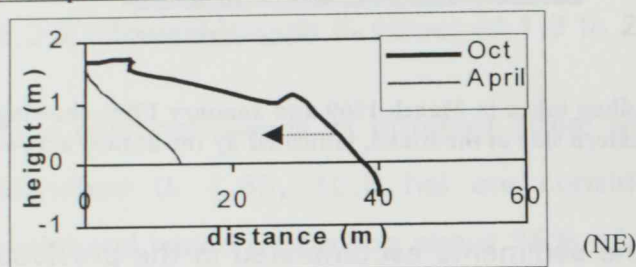


Figure 6.3 Beach profile changes on the western (top) and eastern (bottom) sides of Maaddoo-hulhudhoo. The arrow indicates changes in beach morphology between October 1996 and April 1997.

Together, these results suggest that the beach sediments moved from the eastern and southern beaches to the western part of the island. The persistence of this pattern from one season to the next is exemplified by the prominent sediment deposition shown on aerial photographs taken 30 years apart (Figure 6.4).

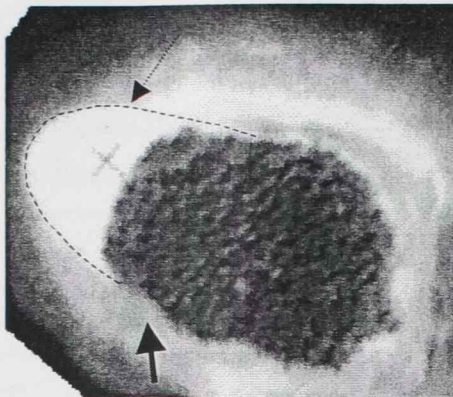


Photo: RAF 1969

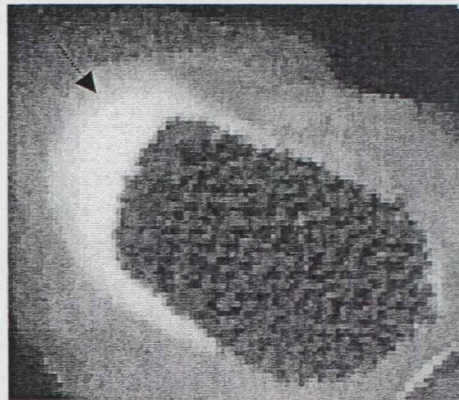


Photo: MCPW 1999

Figure 6.4 Aerial photos of Maaddoo-hulhudhoo taken in March 1969 and January 1999, showing the prominent sediment deposition on the western side of the island, indicated by the dashed arrow. (NB. North is indicated by the bold arrow).

The gradual return eastwards of the sediments accumulated in the previous season on the western part of the island in response to *Hulhagu* (westerly season) have been illustrated by Riyaz (1999) based on repeated beach surveys of the island in May and June 1999, as shown in Figure 6.5.

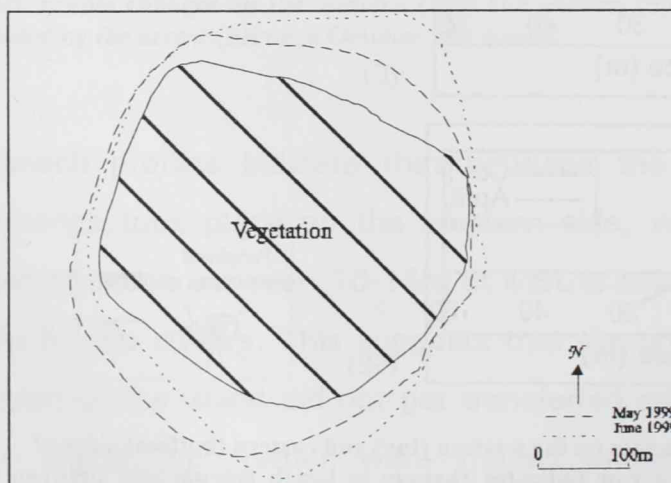


Figure 6.5 The eastward shift of sediments from the western side of Maaddoo-hulhudhoo between May and June 1999. The extent of beach in May (dashed lines) and in June (bold line) is indicated. (Source: After Riyaz 1999).

Olhugiri

On Olhugiri, which for the most part is comprised of coral gravel and rubble, observations showed that there were no significant seasonal changes to beaches around the island, suggesting that sediment calibre is an important factor in determining beach response to seasonal changes.

These three examples of circular islands have shown considerable differences in the seasonal erosion and accretion patterns, extent, magnitude and direction of change. In addition to sediment type, the proportion of reef occupation, and island size may explain some of the differences in the patterns observed, recognising that the results from the smallest of the three islands registered the most comprehensive changes.

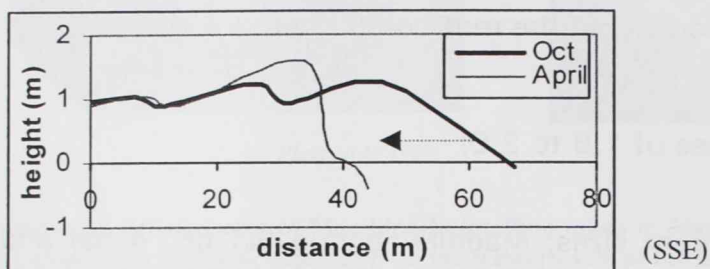
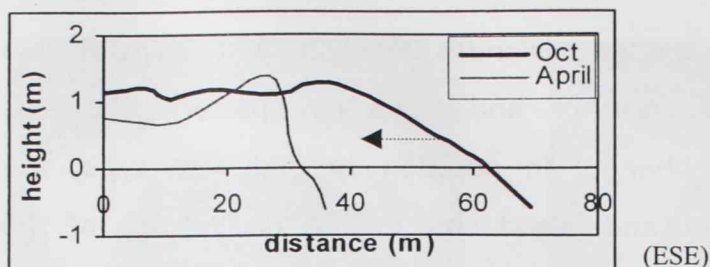
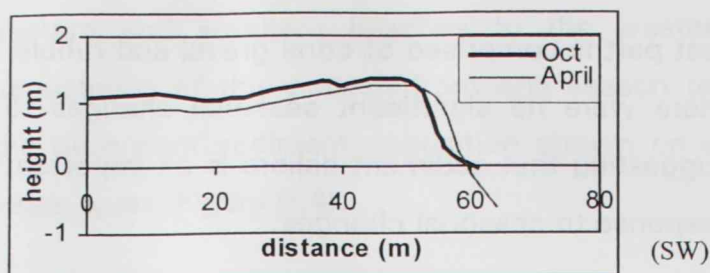
6.2.2 Elliptical islands (I_e values of 1.6 to 2.0)

Two elliptical islands of different sizes; Madhirivaadhoo (I_e 1.65, 4 ha) and Mendhoo (I_e 1.85, 10.5 ha) are considered here. Madhirivaadhoo is a peripheral island occupying about 35% of the reef platform, and oriented in an east-west direction, in the NE quadrant. Mendhoo is a lagoonal island occupying about 26% of the reef platform, oriented in a northwest-southeast direction, and located about the centre of the atoll. Thus, the results should give some insight into the response of an 'exposed' (peripheral) island and a 'sheltered' (lagoonal) island. The beach profile locations on Madhirivaadhoo and Mendhoo are shown in Figure 6.1.

Madhirivaadhoo

Three beach profiles (SW, SSE, and ESE directions) were measured at the southwest end and close to the northeast end of the island. It was not possible to survey any beach profiles at the extreme seaward end of the island due to the presence of numerous boulders and large cobbles, which remained exposed during both seasons. The surveys of October 1996 and April 1997 are presented in Figure 6.6.

Southwestern end profiles



Northeastern end profile

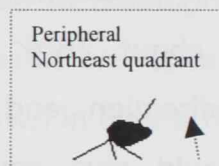
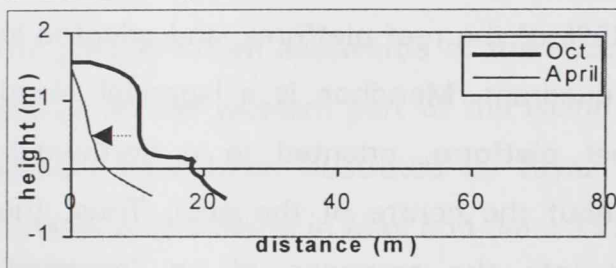


Figure 6.6 Changes in the beach morphology on the southwest (top) and the northeast sides of Madhirivaadhoo between October 1996 and April 1997. The dashed arrow indicates the extent of sediment loss between the period.

Results of profile surveys on the southwestern end of the island indicate substantial loss of sediments on the SSE and ESE profiles between October to April, in response to the easterly season, though virtually no change is evident on the southwest beach profile. The profile surveyed close to the northeastern end of the island also shows erosion between October and April of about 10m, substantially less than in the southwest.

These combined results indicate that sediments on the southern side of the island move westwards during the easterly season, and *vice versa* during the westerly season.

Mendhoo

Beach profiles on the larger elliptical island of Mendhoo, (which is more than twice the size of Madhirivaadhoo) were surveyed in October 1996 and April 1997 on the northwest end of the island (Figure 6.7).

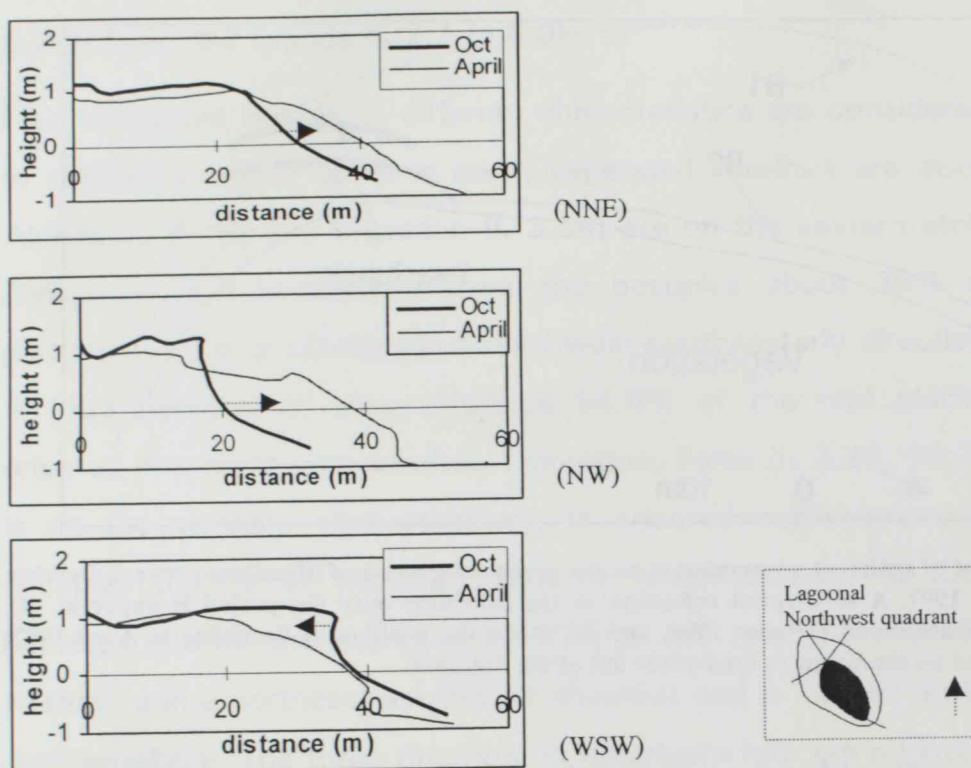


Figure 6.7 Changes in beach morphology between October 1996 and April 1997 on the northwestern end of Mendhoo.

The beach area on the southeastern end of the island was also mapped, with a single profile surveyed across the maximum extent of the beach in October 1996 and repeated in April 1997. The beach profile changes are shown in Figure 6.8, and the changes in beach plan are illustrated in Figure 6.9. These data show that the beach extended out further under the influence of the westerly season, and contracted under the easterly influence.

Southeastern profile

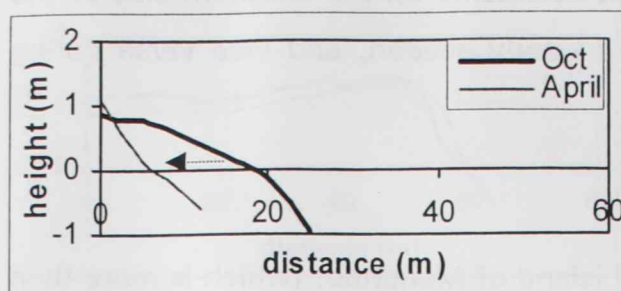


Figure 6.8 Beach morphology difference between the survey period on the southeastern end of Mendhoo.

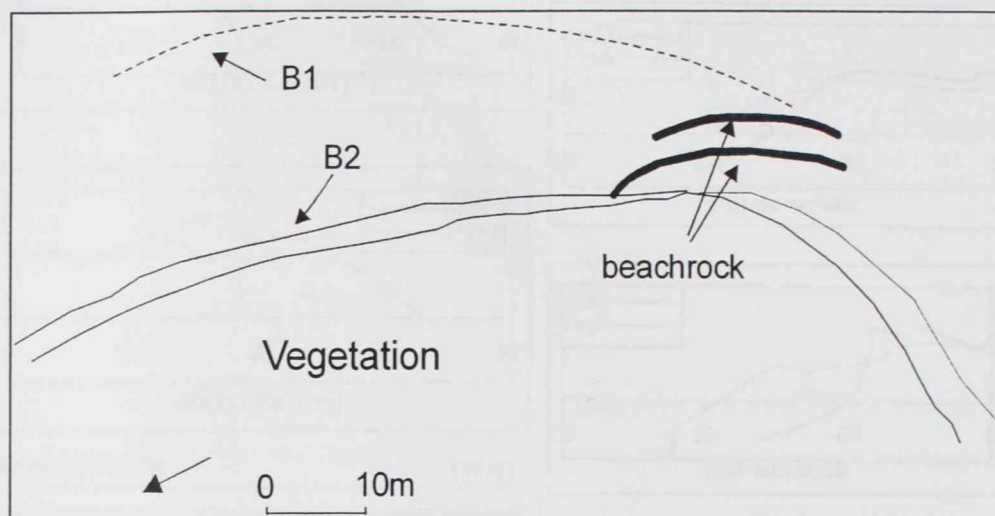


Figure 6.9 Extent of sediment accumulation on the southeastern end of Mendhoo between October 1996 and April 1997. A substantial reduction in the beachline over the period is apparent. B1 represents the beachline in October 1996, and B2 shows the position of beachline in April 1997. North is indicated by the arrow at the bottom left of the diagram.

The beach profile differences over the two seasons obtained from the northwestern end of the island suggest that most extensive change occurred on the centre (northwest) profile. Moreover, some sediment losses in April were evident on the southwest transect. This implies that sediments accumulate to the south on the southwestern side with the westerly season and are moved northwards during the easterly season.

In summary the response of the beaches to seasonal wave and current conditions on these two elliptical islands of different sizes are not the same. Sediments on the southwestern side of Madhirivaadhoo moved westerly in response to the easterly season and *vice versa* during the westerly season.

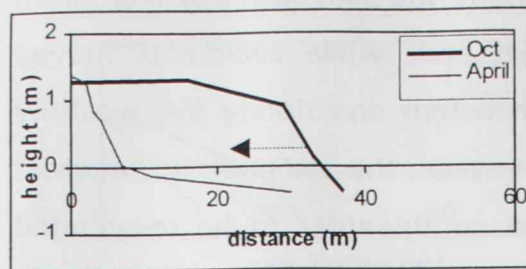
On Mendhoo, sediments on the northwestern end moved north and south reducing the amount of accretion at that end, while sediments moved alongshore and accumulated at the southeastern end during the westerly season. With the influence of the easterly season, the sediment accretion at the southeastern end of Mendhoo moved southwards, to be re-accreted under the westerly season later. The location and position of Mendhoo within the atoll is likely to account for this complex pattern of change.

6.2.3 Elongated islands (I_e 2.1 to 5.0)

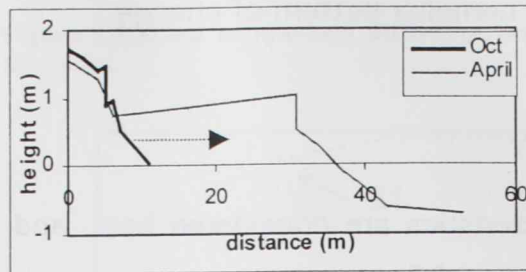
Four elongated islands of different characteristics are considered here, and in addition a string of three partly-vegetated *finolhus* are also examined. Aidhoo (I_e 2.15) and Maaddoo (I_e 3.94) are on the eastern atoll periphery. Aidhoo is two hectares in area and occupies about 35% of the reef platform, and it is oriented in a northwest-southeasterly direction. Maaddoo is 18.8 hectares in area, occupies 54.6% of the reef platform, and is oriented in a northwest-southeast direction. Fares (I_e 2.86, 10.2 ha.) which is on the western atoll periphery, is oriented northwest-southeast, and occupies 3.49% of the reef platform. Maamaduvvari (I_e 2.69) is 29.6 hectares in area and occupies 37.98% of the reef platform. The island is orientated in a northeast-southwest direction and is located on the southern atoll periphery. The three *finolhus* on Kanufushi faro are oriented northeast-southwest, and each of them occupy less than 0.04% of the reef platform.

Aidhoo

Beach profiles were surveyed on the northeastern and northwestern sides of Aidhoo (see Figure 6.1). In addition, the plan position of the beachline on the northeastern side was also mapped. The beach profiles are presented in Figure 6.10. Figure 6.11 shows the mapped base of beach on the northeastern side of the island.



(a)



(b)

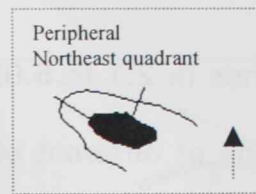


Figure 6.10 Difference in beach morphology on Aidhoo.

(a) Beach profiles surveyed on the northeastern side of Aidhoo between October 1996 and April 1997. The dashed arrow shows the extent of retreat in beachline by April.

(b) Difference in beach profiles between October and April at the northwestern end of Aidhoo. The figure indicates that the beachline extended out by about 25m in April, as the dashed arrow shows.

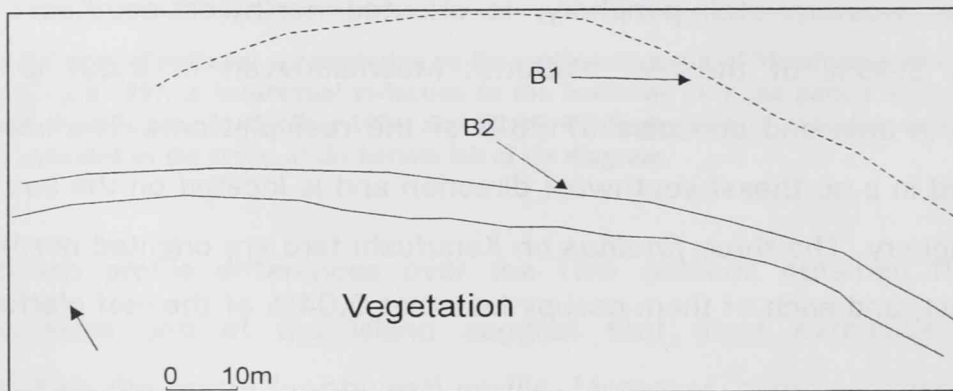


Figure 6.11 Position and extent of sediment deposition on the northeastern side of Aidhoo.

B1 shows the extent of the beach in October 1996, B2 represents the beach in April 1997. North is indicated by the arrow at the bottom left corner of the figure.

The extent of sediment accumulation on the northeastern side of Aidhoo on 26th October 1996 is shown by the photo in Figure 6.12a. A comparative photo of the same site taken on 2nd April 1997 is shown in Figure 6.12b.



(a)



(b)

Figure 6.12 Sediment accumulation on the northeastern side of Aidhoo.

(a) The photo shows the northern side of Aidhoo looking in a northwesterly direction during *Hulhagu*.

(b) Erosion of the sand accumulation on the northeastern side of Aidhoo during *Iruvai* and exposure of coral rubble. Comparison of the above photo (6.12a) with this one together with the beach profile (Figure 6.10) shows the magnitude of changes involved over the two seasons on Aidhoo.

The pattern of sediment transport on Aidhoo is also evident on the aerial photograph taken on 1st February 1999 (Figure 6.13) which is interpreted to show the movement of sediments westwards with the influence of the easterly wind and wave climate which prevail at that time of the year.

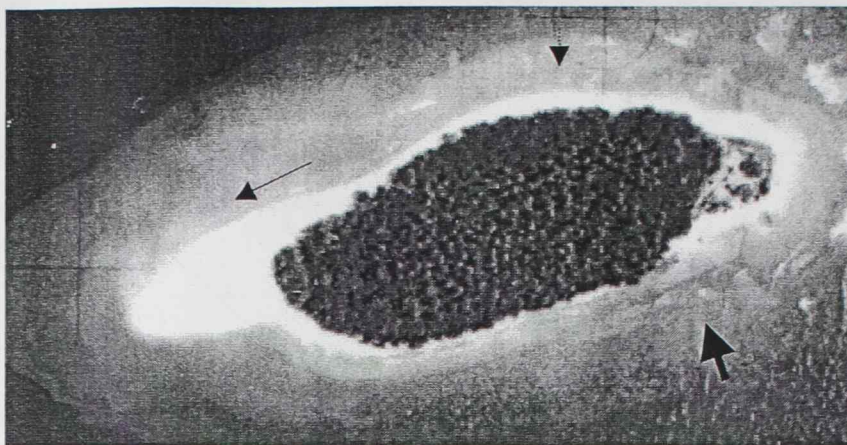


Photo: MCPW 1999

Figure 6.13 Aidhoo and the sediment deposition on the north west of the island. The dashed arrow indicates the position of the sediment deposition during Hulhagu, and the solid arrow shows the direction of sediment movement under the easterly (*Iruvai*) conditions. (North is indicated by the bold arrow).

Collectively these results suggest that on Aidhoo sandy sediments are seasonally moved back and forth along the northern shore. On the southern side of the island, no sediment accumulation was observed in either season, the shore remaining in an eroded state, due to the degree of exposure to waves and swells from the open sea.

It is interesting to note the size of sediments that moved around during the seasonal regimes. These were predominantly in the medium to very coarse sand fraction (from 2ϕ to -2ϕ ; 0.25mm to 4mm in diameter), whereas on the northwestern end of Aidhoo, the stable part of the island during October at the end of the westerly season comprised a lag deposit of coarse pebble to medium boulder size particles (16mm to 256 mm) as shown in Figure 6.14.



Figure 6.14 Exposed rubble on the northwestern end of Aidhoo after *Hulhagu* season. The size of the particles ranges between 50 to 250mm.

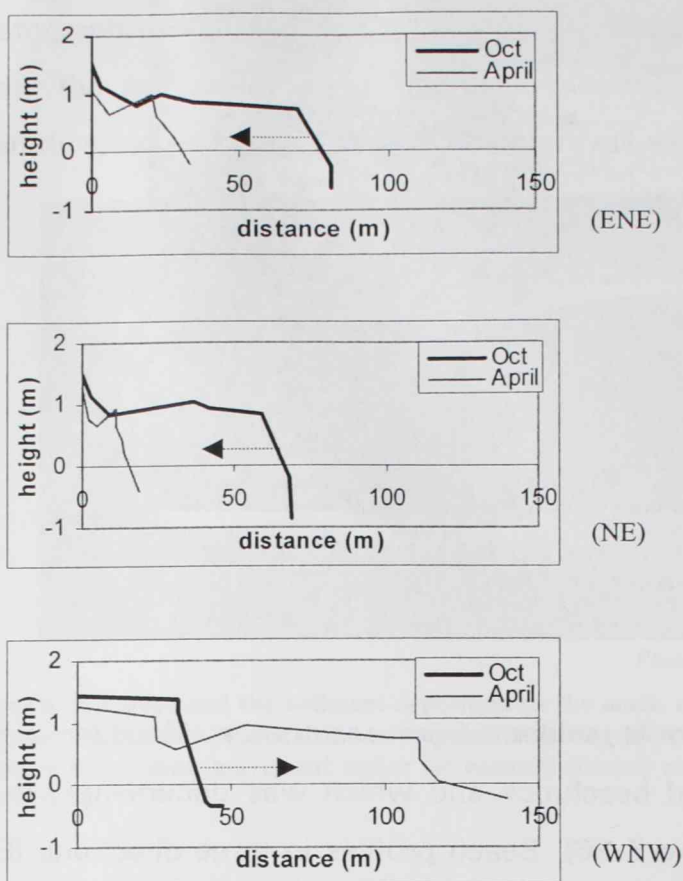
Maaddoo

Similar to Aidhoo, erosion is evident from results on Maaddoo which exposed cay sandstone and beachrock and which was documented in the previous chapter (e.g. Figure 5.26). Beach profiles in three directions (ENE, NE and WNW) were surveyed at the northwestern end of the island. One profile was also surveyed on the northeastern side, before island end. The location of the profiles surveyed on Maaddoo is shown in Figure 3.5(g). Results are presented in Figure 6.15.

The beach profile changes at the northwestern end of the island (Figure 6.15) indicate that sediments, accumulated on the two northerly transects (ENE and NE) during the westerly season, are moved to the southwest in response to the easterly influences.

Noticeable changes to the profiles on the northeastern side of the island during the survey period is also evident as shown in Figure 6.15. Given the orientation of the island (northwest-southeast) sediments move westwards, along the northern side of the island under the influence of the easterly waves and currents.

Northwest end profiles



Profile surveyed close to the northeastern end of Maaddoo

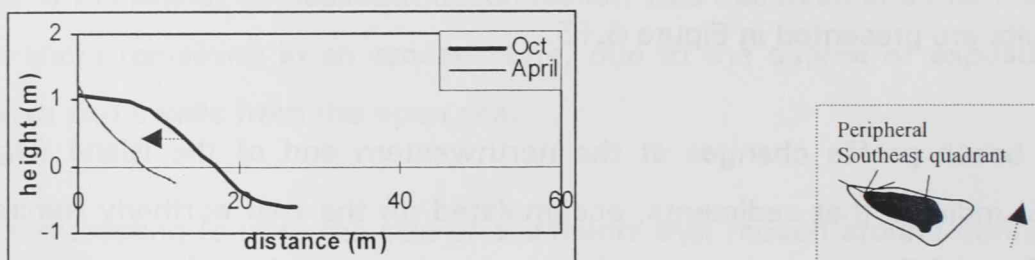


Figure 6.15 Beach profile changes on the northwest end and close to the northeastern end of Maaddoo. The magnitude of changes is greater on the northwest end compared with changes on the northeastern side. Note the scale difference on the bottom diagram.

It was also evident that sediments were moved northwards on the northwest end of the island during the westerly (*Hulhagu*) season (as indicated from the beach profile figures), to such an extent that sediments were being lost from the platform, over the reef edge and into the deep water (Figure 6.16). The movement of sediments on the northwest end

of the island is also clearly evident on the aerial photo of the island taken in January 1999 (Figure 6.17).



Figure 6.16 Sediment losses over the reef edge on the northwestern end of Maaddoo. This photo was taken towards the end of the westerly season, in October 1996.



Photo: MCPW 1999

Figure 6.17 Sediment accumulation on the northwestern end of Maaddoo. The dotted line marks the position of sediment accumulation in the previous season, and the red arrow shows the point from where sediments were lost over the reef as shown in the previous figure (Figure 6.16).

The beach profile changes and the two photographs (Figures 6.16 and 6.17) suggest that the sediments at the northwestern end of the island move between a northerly and a southerly position in response to the alternating wind and wave climate.

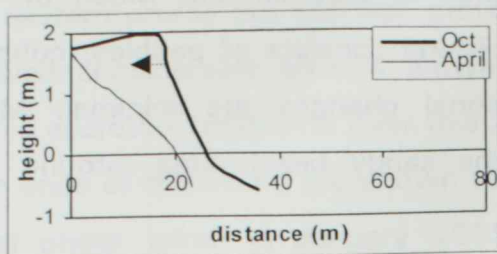
Comparing Maaddoo and Aidhoo, it is evident that erosion and accretion patterns over two seasons are different on these elongated islands both of which are located on the eastern atoll periphery. The magnitude of change on Aidhoo is greater than on Maaddoo, as sediments from the northeastern side are moved westwards to form an extensive accumulation at the northwestern end of the island. In contrast, sediments at the northwestern end of Maaddoo are moved between a northerly to a southerly direction with the seasonal change. The reasons for these patterns are believed to include differences in size, and proportion of reef platform occupation.

Fares

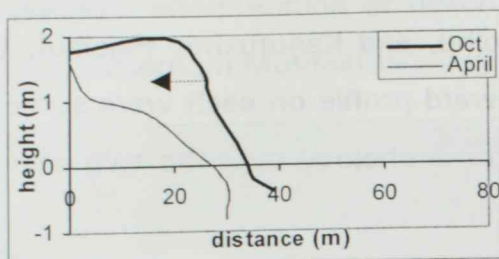
Fares is different to many islands considered earlier as it occurs at the lagoonward (eastern) end of an extensive peripheral faro in the west of the atoll. Three beach profiles were measured at the northwest and southeastern ends of the island (Figure 6.1), with results shown in Figure 6.18.

In contrast to results from other islands which show alternate erosion and accretion patterns at opposite island ends, those on Fares show the existence of broad beaches at the end of the westerly season, on both ends of the island, which were eroded by the end of the easterly season (*Iruvai*). It is envisaged that during the following season the profiles would accrete, and return to a similar condition as in October 1996.

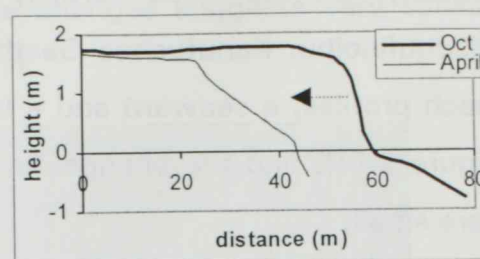
Beach profiles at the northwest end



(NNW)

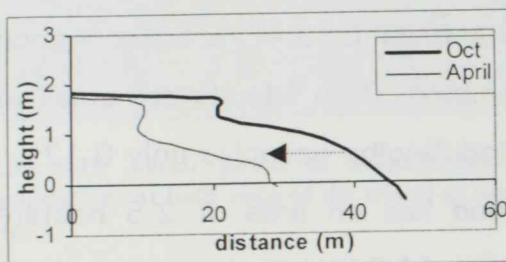


(WSW)

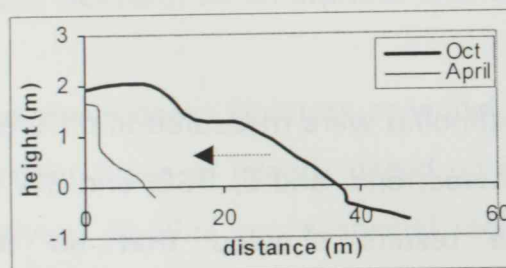
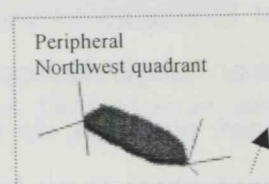


(SSW)

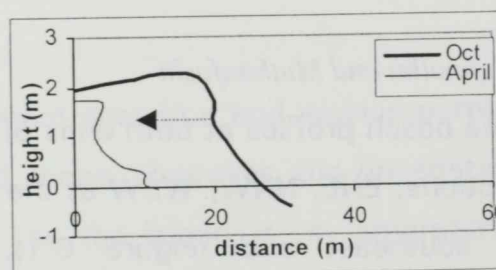
Beach profiles at Southeast end



(NNE)



(ENE)



(SE)

Figure 6.18 Changes in beach profiles at the northwestern (top) and southeastern (bottom) ends of Fares.

Maamaduvvari and Kanufushee faro finolhus

On Maamaduvvari the sandy beach area is very limited. Much of the southeast to southwestern part of the island consists of pebbles, cobbles and boulders, and in this area seasonal changes are minimal. More significant beach change occurs on the sandy beach area, around the northeastern 'horn' of the island.

Similarly, on the three partially vegetated finolhus on Kanufushee faro (Medhufinolhu, Kanufushee Gaathu Finolhu, and Kanufushee Finolhu), two beach profiles, a seaward and a lagoonward profile on each were surveyed (Figure 3.5f), and the changes in beach morphology over the two seasons were small.

6.2.4 Linear islands ($l_e > 5.1$)

Bodufinolhu (l_e 12.5), which is located on an extensive peripheral reef platform in the SW quadrant, and Muthaafushi (l_e 8.4), a linear lagoonal island in the same quadrant will be examined. Both islands are small and occur on relatively large reef platforms. Bodufinolhu occupies only 0.12% of the reef platform, is oriented NW-SE, and has an area of 2.5 hectares. Muthaafushi is three hectares in area, oriented NE-SW, and occupies 4.32% of the reef platform area.

Bodufinolhu and Muthaafushi

Three beach profiles at both ends of Bodufinolhu were measured in different directions: ENE, NNW, WSW at the northwest end, and E, SSE, and SW at the southeast end (Figure 6.1). The results showed that on the northwestern end of the island sediments were lost on the ENE and NNW profiles, with significant deposition on the WSW profile under the easterly wave and current conditions, the sediments returning during the westerly season.

On the southeastern end of Bodufinolhu, very little change was evident on the eastern profile but the SSE profile surveyed towards the open channel showed considerable erosion between October and April, while the SW profile accreted sediments over this period. The sediment accumulations at both ends of the island are shown to be recurved towards the west on the aerial photo taken in January 1999 (Figure 6.19). During the westerly season they recurve towards the east, suggesting an oscillatory motion over the seasons. Interpretation of beach profile changes suggests very similar seasonal pattern on Muthaafushi (Figure 6.1).

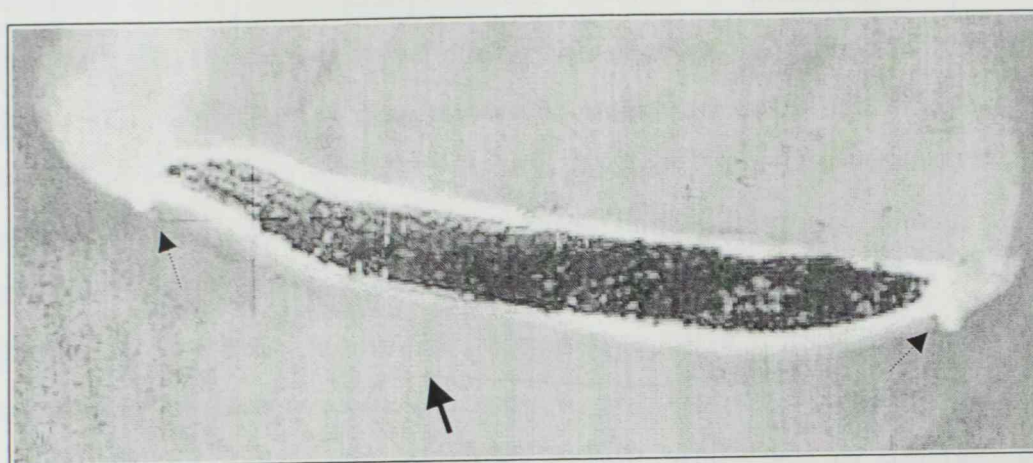


Figure 6.19 Aerial photo of Bodufinolhu taken in January 1999 showing the sediment accumulations at both ends of the island as indicated by dashed arrows. The bold arrow indicates north.

6.2.5 Nelivaru: an amorphous island

The above cases illustrate seasonal sediment accretion and erosion patterns for four types of islands based on island shape. However, the unvegetated Nelivaru *finolhu* needs special mention, as the island is so 'amorphous', varying between linear to elliptical in shape over the year. Nelivaru is located on the lagoonward edge of an extensive faro.

Investigation of seasonal changes on Nelivaru, indicates that sediments from the side exposed to the prevailing wave and current condition at the time moves to leeward to such an extent that the island as a whole moves

around on its reef platform. Figure 6.20 shows the different outlines that Nelivaru has taken between both seasons and in successive months. Thus, unlike the seasonal changes on other islands which primarily impact the active beach zone and rarely the vegetated outline, in the case of Nelivaru morphodynamics change is an on-going process that reworks the sediments and affect the island as a whole.

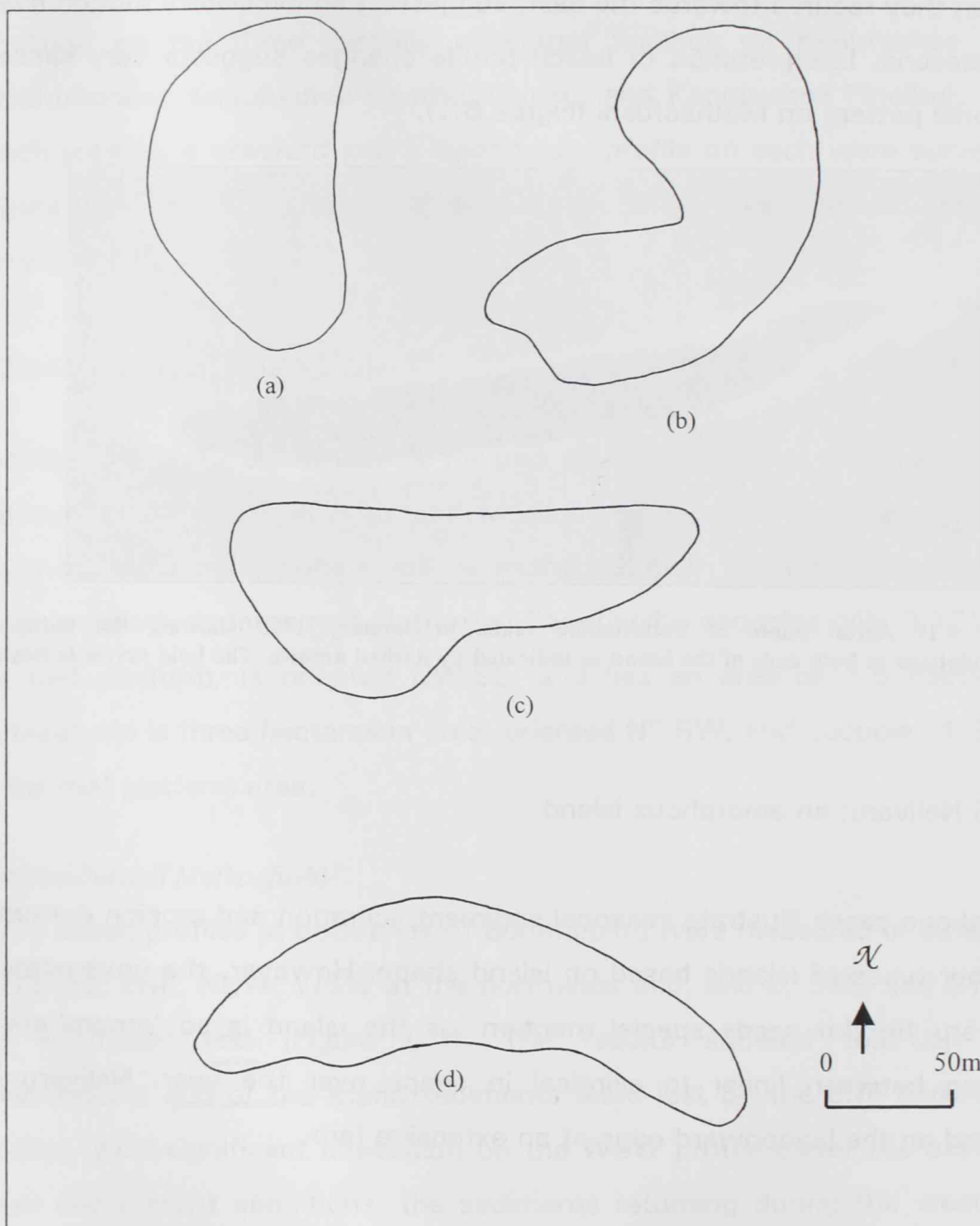


Figure 6.20 Changes on Nelivaru. The shape of Nelivaru in (a) October 1996 (b) April 1997, (c) May 1999 and (d) June 1999. May (c) and June (d) figures are from Riyaz (1999).

6.3 Patterns of seasonal changes

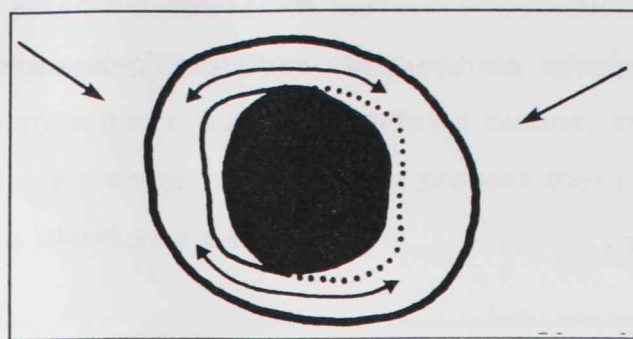
Three generalised patterns of seasonal sediment movements can be identified as follows.

6.3.1 Circulating pattern

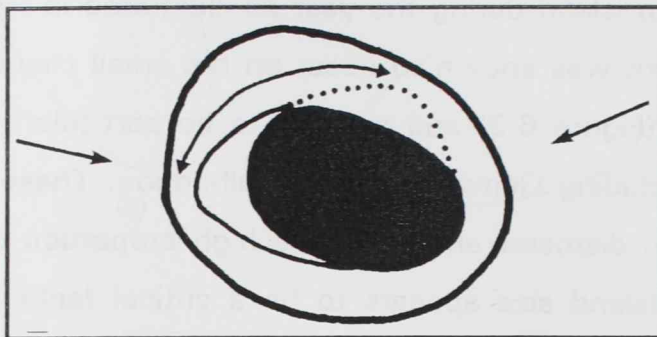
Beach sediments can be eroded from one part of an island and shifted alongshore to accumulate on the opposite part during one season and returned in the subsequent season. In such a situation, sediments may circulate all around an island during the year as illustrated in Figure 6.21a. This circulating pattern was shown to occur on the small circular island of Maaddoo-hulhudhoo (Figure 6.3) and appears to be particularly associated with such islands including Gemendhoo and Hulhudhoo. These islands are all less than 200m in diameter and occupy a high proportion of their reef platform (35-44%). Island size appears to be a critical factor in that the circulating pattern was not observed on Udoodhoo (Figure 6.2) another circular island which also occupies a high proportion of the reef platform (51%) but differs in being very much larger (9.3 ha).

6.3.2 Semi-circulating pattern

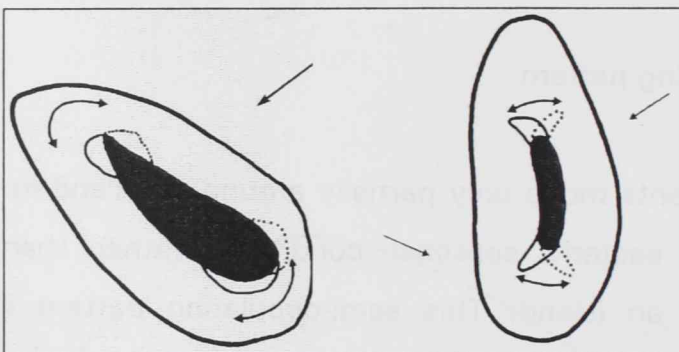
In this case, sediments move only partially around an island in response to the westerly and easterly seasonal conditions rather than circulating completely around an island. This semi-circulating pattern illustrated in Figure 6.21b is based on results from the elliptical island of Madhirivaadhoo (Figure 6.6) and the elongated island of Aidhoo (Figure 6.10). Both of these islands are small (Aidhoo 2ha; Madhirivaadhoo 4ha) and are located on the eastern periphery of the atoll. The semi-circulating movements take place around the lagoonal half of the islands; their ocean sides consist of coral rubble and boulders and are subject to erosion as a result of exposure to easterly conditions.



(a)



(b)



(c)

Figure 6.21 Seasonal sediment patterns. (a) Circulating (b) Semi-circulating, and (c) Oscillating. Details are explained in the text. The dotted lines show the extent of sediment accumulation in one season (westerly), and the bold lines, the other (easterly).

6.3.3 Oscillating type

A particularly common type of seasonal movement occurs on the elongate or linear islands which have distinctive 'ends' made up of recurved beach-lines, which inflect one way during the easterly season and the other way during the westerly season as shown on Figure 6.21c. In some instances oscillation takes place at both ends of the island, such as on Bodufinolhu and Muthaafushi or, at one end like on Maaddoo. Islands subjected to the oscillating type vary in size, shape and position around the atoll, and in the proportion of reef area occupation as well.

6.3.4 Other types

While erosion and accretion is evident on most beach profiles measured over one seasonal cycle, the changes on Fares show that erosion took place all around the island by the end of the easterly (*Iruvai*) season, suggesting that the island as a whole responds in much the same way. Similarly on Nelivaru, as described in the previous section, the entire *finolhu* was translocated in response to seasonal and even shorter-term influences. The small size of the island and the absence of vegetation probably account for much of this 'translocational' behaviour.

6.4 Episodic/unusual events

These include extra-tropical swell events and locally generated storms. During the period of fieldwork, no unusual/episodic event was experienced in Eta atoll. Thus it was impossible to directly study the impacts of such events, and instead reliance had to be placed on previously documented situations. These events are examined here, for two main reasons. First, to get an appreciation of the magnitude and extent of changes that can be

induced by such events, and second, to get some idea of their frequency in this part of the Maldives.

6.4.1 Swell incident

A swell incident affected the Maldives between 10th to 13th April 1987. These swells were generated by a distant storm 4-5,000 km southeast of the Maldives, in the Indian Ocean (Goda 1987; Harangozo 1992), and caused flooding and infrastructure damage on islands throughout the archipelago. In a detailed study to identify the cause of flooding, Harangozo (1992) suggested that it was the directional constancy of swell in mid-April rather than significant wave height (H_s) alone which caused the flooding in the Maldives, as H_s values comparable to those on the 11th April 1987 occur on many other days during the year. Indeed, daily H_s values for three years show that the 2.05m which occurred on the 11th April is frequently exceeded, particularly during the westerly season (Figure 6.22).

The geomorphic impact of this swell event on some islands was significant. In one case accumulation of coral rubble led to the emergence of a new island (Udhafushi) in North Male' Atoll (λ). In Eta atoll, it resulted in the deposition of an 11000m² of rubble and coarse sand foreland on the southeastern end of Aidhoo, the extent of which is still evident nearly 12 years after the event (Figure 6.13). The type and extent of material involved in the deposition and the distinct boundary between the existing sediments on the island and the 'fresher' deposition is shown in Figure 6.23.

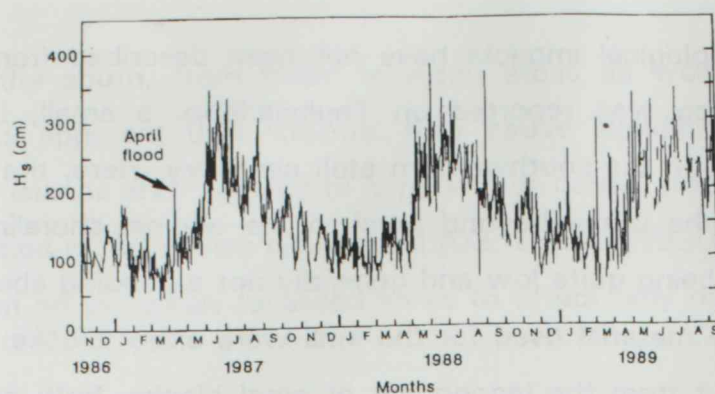


Figure 6.22 Daily time series of area averaged significant wave height (cm) based on altimetric data from GEOSAT for a 20 by 20 degree box centred on Male' (Maldives). (Source: Harangozo 1992).



(a)



(b)

Figure 6.23 The 1987 rubble deposition on Aidhoo is still quite visible nearly 12 years later, when this photo was taken in January 1999.

(a) Part of the deposition on the southeastern end of the island showing the distinct boundary between the older deposition (A) from the 'fresher' deposition (B).

(b) A close up of the sediment boundary between the 'older' and the 'newer' depositions on the island. *The arrows indicate the boundary.*

Other geomorphological impacts have not been described from Eta atoll. However, flooding was reported on Thulhaadhoo, a small, but densely populated island on the southwestern atoll periphery. Here, the inhabitants have reclaimed the island beyond much of its original shoreline with the reclaimed areas being quite low and generally not extending above the high water mark. The material used for the infill were either blocks of seagrass and sediment cut from the lagoon flat or coral blocks, both of which are quite porous and of allow flooding from within.

Thulhaadhoo also experienced flooding from high water levels in July 1988, apparently caused by high SW waves (2-2.5m period 12-15 seconds) in association with high spring tide and a SW wind as described by Pernetta and Sestini (1989). They reiterate that damage was enhanced by the absence of beaches and the presence of low vertical sea walls, which magnified overtopping, and flooding.

The studies of Harangozo (1992) and Pernetta and Sestini (1989) provide examples of the exaggerated impact of such short-term events on island/reefs that have been severely modified by human activity. In this thesis such islands have not been investigated in any detail. Instead, emphasis is placed on islands where natural morphodynamic processes are primarily at work.

6.4.2 'Storm' incidents

Although the Maldives archipelago is located outside the tropical cyclone-generating area, it has become a common contention that storms are not significant in the Maldives. Whilst it is true in that the Maldives only rarely experience severe storms in comparison with the Laccadive group to the north of the Maldives, Woodroffe (1993) has argued that storm impacts are also felt in the northern Maldives. Storms are also reported to have affected

islands in the south, from Male' to Addu atolls as well (Maniku 1990). Hence, it is apparent that 'storms' may cause significant morphological changes to islands and can lead to complete or partial erosion of islands, or to the creation of new ones (Gardiner 1903; Maniku 1990). At times, such 'storms' can be extremely localised so as to affect only one island (Maniku 1990).

In a study of the morphodynamics of reef islands in Male' Atoll (λ), Preu and Engelbrecht (1991) identified two main types of storms affecting the islands. First, the 'eastern depressions' which are tropical depressions with violent cyclonic circulation of wind mainly occurring during the months of November and December, that move from the east. The second type is the 'cyclonic storm' in which winds reach or exceed Beaufort force 8. The highest frequency of this storm type is at the onset of the SW and NE monsoons.

The history of storms experienced in the northern parts of the Maldives is well documented (Maniku 1990) in that there are records of storms affecting islands in 1812, 1819, 1821, 1955. On 29th December 1819, the island of Thiladhoo in the northeast corner of Eta atoll was devastated by a 'storm' that resulted in the depopulation of the island. With reference to Kulhudhuffushi and Kurendhoo, Maniku (1990) simply states that these islands were ...*washed away in a storm on 8 December 1821.*

Thulhaadhoo, on the southwestern atoll periphery also has a history of instability. Gardiner (1903, p.382) commented on the devastating effect of cyclones in 1896 and 1898, prior to his visit in that *The former is said to have swept down along the island from the N.W., while the greatest force of the latter was experienced at high spring tide from the S.W.* He further comments that the combined result of the two had reduced the island to less than half its original size.

More recently in Eta atoll, what Maniku (1990) described as 'freak storms' were reported to have affected Eydhafushi in 1977, Kendhoo in 1978, and Kihaadhoo in 1987, and flooding from waves (cause unknown) also affected the islands in 1988 and 1989.

A more recent event that can be documented occurred at the end of May 1991. Maximum wind speeds recorded on Male' during May and early June 1991 are shown in Figure 6.24, with maximum wind gusts between 100-103 km/hour from WNW.

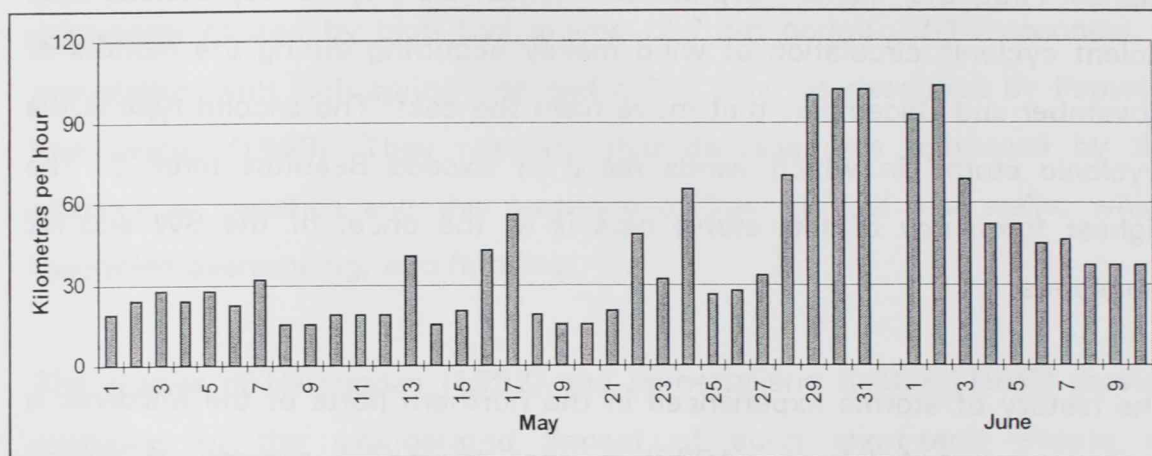


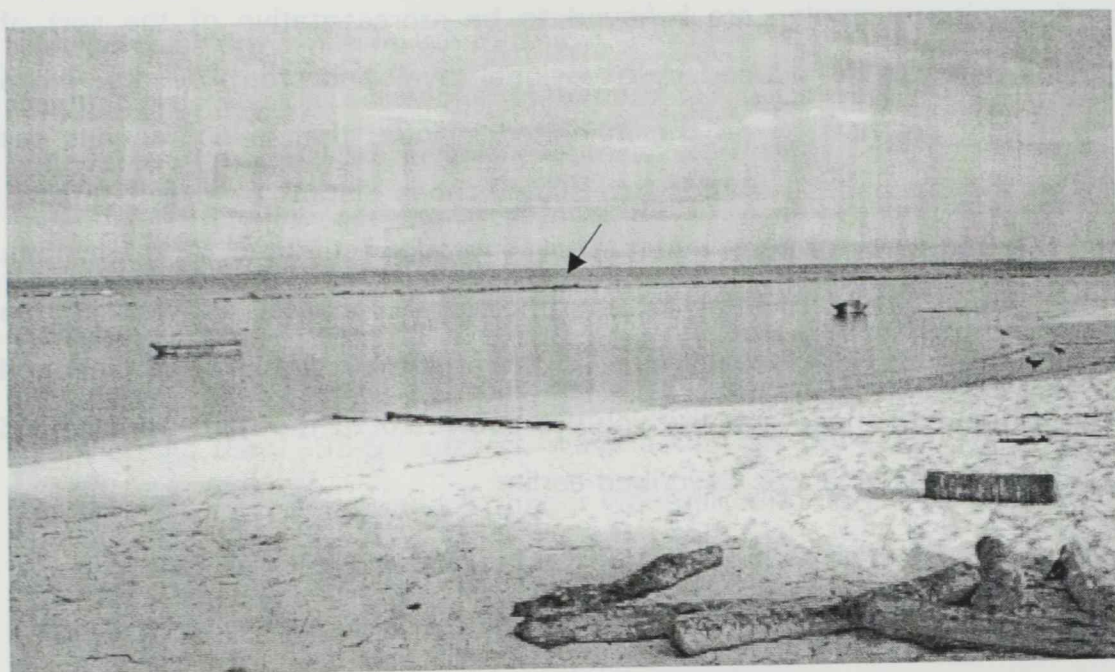
Figure 6.24 Maximum wind speeds recorded on Male' (May to early June 1991).

This incident caused deposition of coral rubble ridges on the western side of many islands in the atoll, including Eydhafushi, Hithaadhoo, Hibalhidooh, Maalhos, and Udoodhoo, as well as on Kudarikilu (an island across Kuda Kanduoilhi, north of Eta atoll). According to inhabitants of the atoll, such depositions usually get reworked and lose their cohesiveness over time.

The ridges deposited on the northwestern side of Udoodhoo and on the southwestern side of Kudarikilu are shown in Figure 6.25. Both ridges curve around the shore paralleling the reef edge and have created local wave shadow areas resulting in an extension of the adjacent beach.



(a)



(b)

Figure 6.25 Coral rubble ridges on Udoodhoo and Kudarikilu formed during 1991 storm incident.
 (a) The 'rubble ridge' on the northwestern side of Udoodhoo is indicated by the arrow. The distance between the end of beach and the 'ridge' is about 10m.
 (b) The 'rubble ridge' (indicated by the arrow) on the southwestern side of Kudarikilu.

According to the inhabitants of Kudarikilu, before the 'rubble deposition' was in place, the beach on the western side of the island underwent seasonal changes, with accretion during the easterly season, and erosion during the westerly season. Since deposition of the 'ridge', the beach has gradually extended out towards it.

In section 6.2.1 the seasonal beach profile changes on Udoodhoo were described. Also evident was the fact that changes on the western side of the island were minimal (Figure 6.2), suggesting that this storm-emplaced ridge may have played some part in restricting the seasonal shifts of sediments from the western side of the island, under the westerly conditions. This example suggests that the presence of such rubble ridges can influence the short-term morphodynamics of the islands and therefore have medium and perhaps longer-term implications.

The foregoing examples are believed to be representative of the sort of changes that can be induced by occasional swell and storm events. While such events are noticed on the inhabited islands, that is not always the case on the uninhabited islands particularly those distant from settlements. Thus the frequency of such events may be under-estimated. Another point is that the at-island location of morphological impacts, as well as the distribution of impacted islands around the atoll may be highly variable and quite different to those areas which are subjected to the more regular and frequent seasonal changes described earlier.

6.5 Summary and implications

Islands of Eta atoll are subjected to short-term weather and wave climate fluctuations on two time-scales: (1) the annual cycle of seasonal variations, and (2) episodic events associated with the occurrence of either externally generated or more localised storm events. These two time-scales are similar to those that have been described by Flood (1986) and Flood and Heatwole (1986) for contemporary sand cay changes on the Great Barrier Reef.

In the Maldives very little work has been done on the island impacts of seasonal variations in monsoon conditions, and one of the purposes of this thesis was to document the magnitude and nature of the geomorphic changes on two separate occasions, (and to put in place a network of

survey stations from which further measurements can be made). Although the results reported here are limited they do provide sufficient evidence to permit some general conclusions:

- Virtually all seasonal changes affected the active beach zone and did not reach beyond the island's vegetation line.
- The magnitude of both erosion and accretion was approximately the same and resulted in horizontal shifts of the beach commonly by 10-25m, but occasionally up to 50m.
- With erosion in most cases the beach face was cut back in parallel-retreat fashion, while in others the beach face was both cut back and combed down, on occasions to expose an underlying layer of coral gravel and rubble. The eroded materials were deposited either on the adjacent reef flat or moved alongshore in a downdrift direction to accumulate towards the lee shore.
- Where accretion occurred it normally took the form of a new berm developed at a lower level than the main vegetated berm, suggesting that during the 1996-97 season, wave action did not reach the levels it is capable of reaching under stronger weather conditions.
- Seasonal changes were minimal on island shores that are usually made up of coral gravel and rubble, which not only provide some natural armouring for the island, but also inhibit accretion.

In addition, three types of seasonal changes were distinguished, as being:

- circulating type - small size and circular shape of island (Cluster groups 3 and 4);
- semi-circulating type - small size and elliptical or elongate island shape (Cluster group 2);
- oscillating type - linear or elongate island shape, and variable size cluster groups 1 and 6).

The significance of island size and shape (length:width ratio) is therefore evident. Aidhoo, Bodufinolhu, and Hulhudhoo have very similar areas

(<3ha), but they have different shapes and seasonal sediment patterns. Hulhudhoo (circulating) has a length:width ratio of 1.12:1 (circular), Aidhoo (semi-circulating) 2.15:1 (elongated); and Bodufinolhu (oscillating) has a length:width ratio of 12.5:1 (linear). Similarly, islands of comparable shape, exhibit different seasonal erosion and accretion patterns dependent on their size. For instance, on the elongate-shaped islands of Aidhoo and Hibalhidhoo which have different sizes; Aidhoo (2ha) and Hibalhidhoo (14ha), the former has a semi-circulating pattern and the latter a more limited oscillating pattern.

In contrast to the demonstrated relationships between island size, island shape and the magnitude and type of seasonal beach change, the brief analysis of unusual or episodic events suggests that the impacts are much less predictable and appear to bear little relationship to island size, shape and other characteristics, including location on the atoll. One reason for this situation may be that there is little direct information on swell and storm impacts on islands, particularly the uninhabited islands and those that have not been subjected to considerable human modification.

Nevertheless, the examples presented here have confirmed that extra-tropical and locally generated swell and storm events do affect the Maldives from time to time, and that in the case of Eta atoll they have been shown to have impacts on island building processes, such as through deposition of rubble on reef flats, as in the case of Aidhoo or Udoodhoo, and major erosional impacts, as in the case of Kurendhoo. It may be that such events have played a more significant role in the Maldives than previously thought, although a true appreciation of this role awaits further research. Such research is clearly warranted given the projected increase in sea level and possibly an increase in the frequency and intensity of cyclones under global warming and climate change.

CHAPTER 7

Medium-term changes on the islands

7.1 Introduction

This chapter examines the morphodynamic changes on the islands that have taken place in the medium term (decades to century) time scale. Thirty-year changes based on aerial photo interpretation will be examined initially, followed by changes that have occurred on the islands over the past century. Gardiner's (1903) descriptions, photographs and maps provide a baseline of conditions 100 years ago and these can be compared with recent observations and maps. Photographs and comments by Agassiz (1903) provide some additional data, while reference is also made to the reports of island changes summarised in Maniku (1990). These historical data are considered along with maps prepared from the 1969 and 1999 aerial photographs. The chapter is structured around island shape in a similar way to the previous chapter.

7.2 Changes on the islands between 1969 and 1999

Vertical aerial photographs were used for mapping qualitative changes on 16 islands between 1969 and 1999. Because the 1999 photos arrived late in the thesis research it was not possible to complete rectification procedures or make quantitative measurements of changes. Thus, the present analysis is based on mapping from the uncontrolled photographs, supplemented by field observations undertaken with the 1969 photographs

in hand. The comparative mapping of the 16 islands studied are presented in Appendix 3.

7.2.1 Circular and elliptical islands

Five islands all with ellipticity values < 1.9 and distributed throughout the atoll were examined (Figure 7.1). *Gemendhoo* and *Maaddoo-hulhudhoo* are both small islands, 1.2 and 1.6ha respectively and occupy 35 and 38% of the reef platform, which is approximately the same shape as the islands. Outcrops of beachrock to the east of *Maaddoo-hulhudhoo* and around the southern shore of *Gemendhoo* are present on both the 1969 and 1999 maps. An additional beachrock outcrop shows on the 1999 map of *Gemendhoo* in the northeast indicating that there has been some erosion in this area. While seasonal erosion and accretion of the circulating type occurs on both islands, the nett effect of this appears limited over the 30-year period suggesting that the seasonal sediment movements are balanced out over the medium term.

Udoodhoo, *Olhugiri* and *Mendhoo* are much more substantial islands (Figure 7.1). Results of the 1969-1999 mapping show on *Udoodhoo*, an extension of the vegetation line in the northwestern part of the island. This growth as shown in the previous chapter was linked to the accumulation of sediments in the wave 'shadow' area following the deposition of a rubble ridge on the northwestern side of the island in 1991. The location of the rubble ridge is shown on the 1999 map. Other morphological changes on *Udoodhoo* are limited. Similarly, on *Olhugiri* which occupies the highest proportion of reef platform in the atoll (71%) and appears to have a stable shoreline composed of coral rubble and gravel that occurs all around the island. An exception to this is the erosion along the northern shore, which does not show on the 1969 and 1999 photos but is evident from field observations. However, such erosion may be only of a temporary nature.

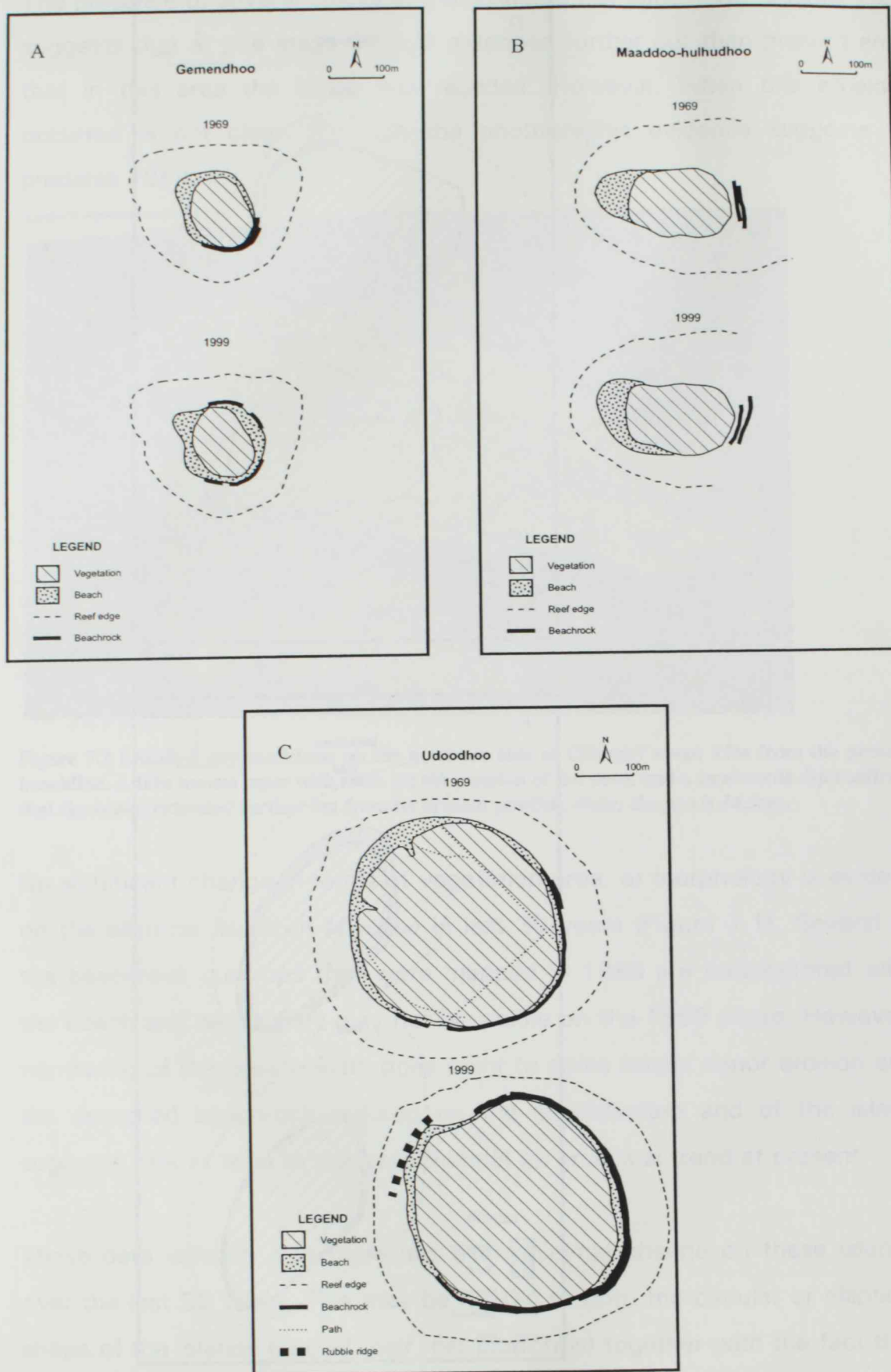


Figure 7.1 Comparative mapping of circular and elliptical islands (1969-1999).

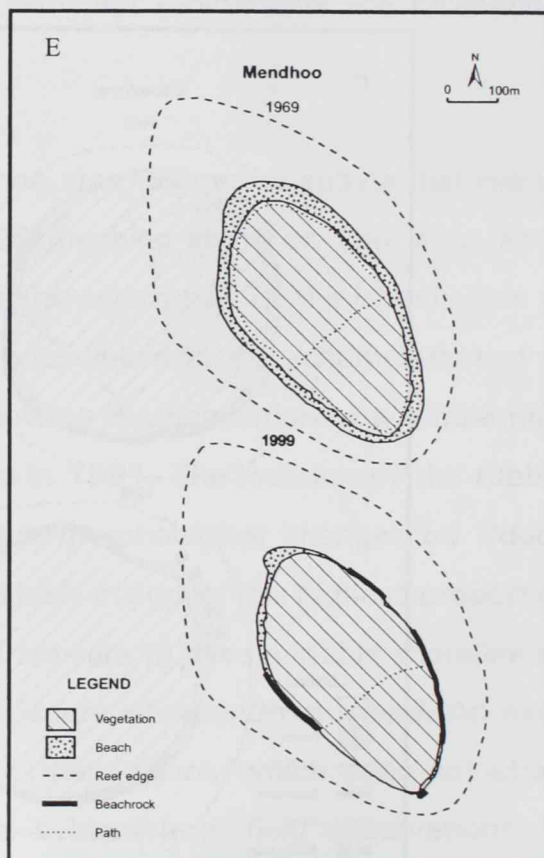
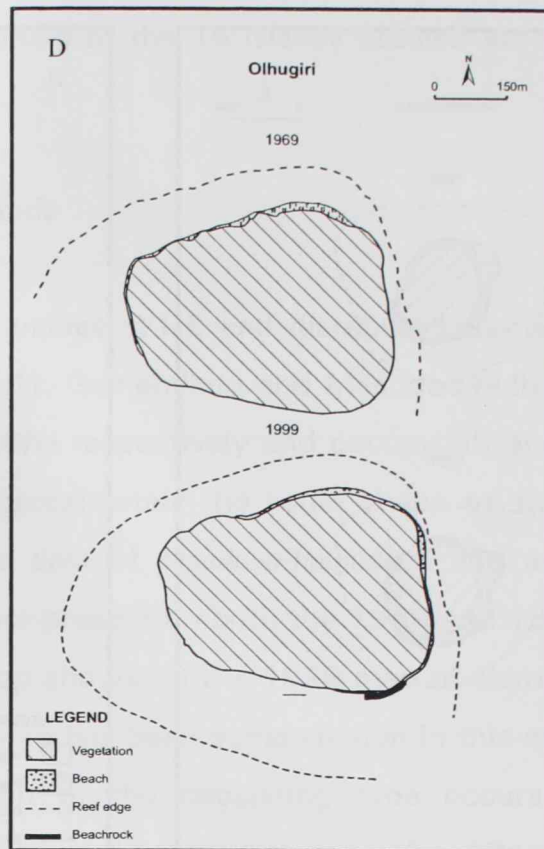


Figure 7.1 (continued)

The presence of several blocks of consolidated cay sandstone (Figure 7.2) suggests that at one stage Olhugiri extended further out than present and that in this area the island has receded. However, when this erosion occurred is not clear, although the photographic evidence suggests it predates 1969.

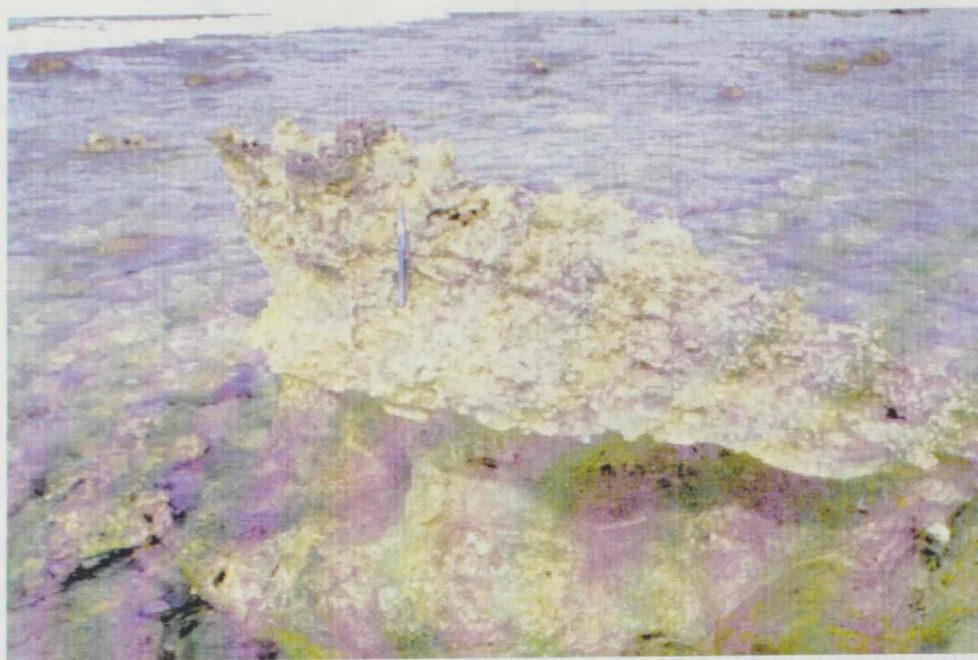


Figure 7.2 Lithified cay sandstone on the northern side of Olhugiri about 15m from the present beachline. A thin humus layer with roots (at the position of the pen), and a landwards dip confirms that the island extended further out from its present position. Note: the pen is 14.5cm.

No significant change in terms of vegetation area, or morphology is evident on the elliptical island of *Mendhoo* in last 30 years (Figure 7.1). Several of the beachrock outcrops that were mapped in 1999 are incorporated with the beach and hence they may not be visible on the 1969 photo. However, narrowing of the beach width does point to some recent minor erosion and the detached beachrock outcrop on the southeastern end of the island suggests that at least in this area there is an erosional trend at present.

These data indicate that there has been minimal change on these islands over the last 30 years. This may be related to both the circular or elliptical shape of the islands (and of their reef platforms) together with the fact that all of these islands occupy a high proportion of the reef platform. Indeed

they may already occupy close to the optimal reef platform area. In such circumstances sediment delivery and removal on these islands may balance out, both in the short and medium term resulting in minimal changes to the island morphology over the 30-year time frame.

It also appears that the two swell and storm events of 1987 and 1991 had little direct impact on these islands, suggesting either that the events were not forceful enough to cause major morphological changes, or that the islands are resilient against such events.

7.2.2 Elongated islands

In contrast to the more compact circular and elliptical islands, significant changes are evident on the elongated islands. Comparative mapping of six islands spread around the atoll is presented in Figure 7.3. The islands range in size from 0.6 to 18ha, of which Hanifaru and Fares occur on faros, while Aidhoo, Hibalhidooh, Maaddoo, or Maamaduvvari occur on patch reefs.

Of the islands located on the eastern half of the atoll *Aidhoo*, has undergone substantial island reduction through erosion in spite of the fact that the 1987 swell incident added some material to the eastern end of the island. In contrast to *Aidhoo*, *Hanifaru* a very small island has almost doubled in area from 1969 to 1999. On *Hibalhidooh* elongation and sharpening at both island ends are apparent, and with this subtle change in shape has come an overall increase in the vegetated area. To some extent the degree of enlargement of *Hibalhidooh* has been offset by erosion of the southeastern shore that has left a series of beachrock outcrops, which provide evidence of the 1969 shoreline position. These changes show clearly on the comparative maps of *Hibalhidooh*.

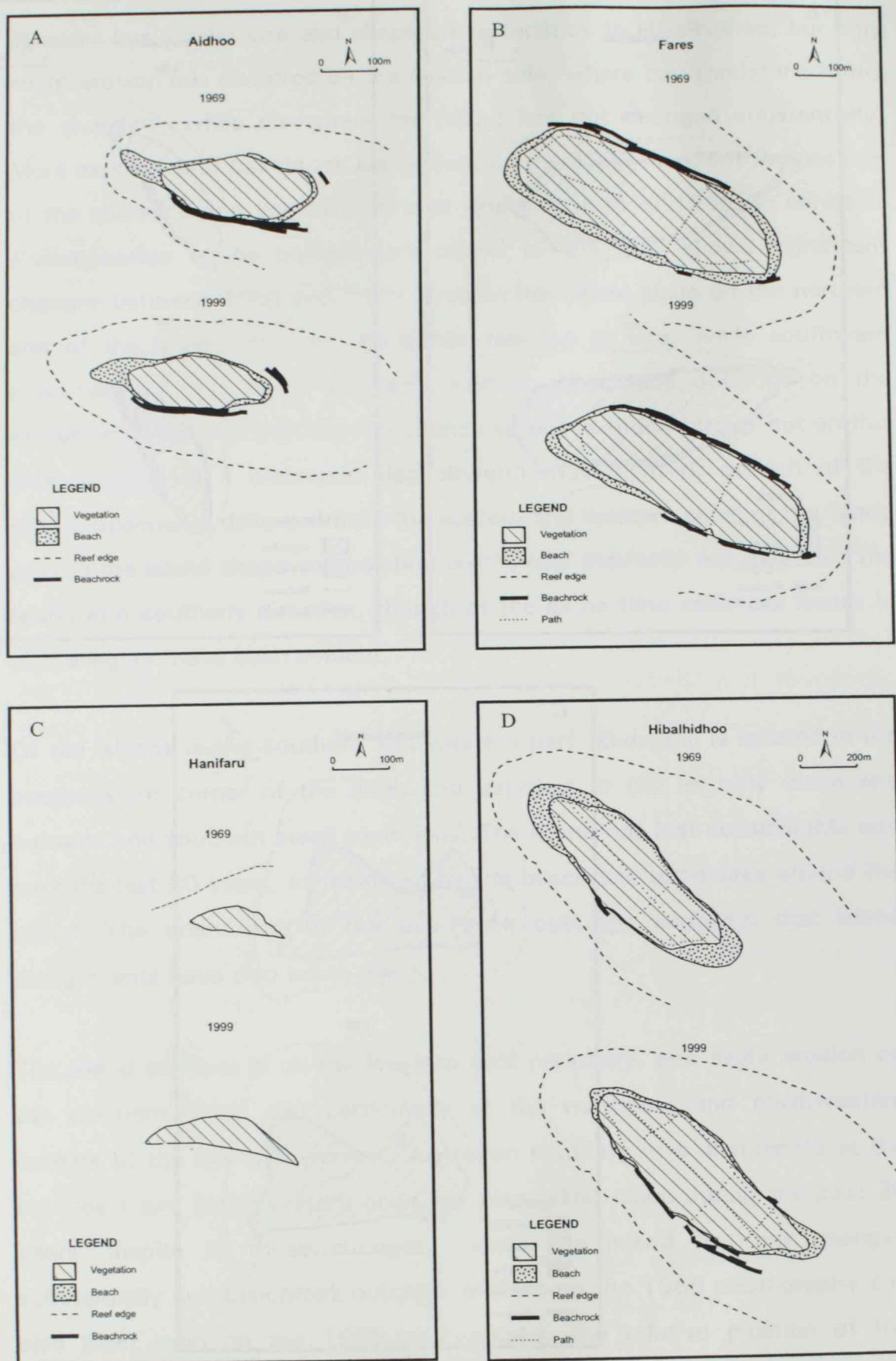


Figure 7.3 Comparative mapping of elongated islands (1969-1999).

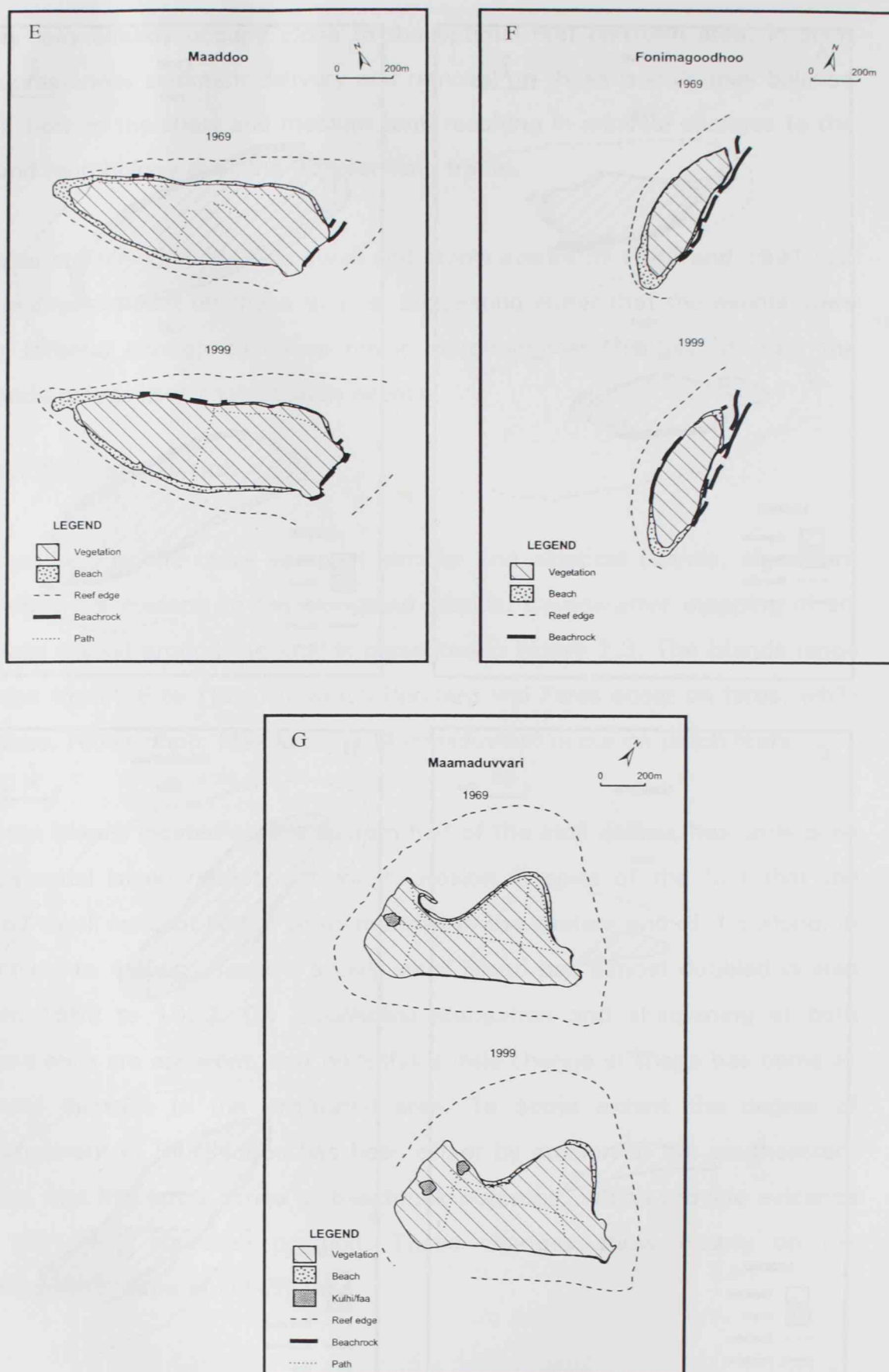


Figure 7.3 (continued)

Maaddoo has similar size and shape characteristics to *Hibalhidhoo*, but only slight erosion has occurred on the eastern side, where cay sandstone forms the shoreline, while elsewhere the island has not changed substantially. More exposures of beachrock are evident on the 1999 map, but the position of the shoreline and vegetation-line is similar to that of 1969. In contrast, *Fonimagoodhoo* in the northeastern corner of the atoll shows significant changes between 1969 and 1999. Erosion has taken place on the northern end of the island, and the island has reduced in size, while southward movement of the island is clearly evident. Beachrock outcrops on the eastern side indicate that the island once extended much further out on this side, suggesting a westward (lagoonward) movement or growth of the island. Sediments delivered from the eastern and western sides of the island (due to the island shape and position on the reef platform) has extended the island in a southerly direction, though at the same time sediment losses in to the lagoon have been evident.

Of the islands in the southern and western part, *Kudadhoo* is located in the southeastern corner of the atoll, and exposed to the easterly wave and currents and southern swell conditions. The island has lost considerable size over the last 30 years, as indicated by the beachrock exposures around the island. The orientation of the beachrock outcrops suggests that island realignments have also taken place.

The island of *Fares* is on the western atoll periphery, and slight erosion on the northern shore and particularly at the northeast and northwestern corners of the island is evident. Accretion resulting in a sharpening at the southeast and southwestern ends has also taken place during the past 30 years. In spite of these changes, overall the island has not changed substantially and beachrock outcrops evident on the 1969 photography can also be seen on the 1999 photographs, the relative position of the adjacent shorelines being in the same place.

Across the lagoon to the southeast of Fares is *Maamaduvvari*. On parts of this island major changes have occurred over the 30-year period. The island has extended lagoonwards from the two northern forelands, with continued infilling of the 'embayment' between them. The formation of a *kulhi*, (which did not exist in 1969) and the extension of the island lagoonwards imply sediment delivery on both sides around the forelands or 'horns', which is believed to be brought about by refraction of waves predominantly from a southerly direction. The southern, eastern and western shorelines of *Maamaduvvari*, composing of coral rubble have not changed in position or form between 1969 and 1999. This suggests that the coarser materials, gravel and boulders on islands may provide some medium-term stability.

7.2.3 Linear islands

Of the three linear islands examined, *Bodufinolhu* has increased in area, *Muthaafushi* has changed very little, and *Ufuligili* has significantly reduced in area, as shown in Figure 7.4. These islands are small (<5ha) and occur on faros in the SW quadrant. *Bodufinolhu* has grown out in a lagoonwards direction all along its northern shore and has extended towards the northeast. The island is positioned a considerable distance away from the seaward reef edge which is to the southeast (see inset Figure 7.4A), suggesting that there will be a substantial reduction in wave energy reaching the island after crossing the reef flat. However, the prevailing westerly and southerly waves and currents do deliver sediments around to the wave shadow area on the lagoon side of the island resulting in lagoonward growth of the island.

In contrast to *Bodufinolhu*, changes on *Muthaafushi*, which is similar in size, shows the island has extended slightly to the west. The presence of beachrock outcrops seen on the 1999 photo to be offset from the alignment of the present southern shore indicate that substantial changes has occurred in this area.

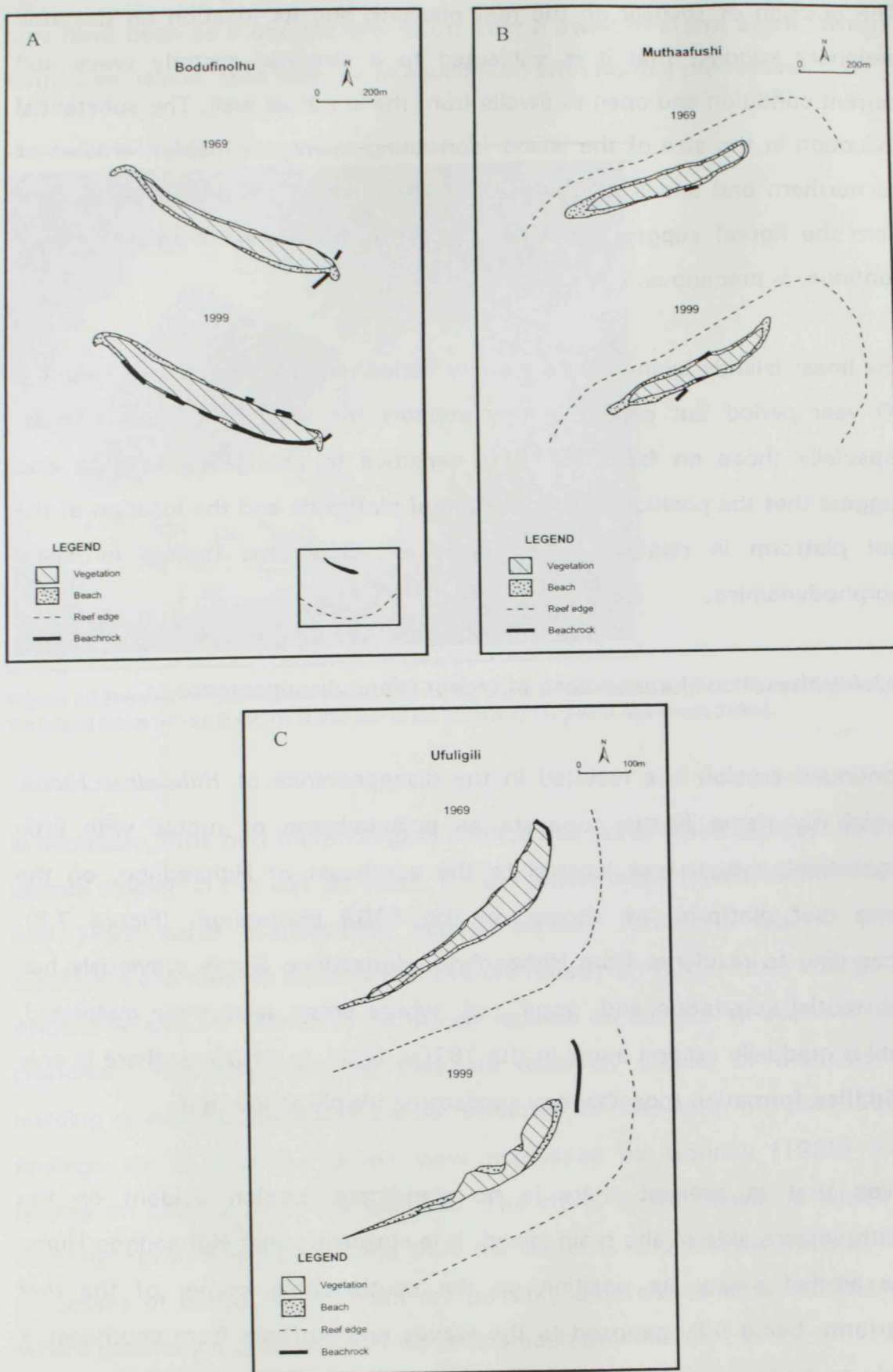


Figure 7.4 Comparative mapping of linear islands (1969-1999)

The position of *Ufuligili* on the reef platform and its location on the atoll periphery suggest that it is subjected to a stronger easterly wave and current condition and open to swells from the south as well. The substantial reduction in the size of the island (consisting mainly of rubble), erosion of its northern end and a southwesterly movement of the island (as evident from the figure) suggests that the future of this island, if present trends continue, is precarious.

The linear islands examined here show varied degrees of changes over the 30 year period but generally they support the view that linear islands, especially those on faros are quite sensitive to changes. The data also suggest that the position of islands on reef platforms and the location of the reef platform in relation to the atoll are significant factors in island morphodynamics.

7.2.4 Hithaadhoo Huraa: a case of recent island disappearance

Continued erosion has resulted in the disappearance of *Hithaadhoo Huraa*, (which by name *huraa* suggests an accumulation of rubble with little vegetation), which was located to the southeast of Hithaadhoo, on the same reef platform, as shown on the 1969 photograph (Figure 7.5). According to residents from Hithaadhoo, Hithaadhoo Huraa previously had substantial vegetation and 'good' soil, where crops were even cultivated, until it gradually eroded away in the 1970s. Now, in its place, there is only a lithified formation (possibly cay sandstone) visible at low tide.

Given that at present there is no significant erosion evident on the southwestern side of the main island, it is surprising that Hithaadhoo Huraa has eroded away. Its position on the southeastern corner of the reef platform, being fully exposed to the waves and currents from southeast is likely to have made it particularly vulnerable. The formation of the island

may have been as a one-off deposition from a swell or storm event, which formed an 'island' that was not in equilibrium with normal processes.

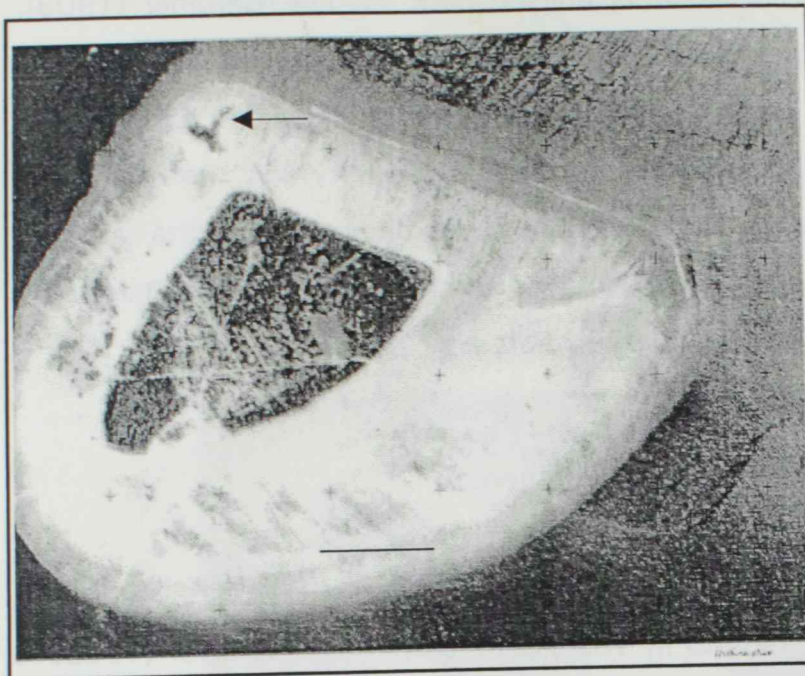


Figure 7.5 Position of Hithaadhoo Huraa (shown by the arrow) evident on the 1969 aerial photo of the island taken by the RAF. (N.B The bar at the bottom of the photo represents 250m).

In summary, little nett morphological change has taken place on most of the islands studied in the last 30 years. On the whole maps based on the 1969 and 1999 aerial photographs appear similar. However, islands with significant changes do occur and these are mostly on faros. Little change is evident on circular islands or on islands located on circular to elliptical reef platforms. This suggests that they are relatively stable, or that island-building or eroding processes are not effective as now as in the past. Such findings are in contrast to the view expressed by Gourlay (1988) that islands on circular reefs are unstable. Therefore, in the Maldives where a seasonal reversal of winds (and thus the currents and waves) occurs, the processes of island development are possibly different to those on islands where generally a unidirectional wave approach prevails.

7.3 Decadal to century-scale changes on the islands.

The historical material available to deduce changes over the 30 to 100 year time frame is very limited. Sources utilised here include (Gardiner (1903), Agassiz (1903), Maniku (1990)), field observations, and interviews. It is argued that the trends and changes in island morphology and dynamics at the century time-scale provide an important link between the short and longer-term developments on the islands. Gardiner visited Eta atoll in October 1899. His accounts and sketches of the islands will be illustrated here with comparable 1969 and 1999 photos.

7.3.1 Islands with sketch maps and comments

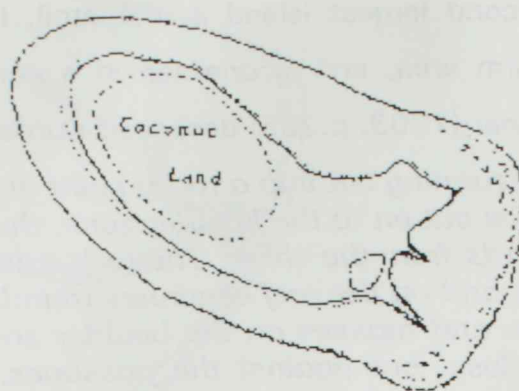
Hibalhidhoo

The morphology of Hibalhidhoo in 1899 as sketched by Gardiner (1903) is compared with that in 1969 and 1999 (Figure 7.6). Gardiner (1903, p.385) referring to Hibalhidhoo noted that:

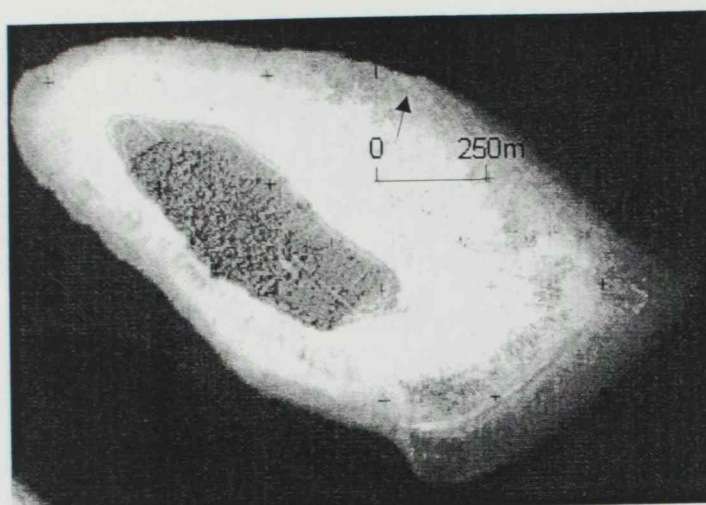
...it is formed of sand, and has three spits marked by beachrock extending out to the east. Round this end, particularly in the northeast corner, the reef has a series of large coral masses in and behind its boulder zone, that seem to have once formed part of the land.

The occurrence of a depression towards the southeastern end of the island was also indicated on his sketch map. Comparison of this map with the 1969 and 1999 photos shows some striking differences. There is:

- No evidence of the three spits or the depression on either the 1969 or the 1999 photo;
- The island appears much further away from the reef edge than in 1899 suggesting it has been eroded in the southeast and/or migrated towards the northwest. The extensive rectangular promontory shown on the 1899 map has been completely eroded away.

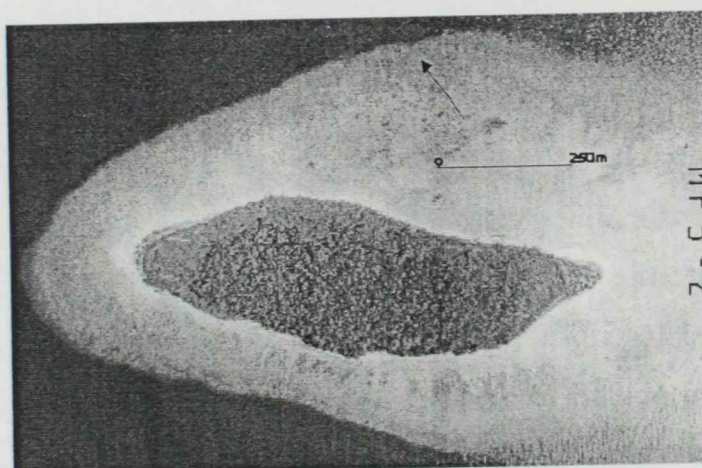


(a)



(b)

Photo: RAF 1969



(c)

Photo: MCPW 1999

Figure 7.6 Century-scale changes on Hibaldhidhoo. (a) Gardiner's sketch of the islands in 1899, (b) aerial photo of the island in 1969 (c) and in 1999. Comparison of the figures indicates significant changes between 1899 and 1969, and some changes between 1969 and 1999. Some of these latter changes have been dealt with earlier.

Kunfunadhoo

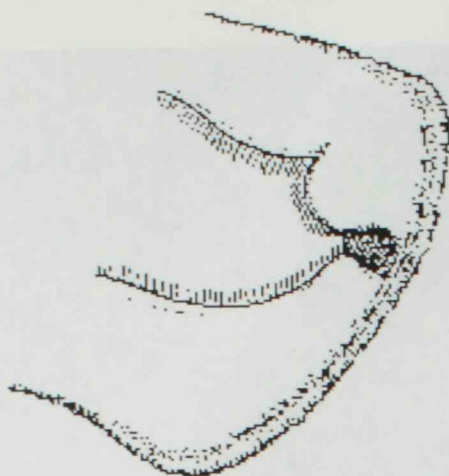
Kunfunadhoo is the second largest island in the atoll. It occupies about 42% of the reef platform area, and is oriented in a northwest-southeast direction. In 1899 Gardiner (1903, p.385) described Kunfunadhoo as:

... a long, sandy island running out into a rocky point at its seaward end. Here the island stretches out on to the boulder zone, the edge of the reef being only about 35 yards from the shore. The rock extends for about 70 yards behind the point, and on the reef continues round its seaward end in a series of pinnacles and masses on the boulder zone. Behind these the land shows rapid loss, but against the passages, although beach sandstone may occur, there is otherwise little change; towards the lagoon a sand spit is, if anything, growing out along the reef.

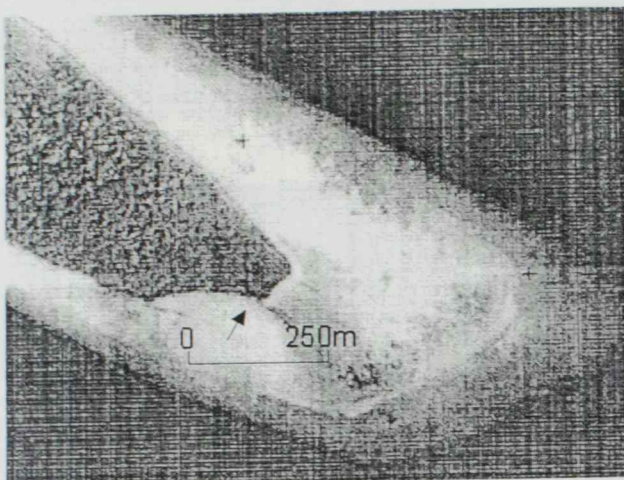
Gardiner did not map the whole of Kunfunadhoo but only the seaward (eastern) end. His sketch of 1899 is compared with the 1969 and 1999 aerial photos, as shown in Figure 7.7. This comparison indicates that:

- Neither the 'rocky point', nor the 'protrusion' on the northeastern side of the island evident in 1899 are present today;
- The eastern edge of the island today is at least 250m away from the reef edge and not 35 yards (32m) as Gardiner indicated it to be at that time;
- Outcrops of beachrock and cay sandstone are presently evident in the field and in subdued form on the 1969 and 1999 photos, not just 'against the passages' but also at the eastern end.

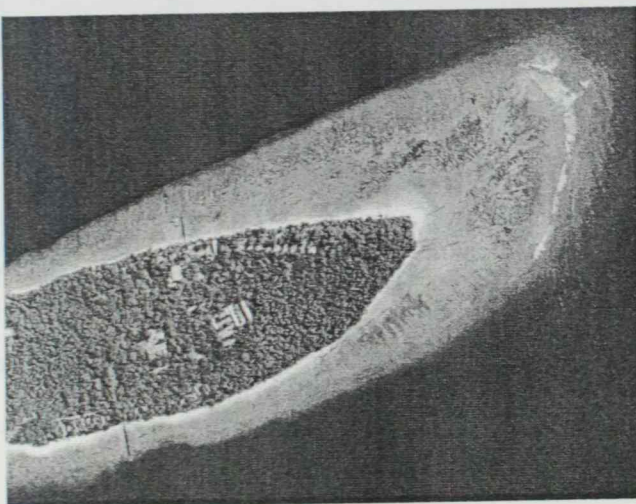
This evidence suggests that substantial erosion has taken place on the eastern end of Kunfunadhoo since 1899. Presently exposed cay sandstone and beachrock outcrops at the eastern end of the island are shown in Figure 7.8, and these suggest that erosion is a continuing process at this site and that there is some evidence that the eroded sediment is being transported along the northern shore.



(a)



(b)

Photo: RAF 1969

(c)

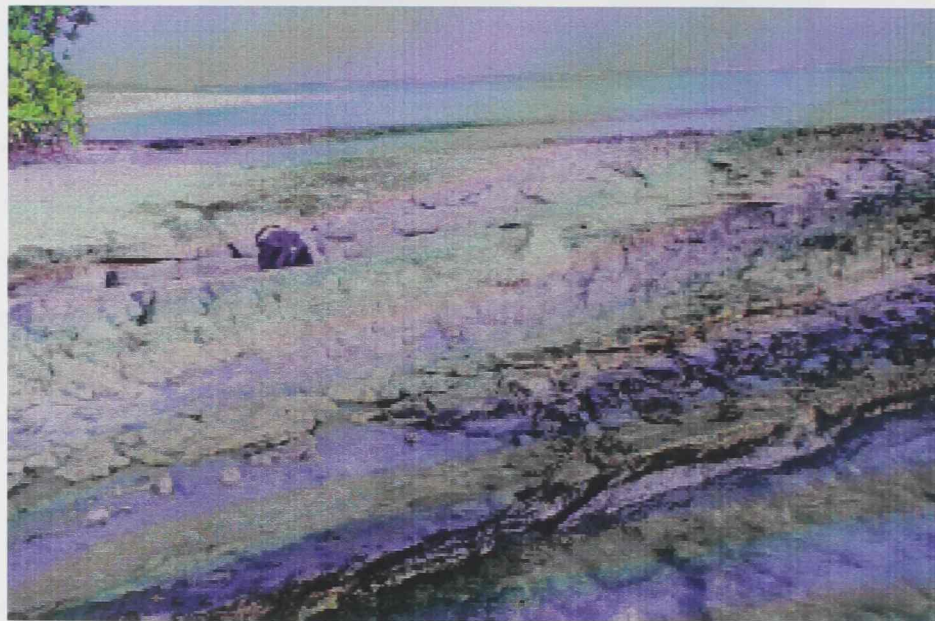
Photo: MCPW 1999

Figure 7.7 Seaward end of Kunfunadhoo, 1899 to 1999.

- (a) sketch map of Gardiner in 1899 showing the pinnacle of rocks,
 (b) aerial photo taken in 1969, and
 (c) the status in 1999.



(a)



(b)

Photos: R. McLean 1995

Figure 7.8 Exposed cay sandstone and beachrock outcrops on the eastern end of Kunfunadhoo.

(a) Exposed cay sandstone outcrops on the island, and (b) beachrock (background) and close up of cay sandstone outcrops indicating the dip.

Maaddoo

Major differences are also apparent between Gardiner's sketch of the eastern end of Maaddoo in 1899 and the 1969 and 1999 aerial photos (Figure 7.9).

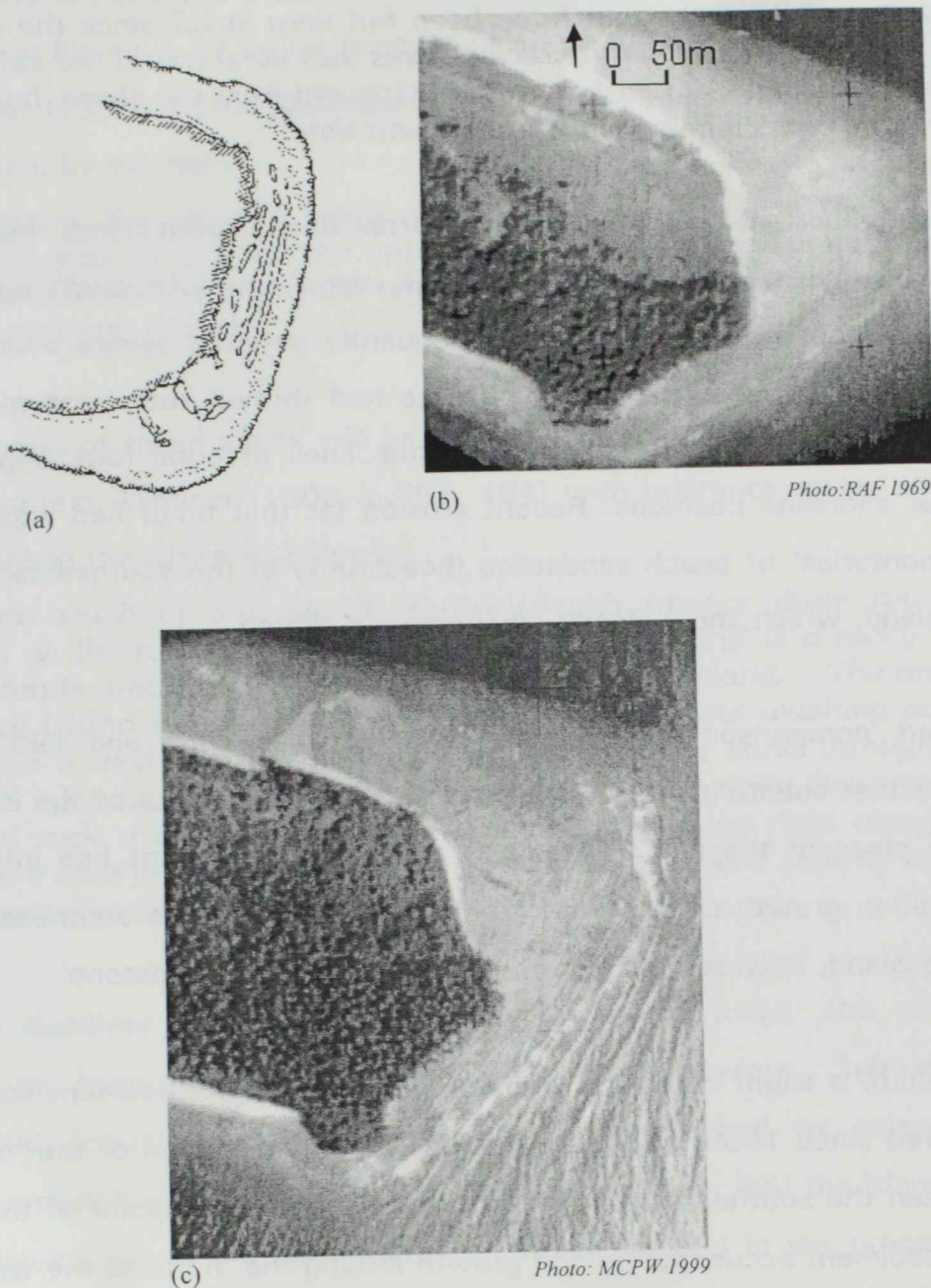


Figure 7.9 Sketch map and aerial photographs of eastern end of Maaddoo, 1899 to 1999.

- (a) Sketch by Gardiner (1903, Figure 95) showing the lines of coral rock;
- (b) aerial photograph taken in 1969, and
- (c) 1999.

At the eastern end of Maaddoo, Gardiner (1903, p.384) stated that:

The reef flat is about 60 yards broad, and there is within it a much broken area covered with large masses of coral rock, which roughly speaking form three lines, a fourth being found in the base of the beach. Other masses also occur where the shore of the island bends round N. and S. towards the lagoon. The rocks to seaward show that the land once extended to within 30 yards of the present reef edge, so that the outward extension of the latter can have been but very small since the elevation that formed the land. As the rock passes into sand round the sides of the island a few lines of beach sandstone run out from the shore, but there is little or no erosion going on at the present time.

Several important points can be made from this account. First, that prior to Gardiner's visit, the eastern end of the island extended much further out seawards on the reef, but had subsequently suffered severe erosion. It is possible that high wave energy events had thrown the 'large masses of coral rock' on to the reef, and that the 'lines of coral rock' represented former shoreline positions. Recent erosion (at that time) had exposed the 'promontories' of beach sandstone (beachrock) at the southeastern end of the island, which show clearly on Gardiner's sketch.

Second, comparison of Gardiner's map with the 1969 and 1999 photos shows that substantial erosion of the northeastern corner of the island has taken place in the last 70 to 100 years, and sediment has infilled and vegetation growth covered the rectangular 'horn' on the southeastern end of the island, between two 'promontories' of 'beach sandstone'.

And third, a slight extension of the island on the northeastern corner has occurred since 1969, and there has been a slight erosion of the 'bay area' between the southeastern 'horn' and the eastern most point of the island, with sediment accumulation and growth around the 'horn' to the west.

These differences suggest that erosion and deposition in the east of the island has been an ongoing process since 1899.

Maamaduvvari

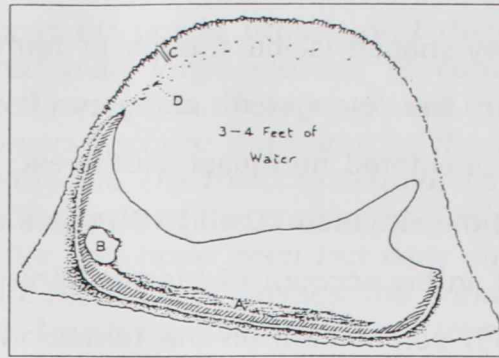
Maamaduvvari is a kidney-shaped island though in terms of its ellipticity index (le 2.7) it fits into the 'elongated' category. It is located in the southeast quadrant and orientated northeast-southwest. Gardiner's sketch of the island in 1899 and the situation 70 and 100 years since that time are presented in Figure 7.10. In his account of Maamaduvvari, called Maduvari by Gardiner (1903, p.163) commented on the formation and development of the island, by stating:

That some of the original reefs were small faro, before they were elevated, is quite clear from the appearances of Raskateen and Hurudu, but the most striking case in the whole Mahlos lies in Maduvari, almost its most southerly island.

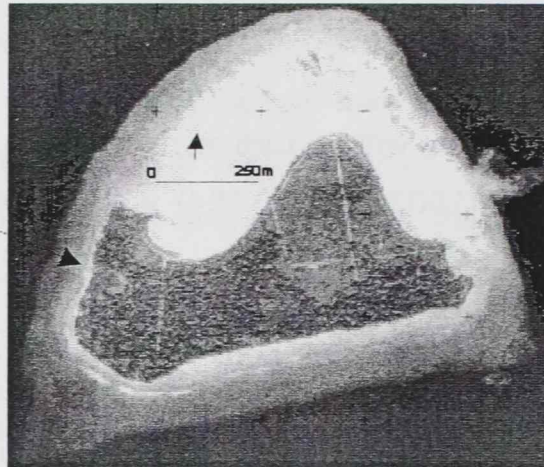
An evaluation of these views will be further reviewed in Chapter 9. In the present context Gardiner (1903, p.163, 164) with reference to his sketch map described the island as follows:

The south beach of the island is rocky, with two or three rows of pinnacles on the reef-flat. Above the beach of the island is a rocky belt, which extends around the east and west ends of the island. ...The central part of the island is entirely of sand-formation and now washing away. In the past it was clearly formed by the piling up of sand through the north-east opening, a horn now extending in this direction. Between the sand and rock a narrow pool was enclosed, stretching right along the island from east to west, represented now by a mangrove swamp with a pool of water (barachois or kuli) to the west.

Although Gardiner suggests the island is 'washing away' the reverse appears to have happened in the last 70-100 years. Subsequent lagoonward growth of *Maamaduvvari* can be established by comparing Gardiner's sketch map with the two photos. These show that the island has grown particularly at the two 'horns' or forelands, and in the process of sediment accretion towards the lagoon, a second *kulhi* has formed as a result of the development of a sand barrier across the former *barachois*. The embayment between the 'horns' has been infilled.

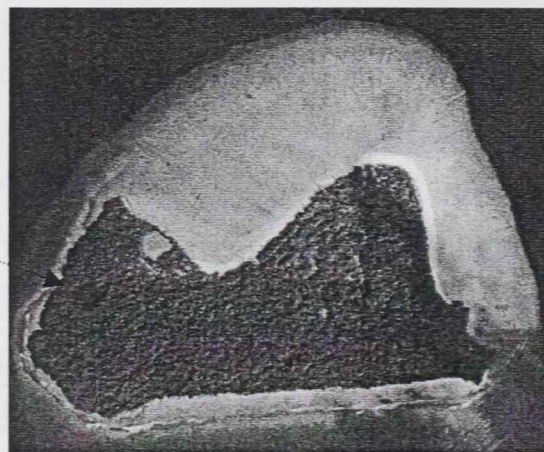


(a) 'Figure 30. Maduwari Island and reef. The rocky area is diagonally shaded. A. Mangrove swamp. B. Pool of water or kuli. C. Boat-channel through reef. D. Rocks represented in Plate XII'.



(b)

Photo: RAF 1969



(c)

Photo: MCPW 1999

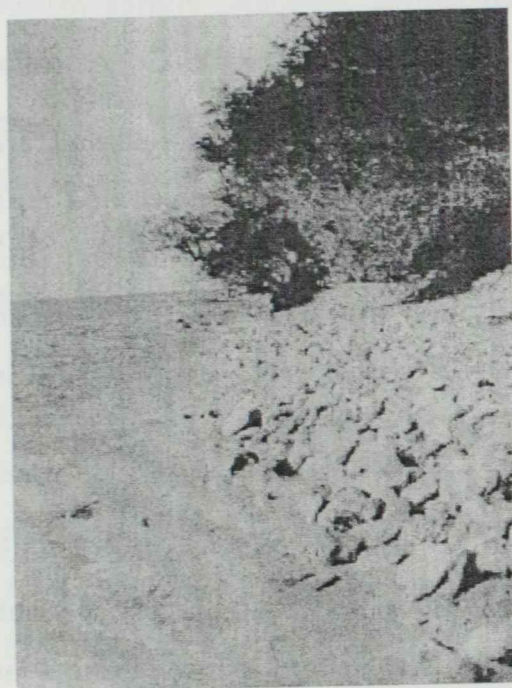
Figure 7.10 Century-scale changes on Maamaduvvari.

(a) Gardiner's sketch map of the island in 1899 with his caption, (b) aerial photo in 1969, (c) and in 1999.

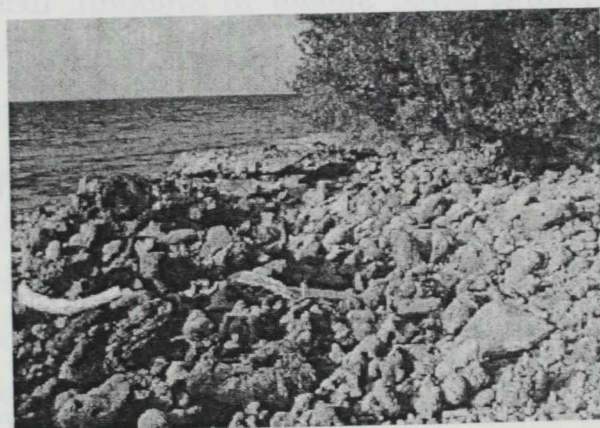
(N.B. The dashed arrows on 1969 and 1999 photos point to the kulhi (B) indicated on Gardiner's sketch).

In contrast to those changes, the presence of the 'rocky belt' of gravel and boulders on the southern and western sides of the island appears to be the reason why there is little change on these shores over the 100-year period. This is confirmed by Figure 7.11 which shows photographs of the material on the western shore of the island in 1901 and in 1997. These photos show that even on this relatively exposed side of the island very little change has taken place over the last 96 years.

An increase in size of the island, between 1899, 1969 and 1999, on the northern side together with no sign of erosion elsewhere, suggests continued island growth on Maamaduvvari, in contrast to the view expressed by Gardiner that the island is 'now washing away'.



(a)



(b)

Figure 7.11 Gravel and cobble material on the western side of Maamaduvvari.

(a) in 1901 (source: Agassiz 1903),

(b) in 1997.

7.3.2 Islands without sketch maps

Aidhoo is another elongated island that Gardiner (1903, p.385) commented upon, in that it was an *...oval-shaped island with a crescentic belt of rock around its E. end, the rest of the island being of sand formation. As usual there is washing away on the seaward end and growth towards the lagoon.*

In this case the seaward erosion and lagoonward growth described by Gardiner was shown by the 1969-1999 comparisons in the previous section, to have continued in this location. The swell incident in 1987 also resulted in a substantial accumulation of rubble and coarse sand here, extending the island seawards. Thus, it is possible that an erosional trend can be offset by an occasional episodic swell or storm event that deposits a fresh bank of coral rubble.

Remarks on two linear islands (one lagoonal and the other peripheral) are also contained in Gardiner's (1903) report. *Muthaafushi*, was described as a *...sand bank, similar to Embudu, washing away slightly N. and S. but growing out in spits to the E. and W.* Although the 1969-1999 photos do not show substantial changes on the island, from Gardiner's comment it is likely that at the time the island had very little vegetation.

Agassiz who travelled through Eta in 1901 took a photo of the island, which is shown against one taken in 1997 (Figure 7.12). These photos show that *Muthaafushi* has persisted over the last several decades and that the height, although not density, of vegetation may have increased during that time.



Figure 7.12 View of Muthaafushi from the south. (a) in 1901 and (b) 1997. The island has acquired more vegetation between 1901 and 1997.

As for *Bodufinolhu*, Gardiner (1903) noted that it was of sandy formation, growing out to the northwest and southeast in sand spits. Similar trends are evident on the island today. The development of the island in a northwesterly direction, similar to that described by Gardiner continues to this day. Such a trend is consistent with the growth and development of the island including its increasing in size over the last 30-years. Although Gardiner also commented that *Bodufinolhu* might have at one time been nearly connected to *Thulhaadhoo* to the north, such a connection has not been evident during the last 100 years.

With reference to *Ufuligili* and *Kudadhoo*, which were mistakenly named *Kudadu* and *Mafuri* respectively, Gardiner (1903, p.384) commented that: *Kudadu (the E. island on Kanifuri reef) and Mafuri are both of sand formation. The former has an extensive formation of beach rock to the N., but the latter is only a tiny bank with two bushes of about 20 feet in height.* However, *Ufuligili* is now comprised of rubble and not sand suggesting that if sand was indeed present in 1899 it has subsequently been washed away. The beachrock outcrops around *Ufuligili* are still 'extensive'. *Kudadhoo* is now a small island, which has seven coconut trees and a thicket of thorny bushes and may be larger than the 'tiny bank

with two bushes' referred above. Extensive beachrock outcrops around the island suggest that it has been larger in the past. An unvegetated sand spit extends on to the reef flat from the northern side of the island. The present status of Kudadhoo and Ufuligili is shown in Figure 7.13.



(a)



(b)

Photo: R. McLean 1995

Figure 7.13 View of Kudadhoo and Ufuligili.

- a) Kudadhoo looking from north (lagoonward side). Note the long sandy spit associated with the island, in contrast to the rubble and coarse sand on the island.
- b) Ufuligili looking from the south (seaward side). The bushes on the island are no more than 2m high.

Gardiner also described the elliptical and circular islands of *Mendhoo* and *Olhugiri*, where *Mendhoo ...is a regular, sandy islet little or not at all changed*. Comparison of the 1969 and 1999 photos show that very little has changed in the past 30 years either. As for *Olhugiri* he stated that *Olhugiri has a rocky beach everywhere and covers the greater part of its reef and its vegetation consists of high timber* (Gardiner 1903, p.384). This comment is equally applicable today suggesting that there has been no significant change in the past 100 years, and that the island may be in a 'steady-state'.

7.3.3 Islands that have 'disappeared'

In addition, Gardiner remarked about islands that once were present but no longer existed in the atoll at the time of his visit. Apart from islands that have disappeared as a result of 'storms' (Maniku 1990), it appears that islands can also disappear by gradual erosion. In this regard, Gardiner pointed out the existence of two 'rocky' islands on the southeast and southwest on Hithaadhoo reef platform, Hithaadhoo Huraa (SE) and Hithaadhoo Fushi (SW) (Maniku 1990).

The status and the disappearance of Hithaadhoo Huraa in the 1970s was discussed earlier in section 7.2.5. The exact timing of the disappearance of the other 'island', Hithaadhoo Fushi is unclear, but its presence on the reef in 1899 (Gardiner 1903) indicates that the island disappeared between then and 1969 (as it is not evident on the 1969 photograph). According to the inhabitants of the atoll, a third 'island', Maafushee Finolhu was a vegetated island located to the north of Kudadhoo, about 100 years ago. No island exists there today, though an accumulation of coral rubble visible at low tide (Figure 7.14), and over which waves break at high tide is thought to mark its former position.

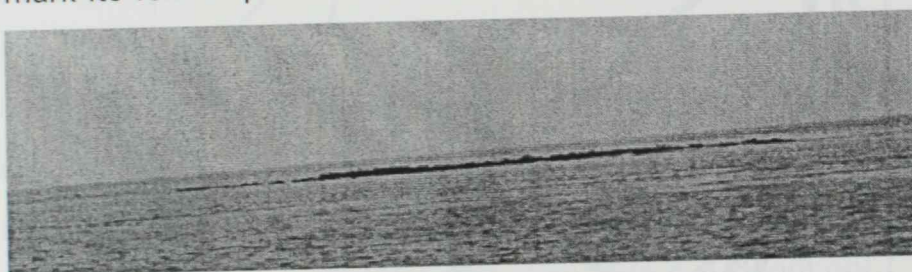


Figure 7.14 Maafushee Finolhu as it appears today. The 'island' is usually visible at low tide.

Similarly, *Kalhunaigili* on the same reef platform had *Pemphis* bushes in 1936 (Maniku 1990), but there is no sign of the island today. Gardiner (1903) also remarked that a large sandy islet existed on Oggali faro (to the north of Kudadhoo faro) but it was not evident in 1899 when he visited.

Today, a small, unvegetated *finolhu* exists there, which, according to residents on Hithaadhoo was vegetated about 50 years ago.

Furthermore, the case of a remnant island on Dhoogadu Finolhu, in the northwest corner of the atoll needs to be mentioned, although the island may have disappeared more than a 100 years ago. This island remnant which now comprises extensive outcrops of cay sandstone indicates the former presence of a considerable-sized island here. A sample of material from one outcrop was radiometrically dated to get an estimate of the approximate age when the island existed. These results are discussed in Chapter 8.4.2.

A further example of an island where only remnants of its initial form and extent exists is Ahivahfushi, though in this case the island has 'moved' rather than disappeared (Figure 7.15). Here the size and shape of the initial island is indicated by bands of beachrock rather than cay sandstone, and the location and patterns of these suggest the island has moved away from the seaward side of the reef platform to the northeast by about 75m.

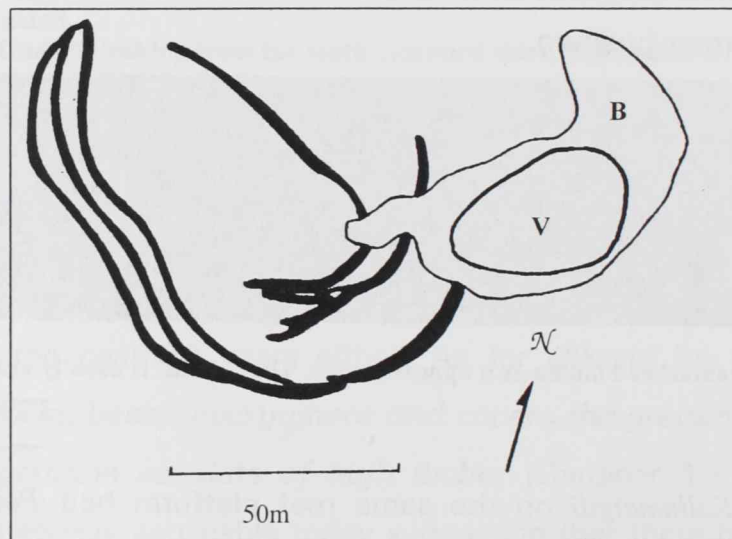


Figure 7.15 Extensive and successive beachrock outcrops on Ahivahfushi. The direction in which the island has moved over time is evident.
V = present-day vegetation on the island, B = present-day beach.

7.4 Summary and implications

This analysis of data derived from comparative mapping of the 1969 and 1999 aerial photographs and sketch maps and comments made 100 years ago refers to less than half of the islands studied on Eta atoll. Nevertheless, it is believed that the results are sufficiently representative to conclude that there has been no one general direction of change throughout the whole atoll. The general comment of Stoddart and Steers (1977, p.99) that worldwide erosion and retreat of seaward shores of reef islands does not appear applicable in this case.

Although there is no overall Eta wide trend, and that changes have been variable from one island to another and one time period to another it is possible to draw several conclusions from this study.

First, that some islands that were 'washing away' 100 years ago have continued to erode (e.g. Kunfunadhoo), and others have accreted (Bodufinolhu). In these cases both erosion and accretion are occurring along sandy shorelines. On the other hand, islands with shorelines composed of coral gravel and rubble appear to have changed little both over the century- and thirty- year time scale (e.g. Olhugiri). And from comparison of the 1969 and 1999 aerial photographs, it appears there is greater exposure of beachrock outcrops in the most recent photographs suggesting a slight erosional tendency although in most instances such exposure is offset by localised accretion with little nett change (e.g. Udoodhoo).

Second, there are apparent differences in the magnitude of change based on the morphometric properties of islands. For instance, generally the circular and elliptical islands have been more stable than the elongate and linear islands; similarly with the larger islands and those that occupy a high proportion of the reef flat. On the elongated islands on the eastern side of

the atoll erosion has occurred on the seaward side often accompanied by accretion on the lagoon side resulting in an east to west migration of the islands. In some instances the erosion has been substantial reaching up to 200m over the last 100 years. In these cases, the trend that Gardiner (1903, p.381) noted in 1899, that the islands were *...generally washing away on their seaward faces and growing outwards on their reef platforms towards the inner part of the bank...* is continuing.

Third, there are also differences dependent on the type of reef platform. Thus, islands on faros have been subjected to greater changes than islands on patch reefs, both gross and nett change. But the changes have not been uniform. In some cases there has been substantial accretion (e.g. Hanifaru) and in others substantial erosion (e.g. Ufuligili), extreme cases being the disappearance of some 'islands' (e.g. Hithaadhoo Huraa) and the creation of others (e.g. Oggali Finolhu).

Finally, two types of island morphodynamics are evident over the decade-century time scale; **changes** in island size through area changes and, **movement** of islands in relation to the reef platform.

Some of these medium-term changes, either over the last 30 or 100 years appear to follow trends that have been in existence for a longer period. Others appear to have reversed the longer-term trend, while in several instances nett changes to island shorelines has been minimal. In relating the medium-term changes to the cluster groups identified in Chapter 5, it is evident that islands in Cluster group 3 is the least dynamic, while those in Cluster groups 1,2 and 4 are most dynamic. Islands in Cluster groups 5 and 6 show moderate changes over the medium-term. The relation between the medium-term changes and the long-term development of islands will be examined in Chapter 9.

CHAPTER 8

Long-term developments and changes on the islands

8.1 Introduction

The short and medium term changes described in the last two chapters are superimposed on the longer-term development of the islands, the subject of the present chapter. Evidence of how the islands have evolved through time is provided mainly by an examination of the nature and distribution of island vegetation and soils. Two main criteria for relative chronology are used: vegetation succession (maturity) and soil development (maturity), while maps of the patterns of vegetation and soil types give an indication of the ways in which the islands have developed. These data are augmented by radiometric dating (C^{14}) of surface and subsurface sediment samples, which provide an absolute time-scale for island development.

8.2 Vegetation characteristics and patterns

The changes on islands identified from aerial photos over 30 years were primarily concerned with island margins and provided only a limited insight into how the islands have developed over time. Moreover, vegetation changes revealed on the 1969 to 1999 aerial photography have been of a minor nature suggesting that vegetation patterns on uninhabited islands persist for some time and can be used to give an indication of longer term changes.

Newbery and Spicer (1979) discuss a simple model, illustrating the successional stages as a longitudinal gradient from bare coral to mature forest as was observed on Wilingili (Addu Atoll, Maldives), and suggest that 'a general trend in the development of soils and vegetation can be traced'. Similarly, Walker (1991) illustrated sequential development of Lady Musgrave Island flora, on the Great Barrier Reef, as having progressed from a belt of small strand trees surrounding a central scrub less than a metre high in 1843, to a mature *Pisonia grandis* forest in the 1980s.

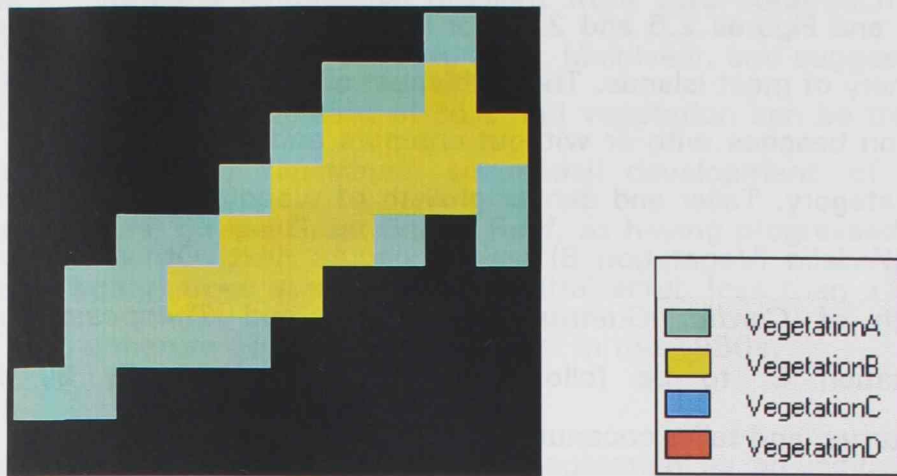
Thus, there is a reasonable basis for using vegetation as an indicator of relative age and/or stability. On Eta, the dominant vegetation types and their spatial distribution was investigated on 15 islands, using the methodology outlined in Chapter 3. Field identification of vegetation types and classified remotely sensed data (and use of 1999 aerial photos for two circular islands due to cloud-cover on the satellite image) were used to map the vegetation patterns on the islands. Four vegetation types were identified.

- 1) Vegetation A consists of grasses and vines like *Tridax*, *Launea*, or *Ipomoea*, and low (<1m) bushes of species like *Tournefortia*. This vegetation type has low species diversity and density.
- 2) Vegetation B includes denser and low stands (1-2m) of shrub vegetation of species such as *Scaevola* and *Tournefortia*, and *Wedelia*.
- 3) Vegetation C identifies the taller (2-5m) vegetation species of *Cordia*, *Guettarda*, *Morinda*, *Thespesia*, and *Scaevola*.
- 4) Vegetation D comprises the major woody species associated with reef islands in the Maldives. Plants are tall (>5m) with high species diversity, and dense canopy-cover. Species such as, *Ficus*, *Hibiscus*, *Hernandia*, *Pandanus*, and *Pisonia*. Dense groves of *Cocos* also occur in this group.

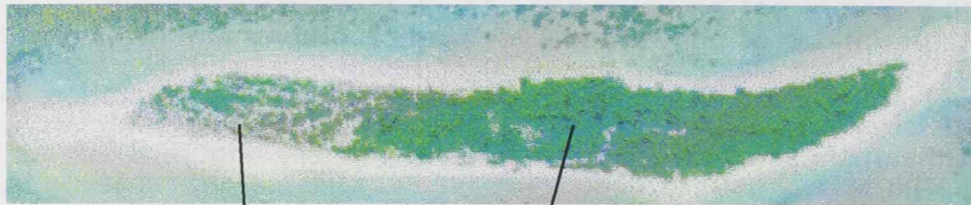
These vegetation units can be envisaged as forming a spatio-temporal sequence from island margin to interior in the manner outlined in Chapter 2.5.1 and Figures 2.6 and 2.7. For instance, Vegetation A is found on the periphery of most islands. The high spectral signature values from the white sand on beaches with or without creepers and grasses helps to distinguish this category. Taller and denser growth of woody plants such as *Scaevola* and *Wedelia* (Vegetation B) usually occurs next. Other woody and taller growth of *Cordia*, *Guettarda*, *Morinda*, and *Thespesia* succeeds as Vegetation C, to be followed further inland usually by *Hernandia*, *Pandanus*, and taller coconuts (Vegetation D).

In order to validate the vegetation classification from SPOT imagery, interpretations of conventional aerial photography and ground truthing were involved. Figure 8.1 shows an example of a vegetation pattern on Muthaafushi as classified from satellite imagery (Figure 8.1a), as well as an aerial photo of the island in 1999 (Figure 8.1b), and a ground level photo (Figure 8.1c) that shows the main vegetation types on the island.

Not only does this case study serve to confirm the classification but it also provides an example of the principles used to analyse one of the simplest vegetation patterns in Eta atoll. In this example it is assumed that Vegetation B represents a relatively 'older' part of Muthaafushi than that covered by Vegetation A. Alternatively, Vegetation A represents a more 'unstable' part of the island and has been subject to recent change in comparison to the more 'stable' area occupied by Vegetation B. These are the assumptions used in the following analyses, which distinguishes vegetation patterns on islands of different sizes and shapes.



(a)



(b)



(c)

Figure 8.1 Vegetation types on Muthaafushi. (a) Vegetation types as classified from 1988 SPOT image, and (b) 1999 aerial photo showing the present-day vegetation distribution on the island. (c) Ground photograph of the southwestern side of Muthaafushi looking eastward. Grasses, creepers and low bushes are seen in the foreground (Vegetation A), while Vegetation B, including scattered coconut trees are evident in the background.

N.B. The arrows point to the appropriate vegetation types.

8.2.1 Linear and elongated islands

Classified images of the vegetation patterns on selected linear and elongated islands are presented in Figure 8.2. The patterns range from simple to complex.

The vegetation pattern on Bodufinolhu (Figure 8.2a), which is one of the smaller and distinctly linear islands (2.5ha, l_e 12.5), is limited to Vegetation types A and B suggesting it is relatively young island or one that has been subjected to quite recent change. Unlike Muthaafushi (an island of similar size and shape, and one that has a clear difference in vegetation between its eastern and western ends) there is no such difference on Bodufinolhu, but rather it comprises a linear band of Vegetation B running along its long-axis with narrow parallel strips of strand vegetation (Type A) on either side. Two different modes of island development are implied by these examples: one where the island has grown laterally from one end to the other (Muthaafushi); the other where growth has occurred evenly along both sides of a long central linear core (Bodufinolhu). The vegetation patterns on Ufuligili, a small linear island conforms to the pattern on Bodufinolhu, while on Medhufinolhu, another similar island conforms to the pattern found on Muthaafushi.

Only Vegetation A occurs on the small linear/elongated islands of Nibiligaa, Kanufushee Finolhu and Kanufushee Gaathu Finolhu, as they are *finolhus* with sparse strand vegetation. On the equally small but more compact island of Aidhoo (2ha, l_e 2.1) all four vegetation units are present (Figure 8.2b), suggesting that island size is not always the most significant factor in vegetation 'maturity'.

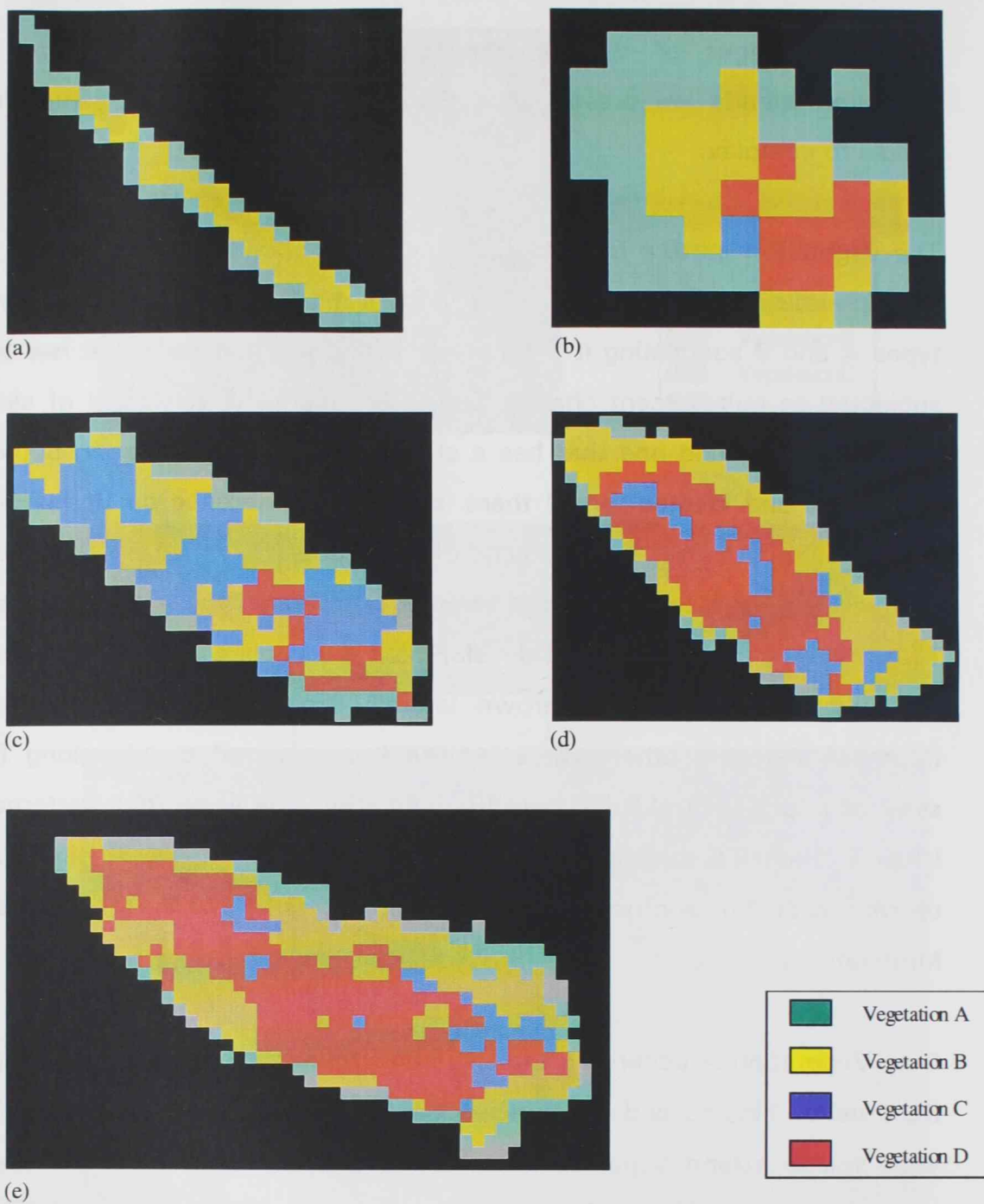


Figure 8.2 Vegetation distribution patterns on linear/elongated islands. (a) Bodufinolhu, (b) Aidhoo, (c) Fares, (d) Hibalhidhoo, (e) Maaddoo.

On Aidhoo a distinct, though small area of Type D and C vegetation occurs on the southeastern end of the island, which is surrounded by Vegetation B. The latter extends northwestwards in turn to be surrounded by Vegetation A. This pattern, like that for Muthaafushi, suggests lateral growth of the island, or increasing instability from southeast to northwest.

Such a trend though more complicated, is also seen on the much larger island of Fares (10.2ha, I_e 2.9). On Fares patches of Vegetation C and D occur at the southeastern end of the island, with two discrete bands of vegetation spreading across the island from northeast to southwest, and separated one from the other by less mature Vegetation C (Figure 8.2c).

On the two other elongated islands shown in Figure 8.2, Hibalhidhoo (14.3ha, I_e 2.8), and Maaddoo (18.8ha, I_e 3.9), the vegetation patterns are quite similar, but they differ from those described for Fares and Aidhoo above. Both Hibalhidhoo (Figure 8.2d) and Maaddoo (Figure 8.2e) have a southeast-northwest trending core of the most mature vegetation (Type D) with pockets of C, which forms a broad band along the long axes of both islands. Peripheral to this are parallel strips of Vegetation B, broadest on the northern shore and narrower on the southern shore. Vegetation B also occurs at the northwestern and southeastern extremities of the island, though in both cases there is a narrow strip of strand Vegetation (A) all around the island.

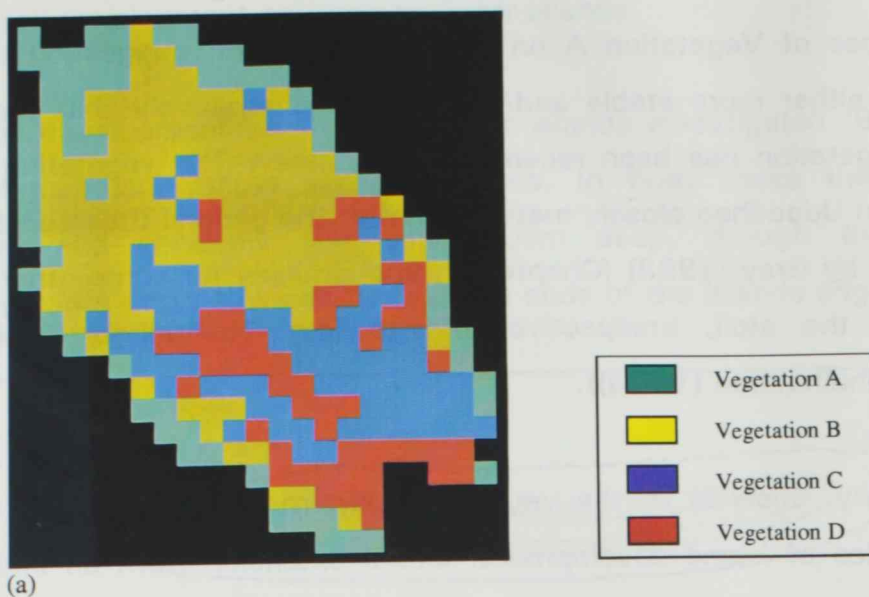
In summary, a concentric oval growth pattern is suggested with greater growth on the northeastern facing side of the island, and more restricted growth on the southwestern facing side. Vegetation types occur progressively outwards towards the island margins from the Vegetation D, or from other most 'mature' type present on the island.

Thus the vegetation patterns on the linear to elongated islands generally show that the most 'mature' vegetation (be it B, C, or D) either occurs towards the southeastern end of the island, or along the island's central axis, suggesting that there are two main types of island growth: lateral extension and concentric expansion.

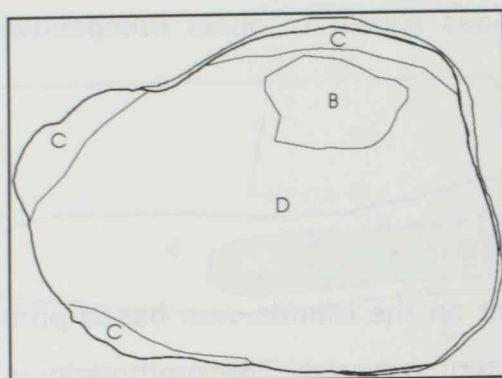
8.2.2 Elliptical and circular islands

The vegetation patterns on three elliptical and circular islands were investigated, two of which are mapped from the 1999 aerial photography. Mendhoo and Udoodhoo are close to the mean size of Eta islands (9.3 and 10.5ha respectively), while Olhugiri is one of the larger island (20ha), but is made up of coral gravel and rubble around the periphery of the island. On Mendhoo, the dominance of Vegetation C and D is confined to the southeastern half of the island (Figure 8.3a), with Vegetation B making up the bulk of the northwest half. A coastal fringe (Vegetation A) occurs around the island, but is broadest in the northwest. This pattern, interpreted as suggestive of island expansion to the northwest, or that part being relatively less stable, has been also described for more elongated and linear islands.

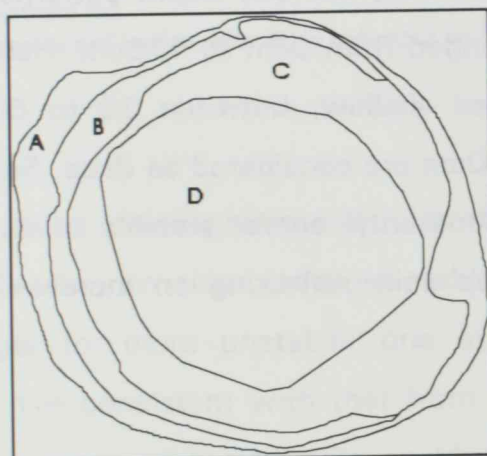
Similarly, with the concentric vegetation pattern which reaches its finest expression on Udoodhoo (Figure 8.3c). In the case of both Udoodhoo and Olhugiri (Figure 8.3b), the most mature vegetation type (D) occupies most of the island. In the first case Vegetation D is succeeded by C, B and A, in circular increments away from the island core, while in the second case the island is dominated by Vegetation D which extends to the margins of the island in all directions except the northern, western and southwestern shores.



(a)



(b)



(c)

Figure 8.3 Vegetation distribution pattern on elliptical/circular islands. (a) Mendhoo, (b) Olhugiri, (c) Udoodhoo. Note: outlines of vegetation types A to D on Olhugiri and Udoodhoo have been mapped from 1999 aerial photographs.

An absence of Vegetation A on Olhugiri is evident, suggesting that this island is either more stable and/or older, or alternatively that the littoral fringe vegetation has been recently eroded away. The vegetation pattern evident on Udoodhoo closely matches that of the general theoretical pattern described by Gray (1993) (Chapter 2), and similarly for some other circular island in the atoll, irrespective of size (e.g. Hulhudhoo (2.2ha) and Maaddoo-hulhudhoo (1.6ha)).

In summary, analysis of the vegetation patterns suggests there are two main modes of island development: lateral extension from an initial core; and concentric growth, which has two variants; symmetrical expansion and asymmetrical expansion. These modes appear to occur irrespective of the size, shape or position of the island.

8.3 Soil development

The examination of soil development on the islands was based primarily on colour and depth to unmodified parent material. The methodology utilised was outlined in Chapter 3. Based on this, the soil depth patterns on 15 islands were mapped. Soil depths ranged from 0cm to 116cm. Hence, soil depths less than 30cm are regarded **shallow**, between 30 to 60cm as **intermediate**, and those more than 60cm are considered as **deep**. Soil depth is seen as a proxy for relative age (maturity) and/or stability of an island, with shallow, intermediate and deep soils reflecting an increase in age and/or stability.

8.3.1 Soil development patterns on linear islands

The soil development on the two linear islands investigated (Bodufinolhu and Muthaafushi) show similar patterns. In both cases the soils are shallow, and generally less than 30cm deep, though the deepest developments occur towards the eastern ends of the islands (Figure 8.4).

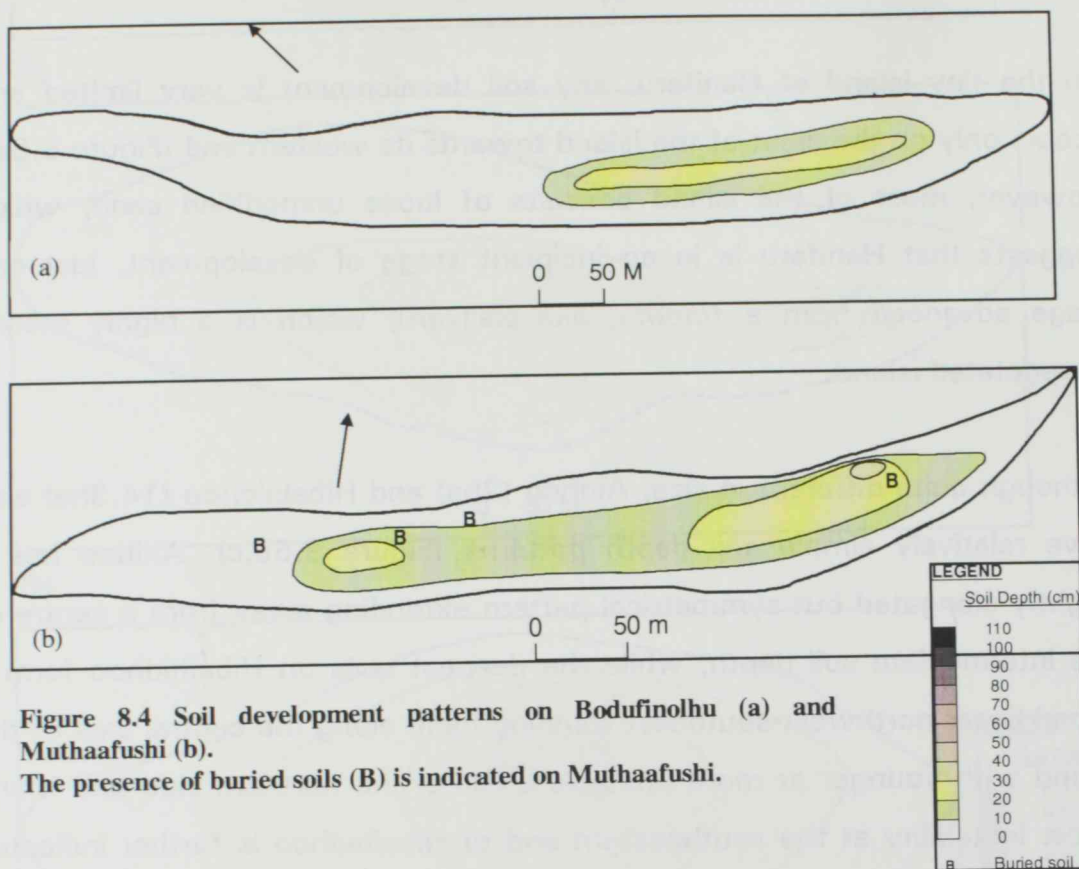


Figure 8.4 Soil development patterns on Bodufinolhu (a) and Muthaafushi (b).

The presence of buried soils (B) is indicated on Muthaafushi.

Two island development (or relative stability) phases are suggested for Bodufinolhu, an older (or more stable) one at the southeastern end and a younger (or more unstable) one at the northwestern end. This simple pattern is consistent with that from the vegetation analysis of the island. The presence of buried soils on Muthaafushi, together with a more solid core to the eastern side of the island suggests that the island has not developed in a simple lateral expansion manner, but rather one that has involved marginal erosion and washover of sediments on to a previously vegetated land surface, that is vertical accretion.

8.3.2 Soil development patterns on elongated islands

The soil development patterns on six elongated islands of Aidhoo, Fares, Maaddoo, Hanifaru, Hibalhidhoo, and Maamaduvvari are shown in Figure 8.5. The first three islands having been considered in the vegetation section. The figures are arranged from simple to complex developments.

On the tiny island of Hanifaru, any soil development is very limited and occurs only on the crest of the island towards its western end (Figure 8.5a). However, most of the island consists of loose unmodified sand, which suggests that Hanifaru is in an incipient stage of development, just one stage advanced from a *finolhu*, like Nelivaru, which is a highly mobile unvegetated island.

Although quite different in size, Aidhoo (2ha) and Hibalhidhoo (14.3ha) also have relatively simple soil depth patterns (Figure 8.5b,c). Aidhoo has a slightly elongated but symmetrical pattern extending away from a centre of the intermediate soil depth, while the deepest soils on Hibalhidhoo form a broad linear northwest-southeast trending band along the central axis of the island with younger or more unstable areas on its northern side and island ends. Instability at the southeastern end of Hibalhidhoo is further indicated by the presence of buried soils in that area.

A broad east-west trending band of shallow and intermediate soil depths is present on the long-axis of Maamaduvvari (Figure 8.5d). It is believed that this band formed the initial core of this large island and was maintained in part by the presence of coral gravel and rubble on the southern and western sides. More recent developments have included the extension of two north-facing forelands (horns), which are still accreting (Chapter 7, Figure 7.10).

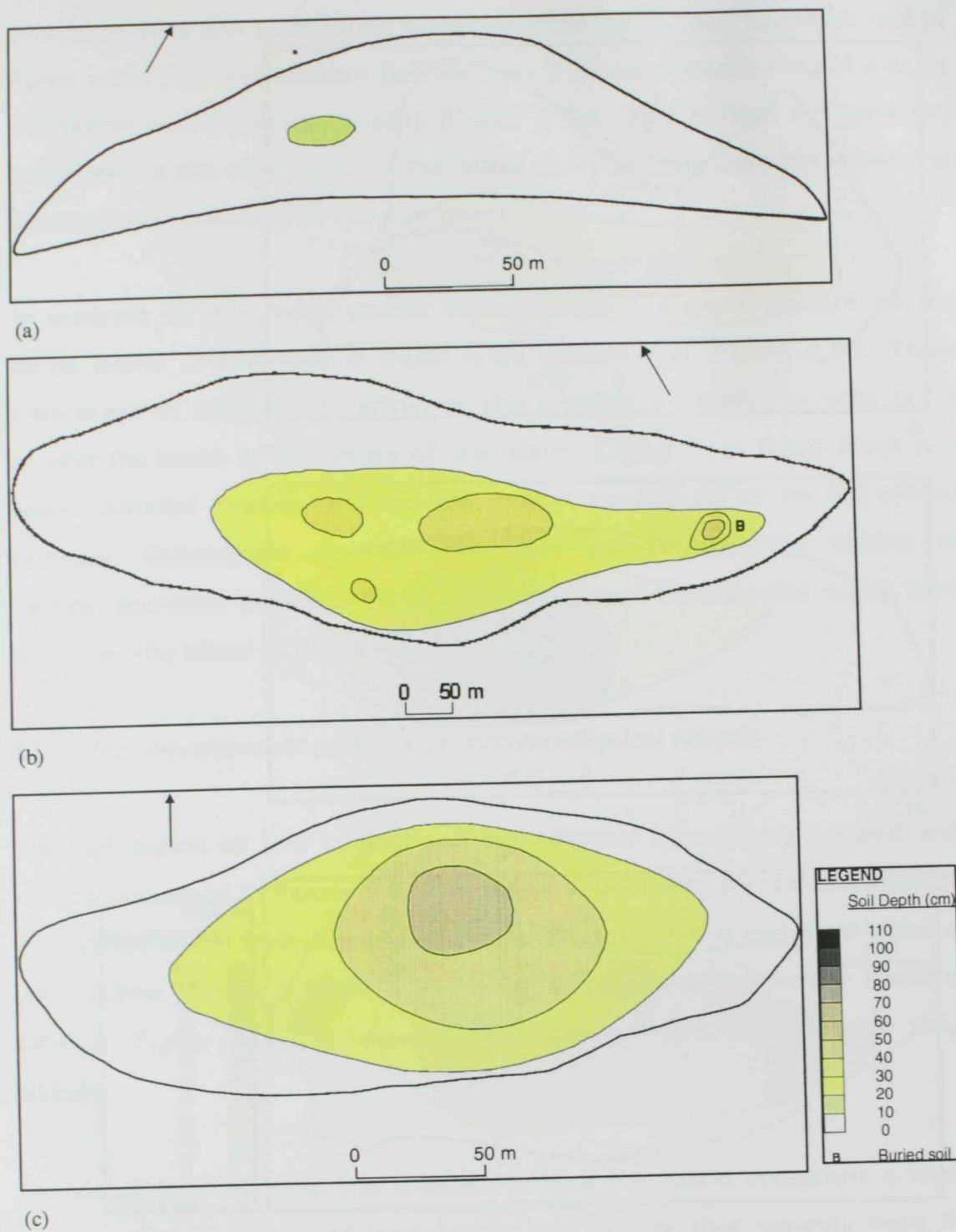
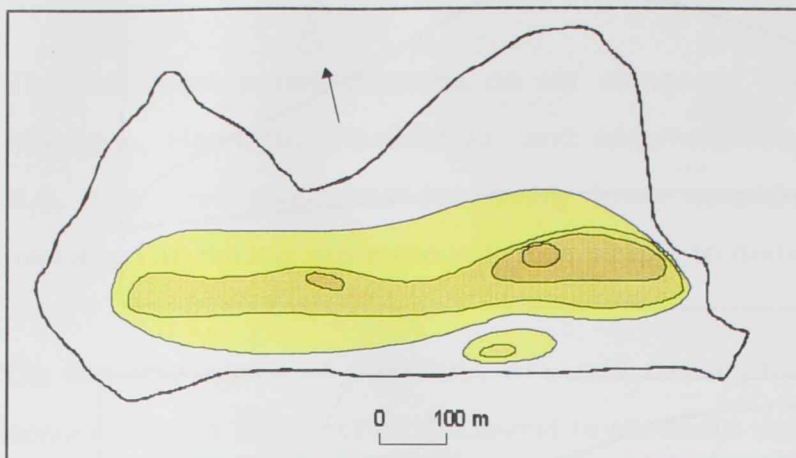
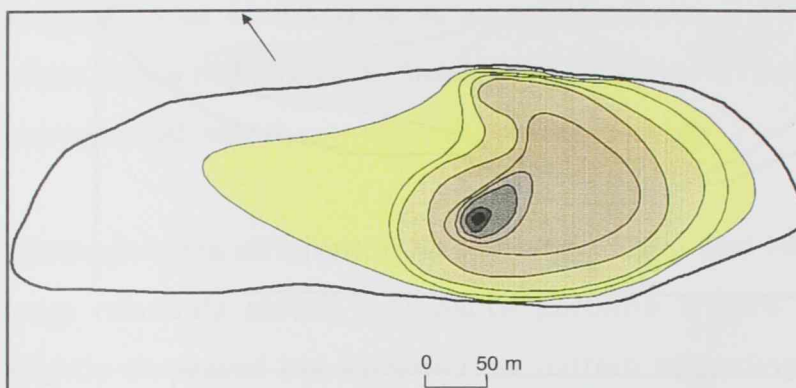


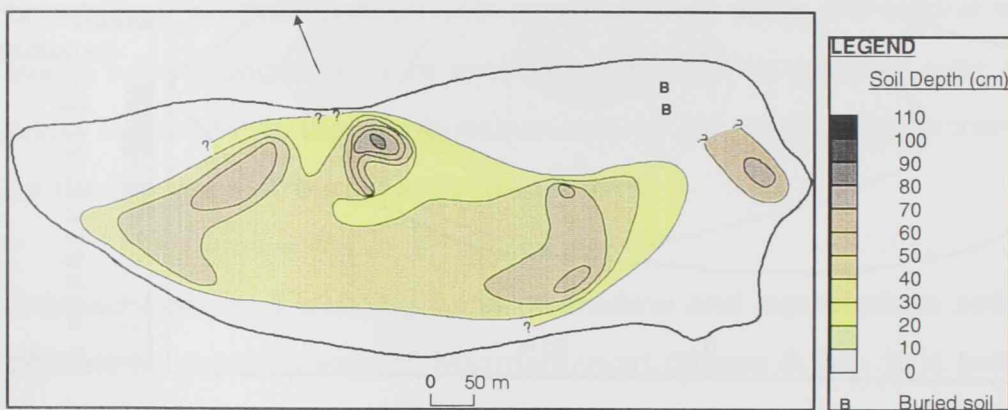
Figure 8.5 Soil development patterns on elongated islands.
(a) Hanifaruru (b) Hibalhithoo (c) Aidhoo.



(d)



(e)



(f)

Figure 8.5 (continued) Soil development patterns on elongated islands.
(d) Maamaduvvari (e) Fares (f) Maaddoo.

Immature soils and unmodified sands characterise the northwestern half of Fares while the southeastern half includes a broad crescent-shaped area of deposition and intermediate soils (Figure 8.5e). This pattern suggests the latter area is the oldest part of the island and that from here the island has subsequently extended to the northwest.

In contrast to this rather simple situation, the soil depth pattern on the larger island of Maaddoo is much more complicated (Figure 8.5f). Three core areas of deeper soils linked to one another by shallower soils occur around the basin in the centre of the island. Offset from these cores is a fourth isolated outcrop of deep soil, which appears to be an old eroded remnant. Subsequent developments have included episodic phases of vertical accretion (as indicated by the presence of buried soils) which have extended the island to the northeast.

8.3.3 Soil development patterns on circular/elliptical islands

The soil depths on four circular and one elliptical island were mapped with results presented in Figure 8.6. The figure shows that the development on the islands varied from simple concentric patterns on the tiny sand island of Gemendhoo (Figure 8.6a) and the large coral gravel and rubble island of Olhugiri (Figure 8.6b), to more complex developments on the other three islands.

On Maaddoo-hulhudhoo, the southern half of the island comprises a broad crescent-shaped region of intermediate soil depths that extends from the southern shore almost to the northeastern and southwestern ends of the island (Figure 8.6c). This pattern suggests the original shape of the island was that of a crescent and that more recently the shallow north-facing 'embayment' between the eastern and western recurves has been infilled to

to give the island its present circular shape. This process is thought to be analogous to that occurring on Maamaduvvari at the present time.

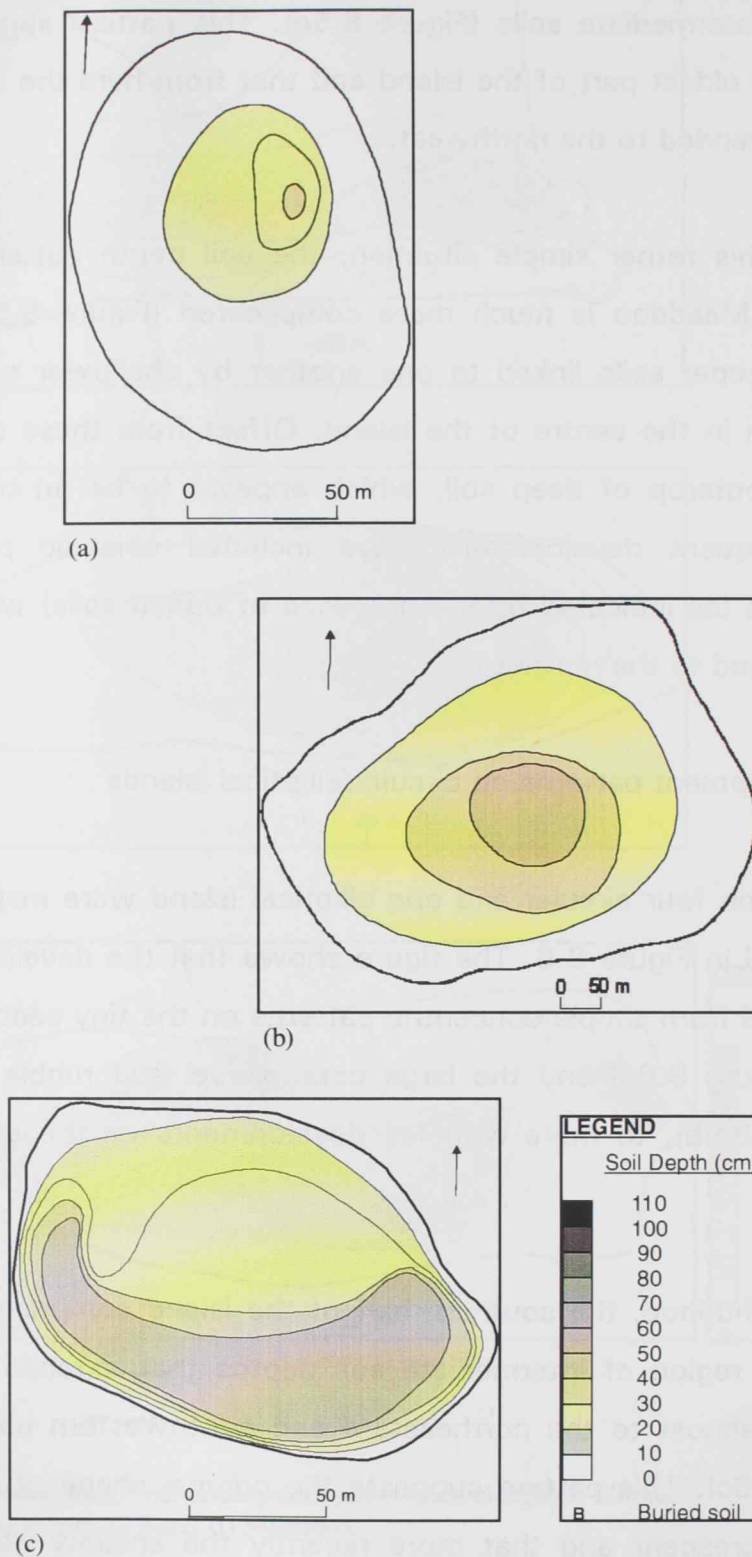
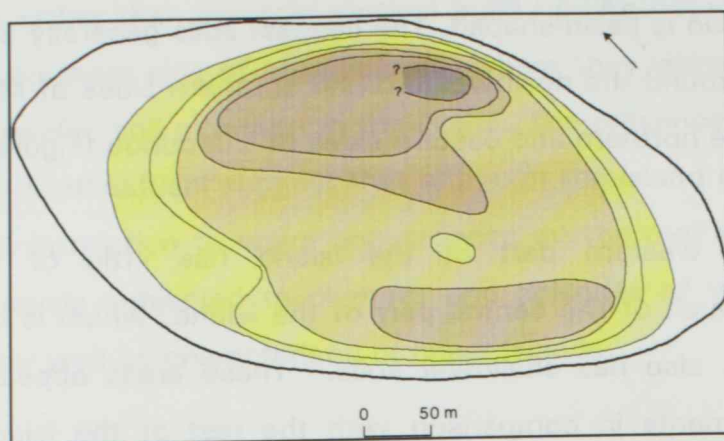


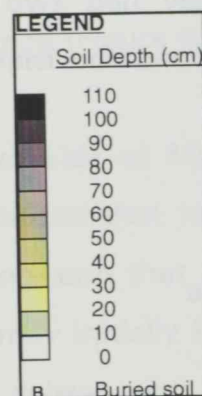
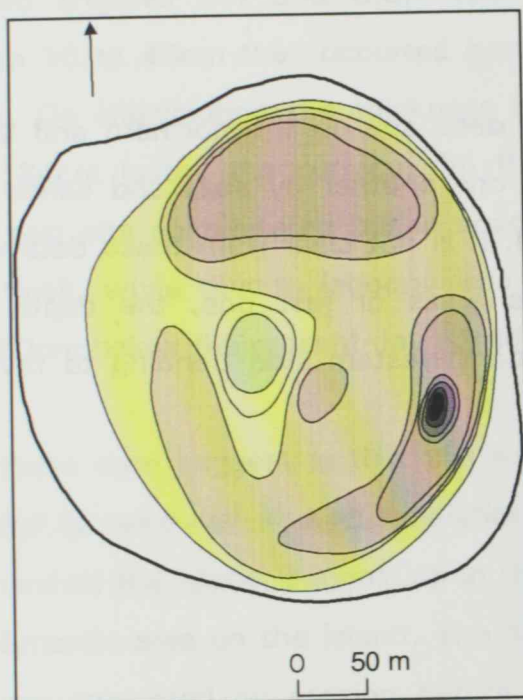
Figure 8.6 Soil development patterns on circular and elliptical islands.
(a) Gemendhoo (b) Olhugiri (c) Maaddoo-hulhudhoo.

(c)

Figure 8.6 Soil development patterns on circular and elliptical islands.
 (a) Gemendhoo (b) Olhugiri (c) Maaddoo-hulhudhoo.



(d)



(e)

Figure 8.6 (continued) Soil development patterns on circular and elliptical islands.
 (d) Mendhoo (e) Udoodhoo.

The islands of Mendhoo and Udoodhoo are approximately the same size (10.5 and 9.3ha respectively). Mendhoo has a discontinuous broad annular ridge, while Udoodhoo is basin-shaped. The deepest soils generally occur on the ridge, curving around the northwestern and southern sides of Mendhoo (Figure 8.6d) and the northern and eastern sides of Udoodhoo (Figure 8.6e).

On Udoodhoo the western part of the island has little or no soil development, and much of the central part of the island, which is close to the mean sea level, also has shallower soils. These areas appear to be much later developments in comparison with the rest of the island, and notably the ridge around the eastern side of the island.

Mendhoo has two core areas of deep soil on the northern and southern sides, which are separated from one another by soils and sands on the western and eastern of the island. It is not clear from these data whether the island initially had two core areas or just one, the depth of soil development around the islands northwestern side trending to favour the latter.

8.3.4 Buried soils

Buried soils are usually indicative of alternating periods of island stability and instability and provide some additional information on the local modes of island development. During stable periods vegetation can grow, provide litter and develop a soil profile, which is later covered over with fresh sand and/or gravel representing an unstable period. In island building, the presence of buried soils usually represents episodes of vertical accretion of islands.

Buried soils were encountered on four islands investigated, suggesting that in most cases island development has been mainly through horizontal growth rather than episodic vertical build up. As noted earlier, buried soils on the northern side of Muthaafushi, where they were encountered in four of the twelve soil pits dug on the island. The presence of these subsurface soils on Muthaafushi suggest that although the island may be in an optimal position in relation to wave convergence on the reef platform, it has been continuously subjected to changes and episodes of vertical accumulation. This may well be characteristic of linear islands.

Buried soils also occur on the southeastern side of Hibalhindhoo and Maaddoo (Figures 8.4 and 8.5). The thickness of buried soils varied between 16 to 40cm they occurred between 4 to 92cm below the island surface. On Hibalhindhoo the thickness of the buried soil is 28cm and it occurs 34cm below the surface. On the northeastern side of Maaddoo, where two pits encountered buried soils, the one located to landwards is 40cm thick, while that to lagoonwards is 16cm thick. These soils occur about 80cm below the present-day island surface (Figure 8.7).

What these data suggest is that the northern side of Maaddoo has been subjected to erosional and accumulative phases that have not occurred elsewhere on the island, suggesting in the long-term that this has been the most dynamic area on the island. The soils may initially have been deeper and were truncated by erosion before the subsequent vertical accretion phase.

The presence of buried soil on a soil profile exposed on Dhakandhoo, from the northwest quadrant of the atoll is shown in Figure 8.

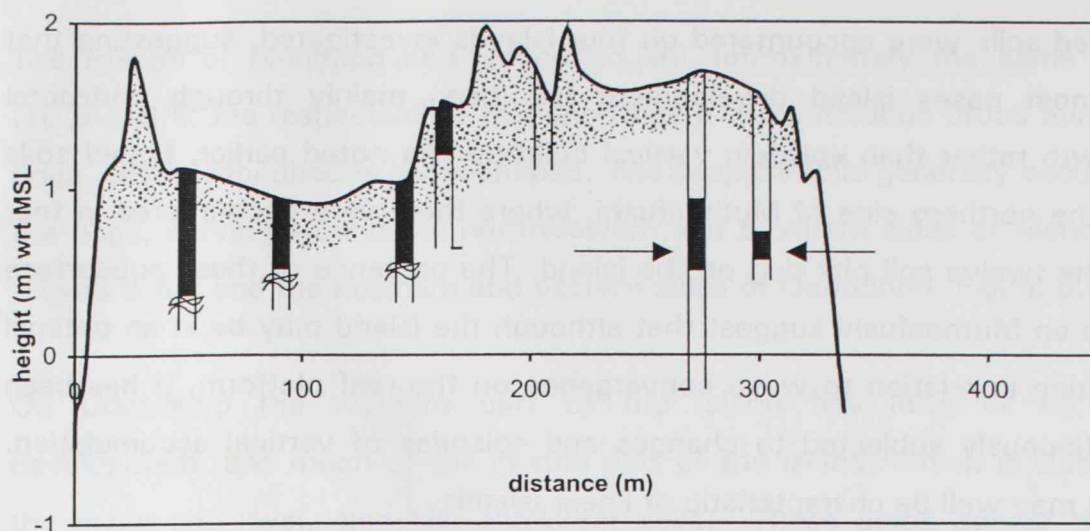


Figure 8.7 Location of buried soils on Maaddoo. The depth of buried soil on the northeastern side of Maaddoo is indicated (by the arrows) in this SW to NE transect of Maaddoo.



photo: R. McLean 1995

Figure 8.8 Buried soil on an exposed beachface on Dhakandhoo.

In the case of Hibalhindhoo and Maaddoo, the previous chapter indicated that significant changes took place between 1899 and 1969, and these changes were attributed to possible episodic/unusual events, suggesting that changes expressed by the presence of buried soils on these two islands may be continuing to this day. The presence of buried soil on Hanifaru, where soil development is very limited, suggests that the island was more extensive in the past, or more stable, and that significant changes to the island are on-going.

In summary, analysis of soil depth patterns on the islands indicates the formation of core areas on reef platforms from which island expansion commenced. In addition, it also suggests two main modes of island development: lateral extension from an initial core, and concentric growth, which is generally evident on circular islands. Episodes of island building are also apparent, along with island reworking and/or vertical accumulation of sediments on old island surfaces. Hence, the soil depths on islands distinguish the 'older' from the younger or the stable from the relatively unstable parts of an island.

8.4 Radiocarbon dating of island sediments

The purpose of the radiocarbon dating program was to get an idea of the time frame of island formation and development throughout the whole atoll, rather than to develop a detailed chronology of specific islands. Of particular interest was to see if the results were evenly distributed throughout the age range or whether there were some concentrations of ages which could indicate periods of enhanced reefal production, sediment supply and/or island accumulation. On several islands more than one age determination has been made and in these cases it may be possible to speculate about the possible development patterns on islands, using a combination of

vegetation, soil depth and radiocarbon dating results. This is a theme that is expanded upon in the next chapter.

8.4.1 Radiometric ages of the islands

The procedures used in estimating age of the sediments have been described in Chapter 3, and the location of some of the samples identified there (Figure 3.6). The material used for radiocarbon dating was limited to bulk surface and subsurface island and beach sediments. Forty sediment samples from 20 islands were radiocarbon dated. Results are given in Table 8.1, and stratigraphic positions are also shown in Appendix 4, along with the soil depth information. The samples include sediments from soil pits dug on the islands, beach sediments from four islands, a piece of coral gravel from within a phosphatic rock, and a cay sandstone sample from a remnant island.

Initially sediment samples were generally taken from the basal layers of pits from the centre of the island, the aim being to recover material thought to have been emplaced early in an island's development. Later, stratigraphically shallower samples were taken and sites towards the island ends were sampled in order to distinguish any significant age variations in island development.

A summary of this information is presented in Table 8.2, indicating specifically the number of samples dated from each island, and their location. These and the dates from other islands in the Maldives (obtained from Woodroffe 1993) are presented in Figure 8.9 to show the frequency occurrence of dates for particular age groups. Note that throughout this thesis environmentally corrected ages are referred to, though the conventional ages are also given in Table 8.1.

Table 8.1 Details of radiocarbon dated material from Eta atoll.

Waikato Lab no. (Wk)	Coral Material	Location	Depth (cm) w.r.t MSL	Conventional radiocarbon age (yrs. B.P)	Environmentally corrected radiocarbon age ¹
7078	Bulk coral sand	Mendhoo, beach	--	1370 ± 50	920 ± 60
6337	Bulk coral sand	Udoodhoo, beach	--	1390 ± 50	940 ± 60
6338	Bulk coral sand	Hanifaru, centre	21	1500 ± 50	1050 ± 60
6173	Bulk coral sand	Nelivaru, centre	230*	1560 ± 50	1110 ± 60
6336	Bulk coral sand	Nelivaru, beach	--	1570 ± 50	1120 ± 60
6168	Bulk coral sand	Bodufinolhu, centre	17	1590 ± 50	1140 ± 60
6166	Bulk coral sand	Hithaadhoo, central northern	201*	1610 ± 60	1160 ± 70
5834	Bulk coral sand	Hibalhidhoo, west side	-48	1630 ± 50	1180 ± 60
6172	Bulk coral sand	Muthaafushi, east	-33	1770 ± 50	1320 ± 60
5833	Bulk coral sand	Hibalhidhoo, east side	-37	1850 ± 50	1400 ± 60
7079	Bulk coral sand	Fonimagoodhoo, north	114*	1910 ± 60	1460 ± 70
6335	Bulk coral sand	Nibiligaa, centre	-31	1980 ± 50	1530 ± 60
6171	Bulk coral sand	Fares, eastern side	-45	1980 ± 60	1530 ± 70
6167	Bulk coral sand	Maamaduvvari, west	-54	1990 ± 50	1540 ± 60
6333	Bulk coral sand	Olhugiri, southern side	43	2010 ± 60	1560 ± 70
6174	Bulk coral sand	Nelivaru, centre	290*	2040 ± 50	1590 ± 60
5832	Bulk coral sand	Olhugiri, southern side	-72	2040 ± 60	1590 ± 70
6329	Bulk coral sand	Maaddoo-hulhudhoo, beach	--	2060 ± 50	1610 ± 60
7080	Bulk coral sand	Maamaduvvari, south	-5	2160 ± 60	1710 ± 70
7081	Cay sandstone	Dhoogadu finolhu	--	2190 ± 60	1740 ± 70
5830	Bulk coral sand	Nibiligaa, centre	-64	2240 ± 50	1790 ± 60
6330	Bulk coral sand	Maaddoo, western end	-33	2250 ± 50	1800 ± 60
7082	Bulk coral sand	Fonimagoodhoo, south	75*	2260 ± 60	1810 ± 70
5836	Bulk coral sand	Maamaduvvari, south east	-24	2270 ± 60	1820 ± 70
6334	Bulk coral sand	Maaddoo, north eastern	-20	2280 ± 60	1830 ± 70
6175	Bulk coral sand	Mendhoo, western side	-35	2300 ± 60	1850 ± 70
ANU 10275	Bulk coral sand	Kunfunadhoo, centre of island	180*	2590 ± 70	2140 ± 80
5831	Bulk coral sand	Olhugiri, centre	50	2870 ± 60	2420 ± 70
5837	Bulk coral sand	Maaddoo, north east	52	2870 ± 60	2420 ± 70
5838	Bulk coral sand	Gemendhoo, centre	-20	2880 ± 60	2430 ± 70
6339	Bulk coral sand	Aidhoo, centre	44	2920 ± 50	2470 ± 60
5835	Bulk coral sand	Aidhoo, close to centre	-6	3130 ± 60	2680 ± 70
5840	Bulk coral sand	Fares, central eastern	-55	3200 ± 60	2750 ± 70
5839	bulk coral sand	Mendhoo, close to the centre of island	-78	3520 ± 60	3070 ± 70
6169	Bulk coral sand	Kamadhoo, south east	188*	3910 ± 60	3460 ± 70
6332	Coral pieces in phosphatic rock	Maaddoo-hulhudhoo	--	4220 ± 80	3770 ± 85
5829	Bulk coral sand	Udoodhoo, central eastern	-80	4500 ± 60	4050 ± 70
6170	Bulk coral sand	Udoodhoo, central western	-64	4710 ± 70	4260 ± 80
6165	Bulk coral sand	Maaddoo-hulhudhoo	12	4850 ± 80	4400 ± 85
6331	Bulk coral sand	Udoodhoo, central eastern	-54	4960 ± 60	4510 ± 70

¹ Environmental correction for ocean reservoir effect of minus 450 ± 35 years following the correction for marine shell adopted by Gillespie and Polach (1979).

* depth of sample from surface.

Table 8.2 Summary of material radiocarbon dated, indicating the islands from where samples were obtained, including the number of samples and their location(s) for each island.

Island	No. of samples	Location (s)	Remarks
Aidhoo	2	~ C	2 depths
Bodufinolhu	1	~ C	
Dhoogadu finolhu	1	--	
Fares	2	EC, SE	
Fonimagoodhoo	2	N, S	
Gemendhoo	1	C	
Hanifaru	1	C	
Hibalhiddoo	2	SE, NWC	
Hithaadhoo	1	NE	
Kamadhoo	1	SE	
Kunfunadhoo	1	~ C	
Maaddoo	3	NE, SE, NW	
Maaddoo-	3	~EC, B, P	
Maamaduvvari	3	E, SE, NW	
Mendhoo	3	EC, NW, B	
Muthaafushi	1	NE	
Nelivaru	3	C, B	2 depths
Nibiligaa	2	C	2 depths
Olhugiri	3	C, SE	2 depths
Udoodhoo	4	E, EC, WC, B	

B=beach sample, P=phosphatic rock sample,

C=centre, E=east, S=south, N=north, SE=southeast, NE=northeast, NW=northwest,

EC=east central, WC=west central, NWC=northwest central,

~ =close to.

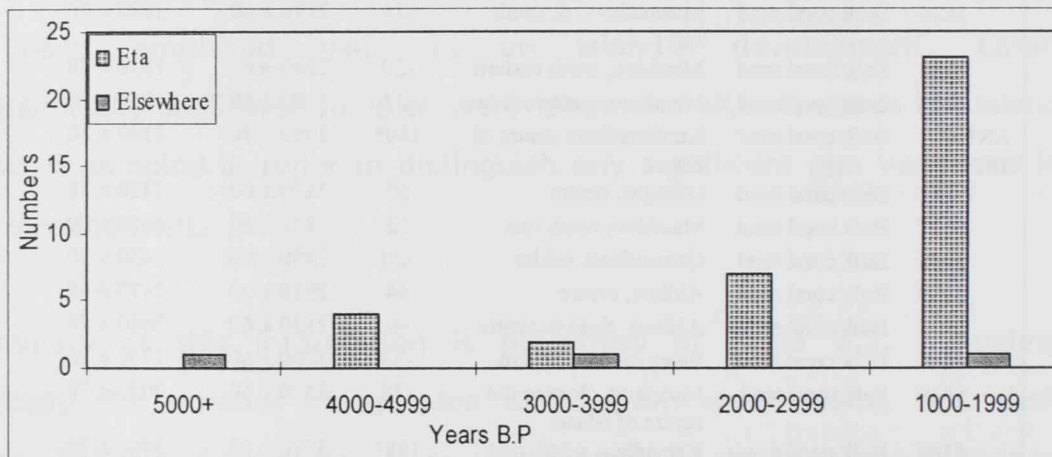


Figure 8.9 Radiocarbon dates for Eta atoll and elsewhere in the Maldives. A prevalence of younger ages is indicated from the figure.

Based on the oldest radiometric date, the islands in Eta atoll can be crudely grouped into four age categories (Table 8.3).

Table 8.3 Relative age groups of islands in Eta atoll. The ages are given in environmentally corrected years.

4000-4999 yrs B.P	3000-3999 yrs. B.P	2000-2999 yrs. B.P	1000-1999 yrs. B.P
Maaddoo- hulhudhoo Udoodhoo	Kamadhoo Mendhoo	Aidhoo Fares* Gemendhoo Kunfunadhoo Maaddoo Olhugiri	Bodufinolhu* Dhoogadu finolhu Fonimagoodhoo Hanifaru* Hibalhindhoo Hithaadhoo Maamaduvvari Muthaafushi* Nelivaru* Nibiligaa*

* indicates island on *faro* reef platforms

Three points can be made from this simple grouping. First that the islands are young and have developed in the Late Holocene. Second that the older dates are associated with islands on patch reefs, rather than faros. Indeed there is only one island on a *faro* (Fares) in the first three columns. And third, none of the sampled islands have ages less than 1000 years B.P, even though at least one of the islands is an unvegetated *finolhu* (Nelivaru).

8.4.2 Phases of island building and extension

A rather more detailed analysis of results in Table 8.1 suggests there is some clustering of ages which may indicate phases of island building and /or expansion. Three phases, separated by periods of over 250 years are identified and summarised below.

1. First phase (between 3000 to 4500 years B.P):
Maaddoo-hulhudhoo, Udoodhoo, Kamadhoo and Mendhoo.
2. Second phase (2100 to 2750 years B.P):
Aidhoo, Fares, Kunfunadhoo, Olhugiri, Gemendhoo, Maaddoo.
3. Third phase (1050 to 1850 years B.P):
-*Episode 1* (~ 1800 years B.P); Maamaduvvari, Nibiligaa, Fonimagoodhoo, Dhoogadu Finolhu,
-*Episode 2* (~ 1550 years B.P); Muthaafushi, Hibalhido, Nelivaru,
-*Episode 3* (~ 1130 years B.P); Bodufinolhu, Hanifaru, Hithaadhoo.

First phase (c 3000 to 4500 years B.P)

Sediments from four islands have been dated in the range of 3070 to 4510 years B.P. and these islands are believed to represent the earliest phase of island building on Eta atoll. There appears little doubt about the validity of the timing, at least for the two islands with the oldest dates. Results from three different subsurface sand samples on Udoodhoo gave ages of 4510, 4260 and 4050 years B.P, and on Maaddoo-hulhudhoo near surface sand and coral fragments incorporated in a surficial outcrop of phosphatic rock gave ages of 4400 and 3770 years B.P respectively. Note that these samples are generally shallow, close to surface, rather than from depth, suggesting that they are minimum ages for the formation of Maaddoo-hulhudhoo.

The two other islands in this group, Kamadhoo and Mendhoo have much younger ages, 3460 and 3070 years B.P. While they are included in the later part of this first phase of island formation, they may represent a second episode of incipient island development within this first phase.

Notwithstanding this possibility the radiocarbon results provide strong evidence for the existence of at least four islands prior to 3000 years B.P. on Eta atoll. Two other points should be noted. First, that the four islands are not spatially concentrated in any one part of the atoll. Rather, Udoodhoo is located in the central north, Kamadhoo in the extreme northeast, Maaddoo-hulhudhoo in the southeast, and Mendhoo is in the middle of the atoll. Second, all four islands are compact with I_e between 1.0 and 1.9, and they presently occupy from 26 to 51% of the reef platform on which they are located.

Second phase (c2100 to 2750 years B.P.)

An age gap of 320 radiocarbon years separates the early phase of island formation from this next phase, which includes six islands located in all parts of the atoll. With the exception of Fares, each of the islands is circular to oval in shape and presently occupies a large percentage of the reef platform (35-71%). Ages of samples from four of the islands Olhugiri, Maaddoo, Gemendhoo, and Aidhoo, fall within 50 years of one another suggesting that this phase of island building was centered around 2400 years B.P. That this was a discrete phase is suggested not only by the age gap between the second and first phase, but also by the 290 years separating it from the third phase.

Third phase (c1050 to 1850 years B.P.)

During this 800 year period both the building of 'new' islands and the extension of established islands took place. Within this phase the distribution of radiocarbon dates suggests there were three major episodes; one centered on ~1800 years B.P, a second on ~1550 years B.P and the third ~1130 years B.P.

In the first episode, eight dates cover the period from 1710 to 1850 years B.P. Six islands are involved, four of which (Dhoogadu Finolhu,

Fonimagoodhoo, Maamaduvvari, and Nibiligaa) appear to have developed during this time, while Mendhoo and Maaddoo which were already in existence probably received a fresh influx of sediments during this episode. Dhoogadu Finolhu, which now comprises only an extensive area of cay sandstone, may well have developed at this time given the radiocarbon age of 1740 years B.P. from a sample of the rock. Extension of existing islands, such as Maaddoo-hulhudhoo, Olhugiri and Fares seems to characterise the second episode which is tightly constrained by dates between 1530 and 1590 years B.P. 'New' islands developed at this time include Hibalhido, Nelivaru and Muthaafushi. The third episode includes Hithaadhoo, Bodufinolhu and Hanifaru, which were probably formed around 1110 to 1160 years B.P.

8.4.3 Horizontal and vertical accretion

While these three distinct phases may represent the earliest timing of island building on specific islands, it is also clear from the previous analysis that subsequent younger phases or episodes of deposition are identifiable on several islands. The following table (Table 8.3) gives an indication of the variations in age between different parts of selected islands, each of which can be associated with one of the phases and/or episodes identified above.

For instance, sediment from the centre of Fares has an age around 2750 years B.P. corresponding to the beginning of the second (2) phase, while sand from the eastern side of the island indicates ages around 1530 years B.P., corresponding to the third phase, second episode (3/2). Similarly, phases 1 and 3/1 are identifiable on Mendhoo, 2 and 3/1 on Maaddoo, 3/1 and 3/2 on Fonimagoodhoo and Maamaduvvari, and 3/2 and 3/3 on Hibalhido. The variations in age from different parts of the same island range between 220–1220 years.

In the case of Fares, Maaddoo, and Mendhoo which comprise sediments from two different phases from 620 to 1220 years apart there is a strong argument to suggest that the islands have grown through horizontal accretion episodically rather than gradually. The situation for the other three islands is less clear. Similarly, for the rest of the islands there is not enough data to confirm whether island development has been episodic or gradual.

Table 8.3 Differences in age from two distinct parts of selected islands.

Island	Location	Age
Fares	centre	2750 $\pm$ 70
Fares	east	1530 $\pm$ 70
Fonimagoodhoo	south	1810 $\pm$ 70
Fonimagoodhoo	north	1460 $\pm$ 70
Hibalhidhoo	southeast	1400 $\pm$ 60
Hibalhidhoo	northwest	1180 $\pm$ 60
Maaddoo	southeast	2420 $\pm$ 70
Maaddoo	northwest	1800 $\pm$ 60
Maamaduvvari	northeast	1820 $\pm$ 70
Maamaduvvari	southwest	1540 $\pm$ 60
Mendhoo	southeast	3070 $\pm$ 70
Mendhoo	northwest	1850 $\pm$ 60

For an estimate of vertical accretion of sediments, data are only available for four islands; Aidhoo, Nelivaru, and Nibiligaa, and Olhugiri (Table 8.4). On Aidhoo, a difference of 210 years is indicated for two sediment samples obtained at 44cm above, and 6cm below MSL (50cm apart). On Nelivaru, a difference of 480 years is indicated for two samples 60cm apart, and 260 years difference for two samples 34cm apart on Nibiligaa. On Olhugiri, no significant age difference between two samples 115 cm apart was obtained.

These results are rather ambiguous and by themselves cannot be used with confidence to infer phases of vertical accretion or mixing. The former may be the case for Aidhoo and Nibiligaa, while contemporaneous deposition and mixing provide a reasonable explanation for the results from Olhugiri.

Table 8.4 Ages indicated for different depths from selected islands

Island	Depth (cm) wrt MSL/ *depth from surface	Environmentally corrected Radiocarbon age
Aidhoo	44	2470 ± 60
Aidhoo	-6	2680 ± 70
Nelivaru	230*	1110 ± 60
Nelivaru	290*	1590 ± 60
Nibiligaa	-31	1530 ± 60
Nibiligaa	-64	1790 ± 60
Olhugiri	43	1560 ± 70
Olhugiri	-72	1590 ± 70

8.4.4 Contemporary beach sediments

Bulk sand samples from contemporary beaches can contain both modern and fossil sand grains. Where recent sediments dominate radiocarbon ages can be expected to be 'modern'. Four samples from present day beaches were radiometrically dated; three are from the 'oldest' islands associated with phase 1, and the other from an unvegetated *finolhu*, (Table 8.5).

Table 8.5 Age of beach sediment samples

Island	Age
Maaddoo-hulhudhoo	1610 ± 60
Mendhoo	920 ± 60
Nelivaru	1120 ± 60
Udoodhoo	940 ± 60

The results show that none of the samples are 'modern', suggesting that there has been some erosion and reworking of the older island sediments in the contemporary beach and/or that the present day reef flats contain both modern and fossil skeletal materials that can be transported to and from island beaches. Further sampling and analysis of island, beach and reef flat sediments from the same reef platform is required to resolve some of the questions that arise from these preliminary results.

From this analysis three significant points can be made in relation to island development. First, on achieving a certain proportion of the reef platform, the amount of fresh sediments that can go into island building or the active sediment zone may be limited by the very presence of the island. Second, extensive sediment reworking can take place, especially on unvegetated islands (*finolhus*) as was demonstrated in Chapter 6. Third, that stability of the sediment accumulation through vegetation establishment and soil development is necessary for island development and growth to take place.

8.5 Summary and implications

The purpose of this chapter was to provide evidence on both the relative and absolute chronology of island formation and development in Eta atoll. Three sorts of evidence were used: vegetation type and distribution; soil depths and morphology; and radiometric dating of island and beach sediments.

A classification of four vegetation types, which theoretically represented a vegetation succession, was used to describe the vegetation distribution on the islands and through that to identify directions of recent island growth or contemporary dynamics. The results showed that:

- On circular and elliptical islands two main modes of island development occurred: lateral extension from an initial core; and, concentric growth which has two variants, symmetrical and asymmetrical expansion; and
- On linear and elongate islands there were also two equivalent types of growth: lateral extension away from a core generally located at the southeastern end of the island; and, concentric expansion around an elongated central axis.

These modes of development appeared to occur irrespective of the size or position of the island on the atoll or reef platform.

The second type of evidence came from an analysis of soil depth patterns. As with the vegetation types some islands possessed a limited suite of soil depths, inferring the islands were relatively young. Others included a range of deep to shallow soils. Together these soil depth distributions confirmed the existence of both the lateral expansion and concentric growth models of island development, though considerable variations with island shape, size and topography were identified. In addition to such horizontal growth patterns, the presence of buried soils on some islands suggested vertical accretion as another process of island building.

The third type of evidence, radiocarbon dating provides some temporal constraints on the above conclusions and also some specific data on the chronology of island development throughout the atoll. This data suggests that:

- The initial phase of island formation took place over 4000 years B.P, and that by 3000 years B.P there were at least four islands in existence in different parts of the atoll;
- Two further phases of island formation and expansion occurred; one centered around 2400 years B.P, the other from 1850 to 1050 years B.P which included three major episodes, centered around ~1800, ~1550 and ~1130 years B.P.
- The basic outlines of most of the present islands on Eta atoll are thought to have been in existence by about 1000 years ago.

- Although they have been modified through subsequent erosion and accretion, the majority of the islands appear to have persisted since that time.

In general, there is no significant relationship between the three parameters discussed in this chapter to the cluster groups identified in Chapter 5. Size or shape of island appears immaterial to the age of the island. Nevertheless, it is evident that there is some relationship between the soil depth, vegetation pattern and radiocarbon ages of sediments that occur on islands. Usually, older ages are associated with deeper soil developments and often occurrence of mature vegetation. However, this relationship is much stronger between soil depth and radiocarbon age of sediments. Islands with deeper soil developments exhibit older ages (e.g. Udoodhoo, Fares (central), or Mendhoo), while islands with shallower soil developments are younger (e.g. Bodufinolhu, Muthaafushi). Further work along this line is required for developing a rigorous methodology for utilising this approach to understand patterns and trends in island development over long-term.

Two other observations are particularly pertinent. First, that the compact circular and elliptical islands appear much more stable than the elongate and linear islands. And second, that islands on faros are much more dynamic and changeable than islands on patch reefs. Indeed, on some faros islands have disappeared altogether, and others have been subjected to dramatic change.

Although there have been many theories proposed to explain the origin of the islands, the majority of them have failed to provide a satisfactory explanation of the facts.

The first theory is that the islands are the remains of a submerged continent. This theory is based on the fact that the islands are situated in a line, and that the water depth around them is very shallow. It is also claimed that the islands are composed of the same material as the surrounding seabed. However, this theory is based on a number of assumptions which are not supported by the facts. For example, the islands are not situated in a straight line, and the water depth around them is not uniform. Furthermore, the islands are composed of different materials, and the seabed is made up of a variety of different rocks and sediments. Therefore, the theory of a submerged continent is not supported by the facts.

Another theory is that the islands are the remains of a volcanic island chain. This theory is based on the fact that the islands are situated in a line, and that the water depth around them is very shallow. It is also claimed that the islands are composed of the same material as the surrounding seabed. However, this theory is based on a number of assumptions which are not supported by the facts. For example, the islands are not situated in a straight line, and the water depth around them is not uniform. Furthermore, the islands are composed of different materials, and the seabed is made up of a variety of different rocks and sediments. Therefore, the theory of a volcanic island chain is not supported by the facts.

A third theory is that the islands are the remains of a coral reef. This theory is based on the fact that the islands are situated in a line, and that the water depth around them is very shallow. It is also claimed that the islands are composed of the same material as the surrounding seabed. However, this theory is based on a number of assumptions which are not supported by the facts. For example, the islands are not situated in a straight line, and the water depth around them is not uniform. Furthermore, the islands are composed of different materials, and the seabed is made up of a variety of different rocks and sediments. Therefore, the theory of a coral reef is not supported by the facts.

CHAPTER 9

Island morphodynamics and models

9.1 Introduction

This chapter considers the implications of the results presented in Chapters 5 to 8 in relation to the literature that was reviewed in Chapter 2. In the substantive chapters reef island morphodynamics has been considered at three time scales (short-, medium- and long-term) and operating over two main spatial scales (whole atoll and individual reef platform/island). Initially the present chapter is concerned with evaluating the mechanisms of island initiation and specifically addressing two questions with reference to Eta atoll.

- What is the temporal relationship between reef platform formation and island initiation?
- How have the reef islands originated?

The second part of the chapter deals with island growth, development and changes and includes an assessment of models of reef island evolution. It addresses the questions:

- How have the islands evolved through time?
- Are there distinct patterns and phases of island development?

The chapter concludes with a discussion of reef island stability and instability, and of the concept of equilibrium as applied in Eta atoll.

9.2 Island formation

Reef islands are either formed on reef platforms soon after reaching a favourable level in relation to the sea (Hopley 1982; Richmond 1993; McLean and Woodroffe 1994), or after a lag when the reef platform has been in existence for some time (e.g. Chivas *et. al.* 1986). In order to determine which of these two possibilities is represented in the study site, ages of both the underlying reef platform and island from the same location are required.

No such data is available from Eta atoll or the Maldives, although Woodroffe (1993) has addressed the issue using data from different locations. His interpretations of the very limited data was that the period between 6000-3000 years B.P in the Maldives appear to have been dominated by vertical growth of reefs (as they attempted to catch up with sea level) *...that the reef platforms had reached a level very close to present sea level around 3000 years B.P, and that the islands have accumulated in the last 3000 years* (p.1217). The fact that sea level in the SW Indian Ocean stabilised without a higher stand between 2000-3000 years (Camoin *et. al.* 1997) may support this contention.

While this may be the general case for the Maldives, the fact that two islands in Eta atoll (Maaddoo-hulhudhoo and Udoodhoo) had subsurface sediment samples with radiocarbon ages greater than 4000 years (Chapter 8.4.1) suggests that in some instances reef platforms reached sea level prior to 3000 years B.P. and quickly accumulated sediments. That both of these islands (together with two other islands, Kamadhoo and Mendhoo, possessing sediments with radiocarbon ages >3000 years B.P.) were associated with smaller patch reefs also suggests that small reefs are able to put down a reef framework more efficiently than larger counterparts thus

enabling them to reach sea level earlier, and/or that the smaller reef platforms provide a more conducive environment for island formation.

Indeed, as Hopley (1982, p.317) with reference to the Great Barrier Reef suggested:

A cay may form as soon as there is sufficient area on a reef flat, the number of cays found on the relatively small reefs less than 1km² suggesting that a large area is unnecessary.

Evidence from Eta atoll supports this suggestion.

9.3 Mechanisms of island initiation

The mechanisms of reef island initiation were reviewed in Chapter 2. Four theories were discussed there and they are now evaluated against the evidence from Eta atoll.

9.3.1 Sea level fall and island initiation

The notion of a fall in sea level, as a general mechanism promoting island formation has been strongly advocated by several authors citing examples from the Pacific including Kuenen (1933) and Schofield (1977). It has also been strongly advocated in the Maldives by Gardiner (1903, 1931), Sewell (1936a, b), and Fosberg (1956). Indeed, Gardiner (1903, 1931) found evidence in Eta atoll to suggest the existence of a higher sea level, and that it was the fall in sea level from that high that caused the emergence of the islands.

In the light of these studies, it is necessary to consider evidence for or against a higher sea level in Eta atoll. Here two types of evidence are evaluated: first, general evidence and then, the specific evidence as outlined by Gardiner (1903) from Eta atoll.

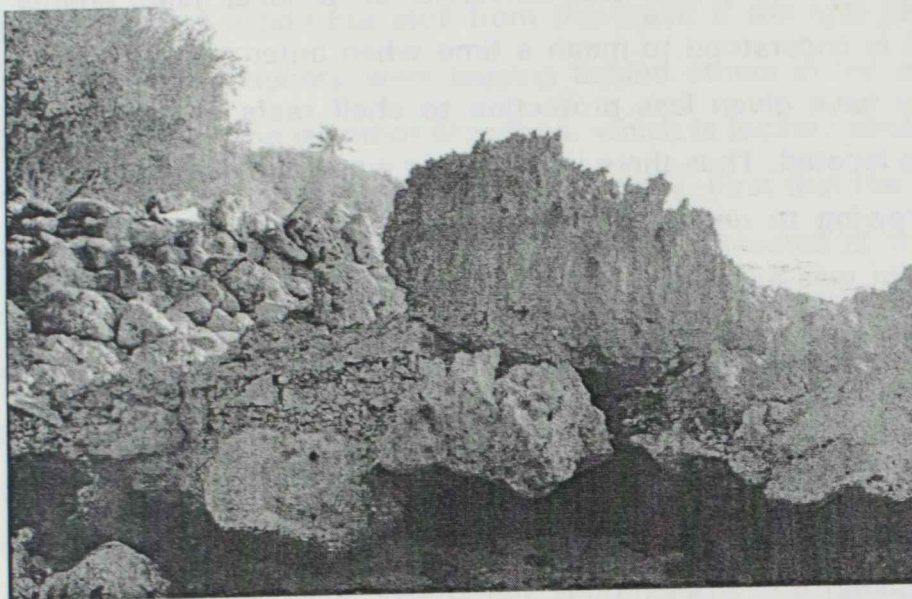
In reefal areas field criteria for evidences of a higher sea level can come from a) the nature and level of reefal materials and rocks, and (b) island elevation, materials and morphology, in relation to their modern counterparts. Examples of the first include fossil *in situ* microatolls, 'raised' reefs and high beachrocks, all used by Woodroffe *et. al.* (1999) in the Cocos (Keeling) Islands, and 'high level conglomerates' which Richmond (1993, p.1190) found '*play an important role in Type IV islet initiation*'. None of these features have been found on Eta atoll. For instance, all microatolls examined were on present day reef flats and none were found in growth position above the mean sea level. Similarly, no 'raised' reef flats or high beachrocks were found; levels of the latter being given in Table 5.5. 'High level conglomerates' are also absent.

Second is the evidence from the islands themselves. None of the islands on Eta atoll have features that can be ascribed to a higher sea level, such as the 'high terrace' described from some of the islands on the northern Great Barrier Reef (McLean and Stoddart 1978). Topographical transects surveyed on 43 islands show that the average maximum height of the islands is 1.96m above MSL, and that this height is reached during high wave activity under present conditions. Invariably, the highest point on any island, including that of 3.19m on Funadhoo (the highest point surveyed on the atoll) is the outer-most recent ridge, which is clearly associated with modern sea level.

It remains to consider the specific reference by Gardiner (1903) to 'raised reefs' on Maamaduvvari. Inspection of this site indicates, that, contrary to Gardiner's view the corals are not *in situ*; rather they comprise coral boulders that have been 'tossed' around. Figure 9.1 shows the nature of this coral rubble tract, and indicates that it is not a 'raised reef'.

This conclusion is similar to that of Stoddart (1971c, p.7) for other sites in the Chagos-Maldives archipelago. Stoddart's '*re-examination of Gardiner's*

example at Addu and Diego Garcia atolls suggests that most such outcrops are lithified island sediments not indicating any sea level change'. Moreover, after examining some of the sites and the literature on sea level history of the Maldives as proposed by Gardiner (1903), Sewell (1936a,b), and Stoddart (1966), Woodroffe (1993) considered that much of the evidence about a higher sea level stand in the Maldives 'remains inconclusive'.



(a)



(b)

Figure 9.1 (a) Coral rubble and boulders forming the 'raised reef' on Maamaduvvari.
(b) A coral piece chipped from one of the corals on the 'raised reef', showing the growth bands which indicate that the coral has been 'tossed' sideways.

In the case of Eta atoll no concrete evidence for a higher sea level has been discerned, and it is reasonable to conclude that the islands in Eta atoll did not result from a fall in sea level.

9.3.2 High energy 'window' and island initiation

A second mechanism whereby islands may be formed on reef platforms has been postulated. This is under the influence of a local high energy 'window', which is understood to mean a time when outer reefs not quite at sea level may have given less protection to shelf reefs on which the oldest islands are located. Thus there was greater wave activity when reefs were actively growing to catch up with sea level (Hopley 1982, 1984). Such a mechanism was suggested for islands within a lagoon or behind a barrier reef. In an open atoll situation, where waves are able to penetrate into the lagoon through the passages, the high energy 'window' may not have been as effective. For instance, in Eta atoll there are 33 passages which occupy 41% of the atoll's perimeter.

Several lines of evidence can be used to assess the potential role of a high energy 'window' operating in a reefal area including:

- the relative age and elevation of outer (peripheral) and inner (lagoonal) reef platforms and their growth in response to Holocene sea level history;
- the presence of coarser materials (coral rubble, boulders etc.) on islands that could have been transported under temporary high-energy conditions; and
- the presence of higher elevation of islands and depositional features relative to equivalent levels of present day features.

In Eta atoll there is no explicit data on the first criteria and no firm evidence for the second and third criteria that cannot be explained in other ways.

However, in the Maldives it is likely that variations in vertical reef growth did occur (Woodroffe 1993), and in the case of Eta atoll, one explanation for the different ages of islands and the phases of island building could be related to the different times reef platforms reached sea level. In such circumstances a local high energy 'window' could have operated.

There are also other possibilities. Greater energy may have affected reef platforms well inside Eta atoll from the west, if the reef platforms on the western atoll periphery were lagging behind others in the atoll. Such may be the case for the island of Mendhoo, which is located about the centre of the atoll. Three factors support this possibility. First that the island is one of the oldest (3070 ± 70 years B.P). Second, it is located at the southeastern end of the reef platform. And third, the nature of the soil development pattern is 'complicated' on the island (Chapter 8). All these factors could be related to higher energy acting on the island from the west. Later, with growth of the western peripheral reef platforms, and closure of the high energy 'window', growth and extension of Mendhoo westwards (which is suggested by the soils, vegetation, morphologic and radiocarbon dates, in Chapter 8) probably occurred.

Similar arguments could be used in the case of Udoodhoo and other islands along the northern atoll periphery, all of which could have been more exposed to higher energy conditions if the eastern peripheral reef platforms of Zeta (ζ) lagged behind those of Udoodhoo etc. The basis for such arguments, however, is slender and a more conclusive statement awaits the collection of the sort of data implied at the beginning of this section.

9.3.3. 'Nodal accumulation' and island initiation

Unlike the first two mechanisms, which involve sea level-reef platform interactions in the Mid- to Late Holocene, the concept of 'nodal accumulation' emphasises sediment accumulation on a reef platform under present sea level and environmental conditions. In simple terms, currents and waves acting on a reef platform refract and diffract to transport and accumulate sediments at a 'nodal' point, which forms the locus for an island.

Factors that influence the position and shape of an island initiated in this way include the size and geometry of the reef platform, a ready supply of sediment, wave convergence and wave-current energy levels sufficiently competent to transport the available sediment.

In areas of persistent trade winds, wave-current convergence usually occurs on the leeward side of the reef platform as illustrated earlier in Figures 2.3 and 2.4. In the Maldives where reversals in monsoon winds cause seasonal changes in wave direction, windward and leeward sides are less clear, and as previously suggested (Chapter 2, p.31) the position of nodal accumulation is likely to be more variable.

In Eta atoll, islands on the eastern side of the atoll are commonly located on the western side of their reef platforms, while on the western side they are commonly located on the eastern side of their reef platforms. Such 'nodal' positions are believed to reflect the dominant seasonal wind-wave activity, which is from the east during *Iruvai*, and from the west during *Hulhagu*. Nodal positions of islands within the lagoon and in the northeastern and southwestern 'corners' of the atoll are more variable and are believed to reflect a combination of both the easterly and westerly conditions and southerly swell in the southwest.

The position and distribution of reef islands also shows some correlation with reef type, reef size and reef shape. In Eta atoll islands are more common on patch reefs than faros, because in the case of faros, if the locus of wave refraction happens to occur about the middle of the faro, sediments that would normally go into island building will be lost into the faro's *vilu*. In instances of islands occurring on faros, they usually are positioned at nodal points on the lee side of the reef platform, such as on Fares, Hanifaru and Nelivaru.

Reef platform size is also important and the absence of islands on the largest reef platforms in Eta atoll was noted earlier. These data are consistent with Hopley's (1982, p.352) view that islands are least associated with large reef platforms: *Probably because the wave refraction pattern does not produce the centripetal action required, but tends to spread sediment more evenly over the reef top.*

Finally, reef platform shape affects the location of the 'nodal' point as well as the initial shape of the island. This is most obviously demonstrated on the circular reef platforms where islands are frequently centrally located, their nodal position being similar to that described by Richmond (1993, p.1189) for Type I islets in the Central Pacific

9.3.4 Tropical storms and cyclones and island initiation

There is good evidence from Central Pacific atolls that 'atoll islets begin as a product of catastrophic storms' (Richmond 1993, p.1185), while on the Great Barrier Reef Gourlay (1988, p.494) has suggested that 'cyclones may initiate the formation of a cay'. Similarly, Siddique (1980) has provided evidence that islands on the atoll of Minicoy, to the north of the Maldives, have been formed by storm waves from the east.

Evidence for the role of storms in reef island initiation comes from the presence of storm ramparts and boulder tracts made up of coral rubble, blocks, cobbles and boulders torn from the reef slope and reef crest and deposited on the reef platform. Lithified equivalents of such features include boulder conglomerates and breccias. Massive reef blocks with diameters greater than 2-3m are also evidence of catastrophic storm wave activity (Scoffin 1993).

Such features are not common on Eta atoll. No reef blocks of the dimensions just described were found on the atoll, the largest being of modest size, such as those illustrated in Figure 9.1 from Maamaduvvari. Indeed, the following comment of Agassiz (1902, p.307) provides some comparative insights into the scale of Maldivian 'storm' features, including those on Eta atoll. In the Maldives Agassiz found:

The boulders thrown upon the reef flat are mere pygmies compared to the gigantic masses moved on some of the reef flats of the Pacific reefs. The boulder belts seem like a newly-macadamized road as compared to the quarry blocks... of the Pacific atolls.

But Agassiz concludes 'the same forces are at work in the Maldives only on a diminutive scale'.

On Eta atoll, most of the islands are made up of exclusively or mainly of sandy materials. However, as described in Chapter 5.4.1 coral gravel and rubble does occur on some islands, notably those in exposed locations particularly in the northeastern and southern parts of the atoll. And it is believed that storm/swell events have been responsible from the initial depositions on the islands of Kudadhoo, Kanufushee Finolhu, Kanufushee Gaathu Finolhu, Medhu Finolhu, and Ufuligili, Viligili and Maamaduvvari.

Such storm deposits which provide the core of these islands, are generally located close to the reef edge and form linear or crescent-shaped gravel

barriers, behind which finer materials have accumulated in the manner suggested by Richmond (1993) for his Type II islets.

In summary the conditions for the formation of islands in Eta atoll include a reef platform near present sea level and wave activity of sufficient competence to transport and deposit reefal sediments in nodal areas of wave convergence, or on to exposed seaward locations under storm/swell wave activity. However, it is unlikely that all reef platforms on Eta atoll reached sea level at the same time. One consequence of this could have been the operation of a local high energy 'window'. A second consequence is that not all islands will have formed at the same time with some being initiated early and some being late 'starters'. While there is good evidence to suggest that the oldest islands on Eta atoll originated over 4000 years ago, there is a lack of evidence for a higher sea level stand in the Mid-Holocene. Thus, contrary to the views of Gardiner (1903, 1931) and Sewell (1936a, b) a fall in sea level as the primary mechanism initiating islands in Eta atoll, cannot be substantiated. Instead 'nodal accumulation' and 'storm' wave activity associated with present sea level are seen as the major mechanisms.

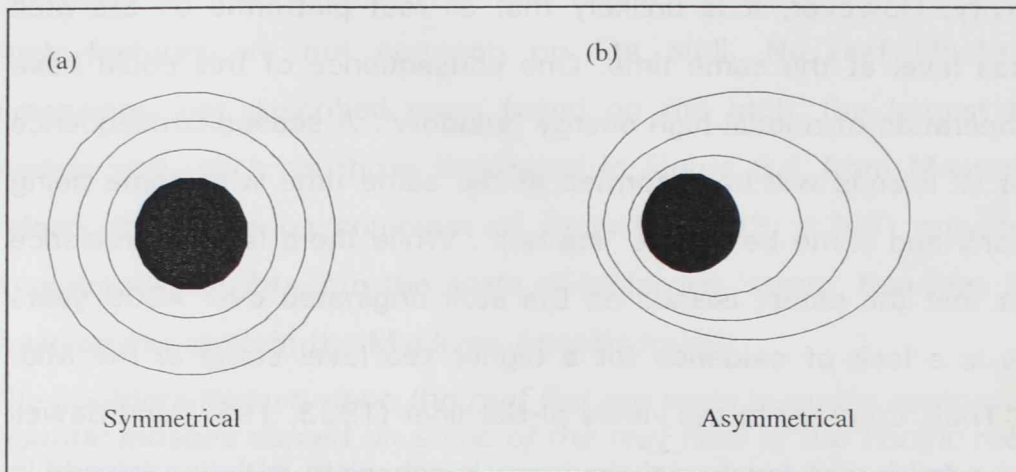
9.4 Island growth and development

Having identified the mechanisms of island formation, attention can now be focussed on how the islands have developed through time. In Chapter 8, two types of island morphodynamics were identified; island **development** through growth and change (or erosion and reduction in size over time), and island **movement**, in relation to the reef platform.

9.4.1 Island growth

With the development of islands two main modes were identified: concentric growth and lateral extension. In both instances growth can be either symmetrical or asymmetrical, as shown in Figure 9.2.

Concentric growth



Lateral growth

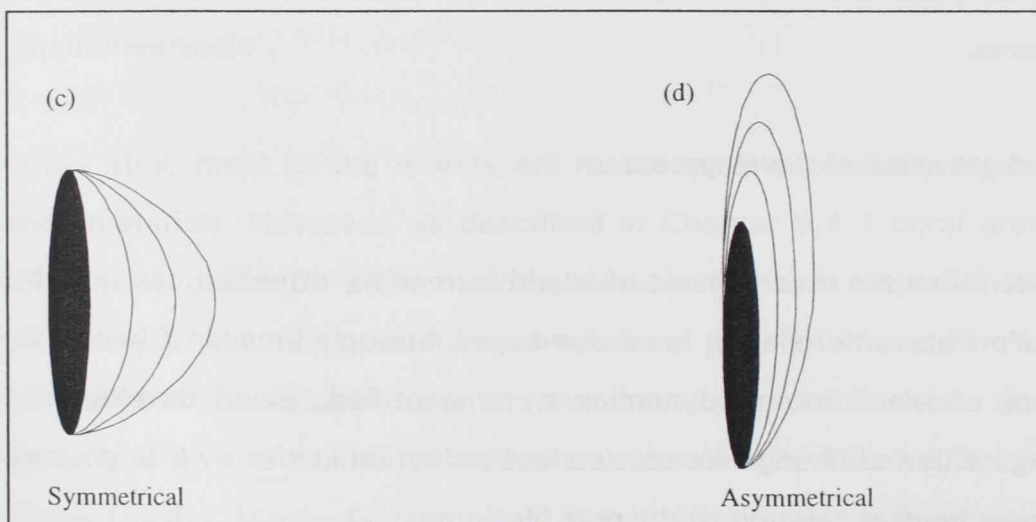


Figure 9.2 Models of reef island growth.

Concentric growth

Two types of concentric growth were identified (Chapter 8), where islands either developed in a symmetrical or asymmetrical manner from a central core. *Symmetrical* growth can be ascribed to islands such as Mendhoo, Olhugiri and Udoodhoo. Typically the reef platforms are relatively small (under 40 hectares) and circular or elliptical in outline. In some instances the island is centrally located on the reef platform e.g. Udoodhoo and Olhugiri, and in others it is located towards one side e.g. Mendhoo. Concentric symmetrical development is best illustrated by Udoodhoo, which is the only island with adequate age control. Udoodhoo is a basin-shaped island (Chapter 5), with a low central area that may have been a *barachois*. The oldest radiometric age for the atoll was obtained from the central area of the island with sediment ages getting progressively younger away from the centre (Appendix 4, p.A48). The pattern of soil development and topography is therefore suggestive of incremental accretion around this core area, with progressive berm developments of increasing height towards the shore right around the island. Udoodhoo and the other islands in this group have developed in a manner similar to the 'central core' mode of island evolution suggested by Woodroffe *et. al.* (1999).

A concentric *asymmetrical* form of growth can be identified with Gemendhoo and Aidhoo (Figure 8.5c and 8.6a). In this case incremental growth, although concentric, is uneven away from the central core (Figure 9.2b). In the case of Gemendhoo growth has occurred more to the western side of the island from the identified central core. On Aidhoo while there is a similar extension both to the west and east from the central core, the extension on the northern side is restricted. This asymmetrical growth is evident regardless of the position of the island on the reef platform, as Gemendhoo is centrally positioned, while Aidhoo is positioned to the west on the reef platform.

Lateral growth

Islands with a lateral growth pattern generally have an initial deposition on one side of the reef platform away from which the island grows laterally in a single or preferred direction in the manner illustrated in Figure 9.2c,d. Lateral growth can be either symmetrical or asymmetrical. On Maaddoo-hulhudhoo and Maamaduvvari (Figures 8.5d, 8.6c and Appendix 4) *symmetrical* island extension has taken place in a lagoonward direction from the crescentic-shaped initial coral rubble and boulder core. In the case of Maamaduvvari lateral growth lagoonwards is continuing as apparent from the 30- and 100-year changes on the island (Chapter 7.2.2, Figure 7.3g).

Lateral growth on Bodufinolhu and Muthaafushi has been more *asymmetrical* with both alongshore and leeward extension away from the central core. In the case of Bodufinolhu growth parallel with the reef passage has been greater than that to lagoonwards.

The lateral growth of these islands is akin to the 'overwash' scenario suggested by Woodroffe *et. al.* (1999), where reef flat sediments rather than lagoonal sediments contribute to the growth.

Composite growth

Although the simple models of concentric and lateral growth appear appropriate for some islands, in many instances the pattern of island evolution is more complicated and involves combinations of these models.

Two examples can be cited. On Fares the soil development pattern (Figure 8.5b) and the radiometric age of sediments (Table 8.1) suggest two modes of growth. First, that growth was more biased towards the eastern (lagoonward) end of the island in a concentric asymmetric manner. Second, the western part of the island developed in a way more akin to the lateral

asymmetrical pattern. Hibalhidhoo is the other example, where limited concentric growth appears to have taken place initially (Figure 8.5b), but is followed by lateral extension towards both ends of the island. In the case of Fares the two growth modes appear to fit the 'lagoonward accretion' and 'oceanward accretion' scenarios from Woodroffe *et. al.* (1999), while in addition to these modes Hibalhidhoo also has the 'central core' growth pattern.

9.4.2 Island movements

The previous section was concerned exclusively with island growth. In reality reef islands are subject to the short- and medium- term changes discussed in Chapters 6 and 7 and they have been subjected to those sorts of erosional and depositional changes since they were initially formed. The growth models assume a static core and subsequent accumulation around or away from that core. No movement of the island is envisaged. However, it is obvious from several examples presented earlier in this thesis that island movement does take place.

Three simple models of island movement can be proposed:

- Where the island migrates and maintains the same size;
- Where the island migrates and increases in size; and
- Where the island migrates and decreases in size.

In all cases both erosion and deposition must occur. Changes in shape may accompany any of these types of movement. Examples of the three types of movement follow.

Island migration without change in size

From the 30-year changes discussed in Chapter 7, it is evident that Maaddoo-hulhudhoo has moved away from the seaward (most exposed)

side but was able to have generally maintained a similar size and shape. The type of seasonal erosion and accretion pattern that takes place on the island (Chapter 6) indicate that sediments in the active sediment zone are moved around the island in a very dynamic manner, but with little nett change to the island itself. This may also be in part due to the nature of the material forming the 'stable' part of the island that comprises coral rubble, which is exposed under seasonal erosion conditions, and lithified cay sandstone on the northeastern part of the island.

The translocational aspect of Nelivaru has been mentioned earlier (Chapter 6) with the seasonal influences. This extreme dynamics was attributed to the lack of vegetation on the island, and also in part to the sand-sized sediments that make up the island. On other *finolhus*, like Nibiligaa which have limited vegetation cover, such dynamics was not observed.

Island migration with increase in size

Islands such as Maaddoo on the eastern atoll periphery have shown evidence of erosion on the seaward side (Chapter 7), with exposed beachrock and cay sandstone developments. At the same time, from the soil development and vegetation distribution pattern on the island, it is evident that the island has also grown and extended lagoonwards (Chapter 8). The radiocarbon data suggests that the sediments on the northeast and western parts of the island are younger. On this basis, Maaddoo appears to have increased in area concurrent with the movement from the seaward side.

Island migration with reduction in size

Numerous examples of this type have been mentioned throughout the thesis (Chapters 7,8). The best example of island migration with a reduction in size of the island is that of Ahivahfushi (Figure 7.15), where extensive beachrock bands mark the positions of a previously much larger island.

Here, the island has moved away from the exposed, seaward position on the southwestern end of its reef platform. Similarly, Kudadhoo has been reducing in size and migrating in a northeasterly direction. The island is presently positioned at the southwestern end of its reef platform. Ufuligili is migrating in a southwest direction with erosion taking place on its northeast end and the products from that erosion going into the adjacent *vilu*.

9.4.3 Erosional remnants

In addition to island growth and movement, small islands, deposits and features were identified on Eta atoll that are the remains of much larger islands. The term 'erosional remnant' used by Woodroffe *et. al.* (1999) to describe an island that is the nucleus of a once bigger island, is appropriate in these cases, although the definition should be expanded to include any remnant (e.g. beachrock) and not just the 'nucleus'.

Several examples of 'erosional remnants' can be cited. For instance Kudadhoo and Ufuligili have been eroding during the past 30 years, and perhaps even longer. In some extreme cases, such 'erosional remnants' include developments or deposits related with former islands. Such is the case of Dhoogadu Finolhu (Chapter 8), where cay sandstone developments indicate evidence of a previously much bigger island. The rubble deposition on Kudadhoo reef platform marks the position of a previous island known as Maafushee Finolhu (Figure 7.14).

9.5 Island stability and instability

Island growth, island movement and island erosion have been considered in the previous section. Examples of each morphodynamic state have been identified with an emphasis on the long-term condition. It is now appropriate to consider the magnitude of contemporary changes and recent

trends, that is changes over the short-term and medium-term, that are superimposed on the long-term condition. Such a task should assist with determining the stability of islands. The question that arises is: Can islands in Eta atoll be classified as geomorphically 'stable' or 'unstable' over the decadal time scale?

A stable reef island would be one that is subject to minimal nett change and movement. This definition accepts within it the expected short-term seasonal variations and minor episodic impacts that affect the active sediment zone (generally below high water level or the vegetation margin) that were described in Chapter 6. A stable island therefore would over the medium-term have no nett change in size, shape or position. On the other hand an unstable island would be one that is subject to nett change in size, shape or position in the medium-term, with erosion and/or accretion extending beyond the active sediment zone.

Given such definition the determination of island stability or instability over the decadal time scale involves a subjective assessment of an island's morphodynamic state as well as its morphometric characteristics and geographic location. Stability and instability are also relative concepts that can operate at several levels. Given below are three factors that are believed to be implicitly related to island stability or instability and that have been identified in earlier chapters. They involve characteristics of the reef platform on which the island is located, the characteristics of the island itself and the magnitude and direction of change as exemplified over the short and medium-term.

Reef platform characteristics

- Islands on patch reefs are generally stable while those on faros are unstable.
- Islands on small reef platforms appear more stable than those on large reef platforms.

- Islands on circular and oval (elliptical) shaped reef platforms appear more stable than islands on linear or elongate reef platforms. Cf. Gourlay (1990) '*cays on near circular reefs are generally unstable*'.
- Islands that are centrally positioned on a reef platform are more stable than those that are positioned on the edge of a reef platform

Characteristics of the reef islands.

- Large reef islands (*rah*, and *fushū*) appear more stable than small reef islands (*finolhus*), but there are several exceptions.
- Circular and elliptical islands are more stable than linear islands while elongate islands can be either stable or unstable depending on local circumstances.
- Islands that reflect the shape and orientation of the reef platform on which they are located are more stable than those that do not. Cp. Gourlay (1990) '*lens-shaped reefs produce more stable leeward islands*'.
- Islands that occupy a large proportion of the available reef platform are more stable than those that occupy a small proportion of the reef platform.
- Islands with Vegetation A through to D (Chapter 8, p.212) are more stable than islands without vegetation (*finolhu*) and islands with only Vegetation A or A and B.

Medium-term and short-term changes

- Islands on faros and particularly linear islands have been subjected to greater magnitudes of change over the 30 to 100-year time period.
- Islands on the eastern atoll periphery have migrated lagoonwards suggesting they are less stable than non-migrating islands.
- Circular and elliptical islands have been more stable than linear islands.
- Larger islands and those that occupy a high proportion of the reef flat have been more stable than others.
- Islands on the western half of the atoll have been less stable than those on the east.
- Islands with coral rubble and boulder shorelines (*huraa*) are more stable in the short-term than those comprised of sand.

Cluster Analysis (Table 5.7, 5.8)

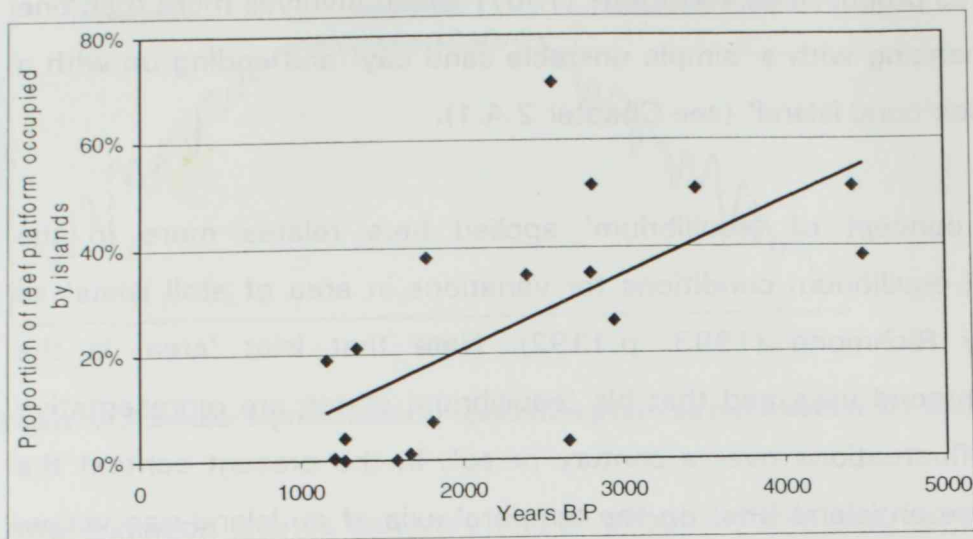
- The most stable islands are included in Cluster groups 3 and 2, while Cluster 4 includes islands that are regarded as being the least stable. Cluster groups 1, 5, and 6 contain islands that fit into stable and unstable categories.

Another indicator of island stability (or instability) is that of the age of the material that goes to make up an island. It is not unreasonable to suggest that the 'older' the island materials are, the 'longer' the island has been in existence then the more stable it is. Moreover, island age also appears to be crudely correlated with the proportion of reef platform occupied by an island as shown in Figure 9.3a, which gives the radiocarbon age of the oldest sample from an island plotted against the percentage of the reef platforms the island occupies. The latter variable is also plotted against reef platform area (Figure 9.3b) for all of the islands included in the six groups based on Cluster Analysis, the groups being determined only on the basis of absolute island size and ellipticity.

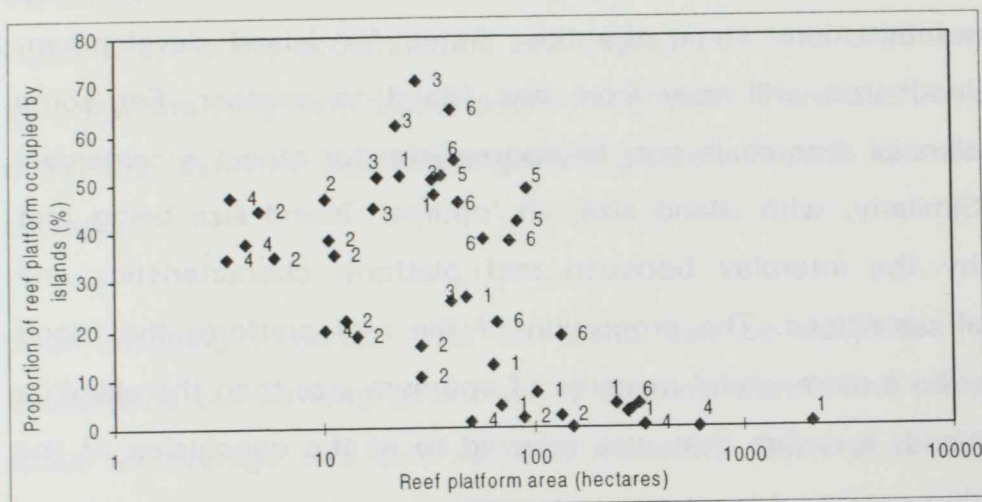
The purpose of presenting this data here is to suggest that there are two broad groupings of islands, the first that occupy an area greater than 35% of the reef platform, the second that occupy an area less than 26% of the reef platform (there are no islands between 26 and 35%, see Table 5.2). In the present context the first group of islands are regarded as 'stable'; the second group 'unstable'. Note also that the maximum reef platform area for stable islands is <100ha. Combined, these two figures (Figure 9.3) suggest that more stable islands are associated with a greater proportion of island occupation and greater age.

There are several other factors that are not included in the above list, some of which can be indicators of stability under some conditions and instability under others, beachrock and cay sandstone being good examples. Other factors such as island elevation and topography have not been included because they are so island-specific or the relationship with stability is ambiguous. Nevertheless the primary purpose of this discussion has been to demonstrate a potential use of the combined morphodynamic, morphometric and geographic results presented in this thesis. It also

provides an introduction to the concept of reef island equilibrium initially discussed in Chapter 2.7.



(a)



reached the very last stage. Each of these phases can be seen as 'equilibrium' phases, though not in the sense of an 'evolutionary succession' as proposed by Fairbridge (1967) which involves more than one island commencing with a 'simple unstable sand cay' and ending up with a more 'complex coral island' (see Chapter 2.4.1).

Rather the concept of 'equilibrium' applied here relates more to the 'hypothetical equilibrium conditions for variations in area of atoll islets' as proposed by Richmond (1993, p.1192). Note that islet 'area' is the measure Richmond uses and that his 'equilibrium states are representative of temporal fluctuations over a century or so'. In the present context the position where an island 'fits' on the temporal axis of an island-size versus time plot is relative, each island having a unique starting point, that is the time of island initiation. Thus, the time frame for island development (changing island size) will vary from one island to another. For some islands, a millennial time scale may be appropriate; for others a centennial time scale. Similarly, with island size, an 'optimal' island size being that determined by the interplay between reef platform characteristics and environmental conditions. The proportion of the reef platform the island occupies may be a more useful measure of optimum size than the absolute area of an island, a notion that was referred to at the conclusion of the previous section.

Theoretically the following three equilibrium phases can be identified (Figure 9.4):

- dynamic growth phase
- steady-state phase
- dynamic degenerative phase.

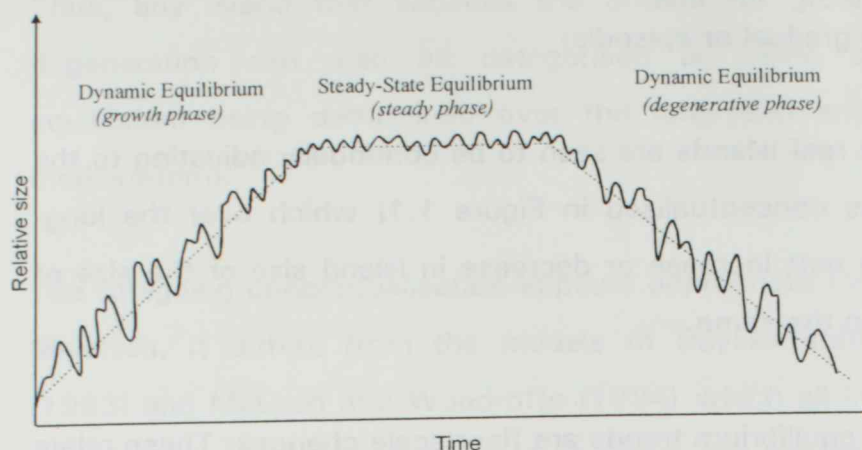


Figure 9.4 Schematic representation of equilibrium phases on reef islands in Eta atoll.

After initiation islands can vary in size about a mean and increase in area over time. This condition is the 'dynamic equilibrium' of Richmond (see Figure 2.8). Island accumulation and degradation is in a constant state of flux, but the long-term trend is one of growth. Here such a condition is called the 'dynamic equilibrium growth phase'. Growth can be gradual or episodic.

Upon reaching a certain size an island can be subjected to constant fluctuations but no long-term trend is evident, that is the island oscillates about an average size that remains constant. Such a condition can be described as 'steady-state equilibrium' as defined by Richmond (1993) and suggested by Bayliss-Smith (1988) as an appropriate term for the 'equilibrium' situation described by Stoddart and Steers (1977) (see Chapter 2.7). Islands that have reached an 'optimum' size in proportion to their reef platform would satisfy the steady-state criteria.

The third phase, like the first, has the island eroding and accreting, in the manner of 'dynamic equilibrium', but in this case the long-term trend is one of degradation and not growth. As Hopley (1982, p.352) has pointed out: *If an evolutionary sequence does exist for reef islands, a degenerative phase of cay erosion may be the last stage of development.* Thus, the

third phase is called 'dynamic equilibrium degenerative phase'. Degeneration can be gradual or episodic.

In all three instances reef islands are seen to be continually adjusting to the controlling forces (as conceptualised in Figure 1.1) which over the long-term may result in a nett increase or decrease in island size or the size of the island may remain the same.

Within the long-term equilibrium trends are finer scale changes. These relate to island stability and instability as defined in the previous section. For instance, criteria for islands in steady-state equilibrium phase would be that they:

- occupy a large proportion of the reef platform (i.e. they would be of 'optimal' size);
- possess sediments that indicate incremental growth up to a certain time and then no nett change subsequently;
- have soil and vegetation characteristics that suggest 'maturity'.

Steady-state criteria may, however, apply to two quite different types of islands in terms of their stability. One island may have undergone minimal change over the last 100 years, seasonal sediment movements are in balance and there is no evidence of island movement (such as may be indicated by fossil beachrock outcrops). These characteristics suggest the island is in steady-state equilibrium and is stable. The other island may have evidence of considerable island movements, both in terms of beachrock exposures as well as historical data over the last few decades, and seasonal sediment movements may not be in balance. Nevertheless the island has remained about the same size that is, there is no nett growth trend, nor nett degeneration. These characteristics suggest that the island is in steady-state equilibrium but is unstable.

Thus, any island that satisfies the criteria for growth, steady-state or degeneration can also be categorised as being stable or unstable; equilibrium being determined over the long-term and stability over the medium-term.

The foregoing conceptualisation appears appropriate for sand islands in the Maldives. It differs from the models of Bayliss-Smith (1988) Richmond (1993) and McLean and Woodroffe (1994) which all include the impact of catastrophic storms having both destructive and constructive effects. In the Maldives unusual storm/swell events do not appear to have the catastrophic geomorphic impacts that they do elsewhere. Here island size changes resulting from such events may fall within the amplitude of short-term variations in island size as indicated by oscillations in Figure 9.4.

It is also important to reiterate that;

- the time and island-size scales are relative; and that
- the steady-state condition may not be reached (for instance in a situation where an incipient island, with potential growth capability, is eroded away).

While it is not possible to determine the equilibrium/stability status of every island in Eta atoll at present, the data in the substantive chapters (Chapters 5-8) together with the analysis in this chapter suggest that several islands have reached the steady-state equilibrium condition (e.g. Olhugiri, Udoodhoo). Critical to this assertion is the persistence of the islands over the last 1000 years, (the timing based on the radiocarbon dates) and the fact that a number of islands appear to have reached their 'optimal' size (based principally on the proportion of the reef platform the island occupies). Examples of other islands in the two dynamic equilibrium states include Maamaduvvari and Hibalhidhoo in the growth category and Kudadhoo and Ufuligili in the degenerative category. In the first instance

historical, geomorphic, vegetation and soils data together with radiocarbon dating results show that the islands have been growing over the long- and medium-terms. And in the second instance, an assessment of the same type of data indicates that they have been eroding over a similar period.

Two other points can be made in conclusion. First, it is evident from the foregoing analysis that there would be considerable variation in the equilibrium and stability status of islands around Eta atoll. And second, that there is likely to be groupings of islands that satisfy similar equilibrium and stability criteria. An expansion in the number of variables used in the Cluster Analysis (see Chapter 5.6) to include (a) reef platforms type; (b) island age; and (c) proportion of reef platform occupied by an island, may well provide sufficient data to determine meaningful equilibrium groupings of islands in Eta atoll.

CHAPTER 10

Conclusions and applications of the study

10.1 Introduction

The broad aim of this thesis was to examine the geomorphology of reef islands in Eta atoll. It included identifying the mechanisms of island initiation and the morphodynamics of the islands at three different time scales: long-term, medium-term and short-term. An essential component of the study was to determine the geographic, geomorphic and geologic characteristics of the islands and how they relate to the locational and environmental factors of the whole atoll, and whether those factors had any role in the morpho-development of the islands. Emphasis in the research was directed towards understanding the variable character and morphodynamics of islands in the atoll as a whole. It was not focussed on just one or two islands in detail. Thus the research involved field measurements, observations and analysis of some 50 uninhabited islands in Eta atoll, an atoll that has been shown to be typical of the 'open-atoll' type that is so characteristic of the Maldives, but so unusual elsewhere.

The major findings of the research are given below, with reference to the four primary objectives of the thesis outlined in Chapter 1, p.15.

10.2 Summary of major findings

10.2.1 Objective 1: Island characteristics

The first objective of this study was:

To describe the geomorphic characteristics of the islands in Eta atoll (Maldives) and to relate those characteristics to the nature of the underlying reef platform and to identify any spatial patterns in island and reef characteristics around the atoll.

Following an analysis of the latitudinal variations and characteristics of the atolls in the Maldives, three types of atolls were identified; 'open', 'closed', and 'table reefs'. Eta atoll represents the typical 'open' atoll type. It comprises about 90 separate reef platforms. Of these 35 are located on the periphery of the atoll and 55 in the lagoon. Fifty-six percent of the reef platforms have islands.

The islands of the atoll were classified on the basis of vegetation (presence/absence), sediment calibre and relative size. They consist of:

- *rah*, large island generally with sandy sediments, and 'mature' vegetation;
- *fushi*, smaller island generally with sandy sediments and vegetation;
- *huraa*, coral rubble island with vegetation;
- *huraagandu*, coral rubble island without vegetation;
- *finolhu*, sandy island without vegetation.

The islands occur on two types of reef platforms, patch reefs and faros (ring-shaped reefs with *vilu*). The distribution of islands on these two types is different. Seventy-two percent of islands are located on patch reef platforms, 28% on faros. Sixty-two percent of the islands are located on the atoll rim (peripheral) while 38% are lagoonal (located inside the atoll).

Most reef platforms with islands (92%) have only a single island, and three of the four reef platforms with multiple islands are peripheral.

In Eta atoll, more islands occur on the eastern half and in particular on the eastern periphery. Although the easterly monsoonal conditions strongly affect the eastern side of the atoll, westerly conditions exert a greater influence over the rest of the atoll. This is evident first in the unequal distribution of islands on the eastern and western sides, a fact first recognised by Gardiner (1903) who believed the E-W difference was due to exposure to strong winds and seas from the west. Second, islands in the eastern half of the atoll are positioned on the west of their reef platforms, and islands on the western half, including many central lagoonal islands are positioned to the east. This fact demonstrates the 'openness' of the atoll, and the extent to which wave energy can penetrate into the atoll's lagoon. It also demonstrates the dominance of the westerly monsoon over the easterly.

The size (area) of islands range from 0.1 to 45.5 hectares. Mean island size is 9.72 ha, but 31 islands have areas less than the mean value. The smallest eight islands (<1ha) occur on reef platforms that are more than 50ha. The largest reef platforms, which occur on the western periphery of the atoll, do not have islands.

The shape of islands was determined quantitatively using an ellipticity index. Four shapes were identified: 'circular', 'elliptical', 'elongated', and 'linear'. The majority (48%) of the islands in Eta atoll are elongated, 25% are elliptical, 19% circular, and only four islands (7%) are linear. The majority of islands are also oriented in a northwest-southeasterly direction. Both island shape and orientation are strongly influenced by the shape and orientation of the underlying reef platform.

Three island surface forms were identified. A simple 'convex ridge-form', which is associated with the smallest islands and *finolhus*. 'Basin-shaped' islands with a distinct depression in the centre, and a relatively high ridge around the perimeter, are typical of the circular to elliptical islands. 'Complex form' islands typically have either a prominent ridge on one side and a relatively gentle decline to the opposite side, or have an undulating topography throughout.

The islands are made up of two main types of material: unconsolidated sediments (which make up bulk of the islands), and lithified 'rocks'.

The unconsolidated island materials are:

- Predominantly sand-sized sediments;
- Exclusively bioclastic and made up of fragments of coral, *Halimeda*, molluscs and *Foraminifera*, derived from the adjacent reef;
- Texturally distinct from the reefal material in being better sorted and finer grained.
- Occasionally coral rubble, cobbles and boulders, which occur on a few islands, located in exposed locations.

Lithified 'rocks' are present on most islands. The most common is beachrock, which occurs either as detached outcrops (indicating previous beach position(s)), or incorporated within the present-day beach. Cay sandstone (*aanu*) is found quite extensively on the 'older' islands, particularly those on the atoll periphery. Phosphatic rock was found only on one island. Beach conglomerate is rare.

Results from measurements of 53 islands and reef platforms showed that the average proportion of reef platform occupied by islands is 28%. Two modal classes (<10% with 21 islands, and 9 islands with 41-50%) occur. Eight islands occupy more than 50% of their reef platforms, and highest being 71%. Reef platforms with more than one island occupy <5% of the

platform. Most islands on patch reefs occupy a greater proportion of the reef platform; those on faros typically occupy less than 5% of the faro area.

Most of the reef island characteristics including island size, shape, orientation, proportion of reef platform occupied, topography, elevation, and sediment calibre and type can be explained in terms of exposure conditions and energy level (often simply by their location, being east or west, peripheral or lagoonal), and by the type of reef platform (faro or patch reef), and its characteristics (size, shape and orientation).

10.2.2 Objective 2: Island initiation

The second objective of this study was:

To establish the mechanism(s) of island initiation and the approximate age of island formation

The present-day atolls in the Maldives are the result of carbonate deposition on a submarine volcanic foundation (dated at 57 million years) which is now at depths of over 2000m. Successive periods of emergence and subaerial erosion of the carbonate banks and submergence and coral growth has occurred throughout the last 50 million years or so, the most recent phase being sea level rise from the last glacial maximum low (-130m) in the past 20,000 years. There is little evidence to suggest that the Maldives archipelago was formed in the classical Darwinian manner of fringing reefs, barrier reefs, and atolls.

Based on the morphological and stratigraphical features constrained by radiocarbon dating of island sediments, it appears that the first islands formed about 4500 years B.P. It is assumed that at that time some reef platforms had reached sea level and were capable of supporting islands.

Three mechanisms were identified as being responsible for initiating islands in Eta atoll. First, 'nodal accumulation', where sediments accumulated at a locus on a reef platform, or in the lee of a rubble/gravel deposition. Second, by unusual or episodic storm or swell events that may have deposited rubble/gravel barrier on a reef platform, behind or around which sand-sized sediments later accumulated. And third, and a more uncertain mechanism, may have been the operation of a local high-energy 'window' particularly for lagoonal islands. These mechanisms are likely to have worked either individually or in combination, to initially form the islands. Evidence for a fall in sea level (emergence) as an initiating mechanism for islands in Eta atoll is lacking.

Analyses of radiocarbon dates for 20 islands suggest there were at least three phases of island initiation on Eta atoll. An early phase from 4500 to 3000 years B.P, which included at least four islands. A second phase centered around 2400 years B.P. And a third phase extending from 1850 to 1050 years B.P. The radiocarbon data also suggest that most of the present day islands (for which C^{14} results are available) were already in existence over a thousand years ago.

10.2.3 Objective 3: Island morphodynamics

The third objective of this study was:

To identify island growth and development patterns over the long-term (centennial to millennial time scales) and to examine the extent and magnitude of changes that occur on islands over the medium-term (decadal to century time scale) and short-term (yearly and episodic event scale).

Once formed, islands may have expanded and developed. Two main modes of growth have been identified: concentric growth and lateral extension, the former being particularly associated with circular and elliptical islands on smaller patch reef platforms. Lateral growth in a lagoonward direction is

common on the elongated reef platforms on the eastern margins of the atoll. In both instances growth could be either symmetrical or asymmetrical away from the island's initial core.

In addition to island growth, there is good evidence to show that island movements have taken place. The most common type of island movement was in a lagoonward direction through erosion of the most exposed side and accumulation to leeward. 'Trains' of detached beachrock outcrops on some islands also indicate significant movements, and suggest that beachrock does not necessarily 'anchor' islands at their original site.

Earlier, three phases of island initiation were identified. During these phases island growth and extension also took place. The radiocarbon dating results and topographic and soil evidence suggest that some island building took place during the second phase (centered around 2400 years B.P), though the third phase (particularly around 1550 years B.P) was primarily associated with island growth and extension. Although limited to four present day beach and *finolhu* samples, the radiocarbon results suggest there has been little new island building in the last 1000 years.

There is also limited data to determine changes over the last several decades. Where possible baseline surveys carried out by Gardiner on a few islands on Eta atoll in 1899 were compared with 1969 and 1999 aerial photographs which were also used for comparative mapping purposes. Results showed no overall Eta-wide trends and that both the magnitude and direction of change varied between islands from virtually none to up to 200m of erosion and accretion. Some islands that were 'washing away' 100 years ago have continued to erode; others have accreted. However, what did become apparent was that the magnitude of changes were:

- greater on islands with sandy shorelines than on islands composed of coral rubble or boulders;
- greater on linear and elongated islands than on circular and elliptical islands; and
- greater on islands on faros than on patch reefs.

Short-term morphodynamic changes resulting from the seasonal reversal of wind-generated waves (and currents), mainly impact the active sediment zones on the islands. While gross changes may be large, the nett effects on islands appear limited. Three types of erosion and accretion patterns were identified:

- On small (less than 200m in diameter) and circular islands, which usually occupy a high proportion of their reef platform (35-44%), sediments are moved between the eastern and western parts of the island (circulating).
- On larger islands (but still under <4 ha), sediment movements take place only around the lagoonal half of the island (semi-circulating).
- On larger elongated and all linear islands, sediments inflect one way during one season and another way in the next, either at one or both end(s) of the island (oscillating).

Eta atoll is subject to both externally and locally generated swell and storm events. Data on the frequency and nature of such events is limited but the analysis carried out in this thesis suggests that the impacts are highly variable and localised and appear to bear little relationship to island size, shape and location. Both erosional and depositional impacts have been cited, though the magnitude of such changes appears more subdued than the catastrophic storm impacts on atoll islets reported elsewhere.

10.2.4 Objective 4: Applications of the findings

The fourth objective of this study was:

To outline possible applications of the findings for: (a) vulnerability assessment studies; (b) management and strategic planning purposes; and (c) future research.

Implications of findings for vulnerability assessments

Although the primary purpose of this research was not to assess the vulnerability of Eta islands to climate change and sea level rise, the study has nevertheless identified some factors that should be taken into account in any vulnerability assessment of reef islands in the Maldives.

Virtually all vulnerability assessments require data on 1) the characteristics of the natural system in the study area and, 2) possible impacts on the natural system, before making an assessment of vulnerability. Two examples can be cited. In the Common Methodology developed by the Intergovernmental Panel on Climate Change Coastal Zone Management Subgroup (IPCC CZMS 1992) these data are required for Steps 2 (inventory of natural systems) and 4 (quantification of physical changes and natural system responses). Similar natural system data are required in the conceptual framework for coastal vulnerability assessment developed recently by Klein and Nicholls (1999), where analysis of coastal vulnerability starts with a notion of the natural system's susceptibility to the biogeophysical effects of climate change and sea level rise, and of its natural capacity to cope with those effects (resilience and resistance).

However, data on natural system characteristics and biogeophysical responses are rarely available for atoll states and reef islands and this has resulted in a tendency to generalise about the vulnerability of all reef islands, such as:

...low lying coral islands will become uninhabitable with a sea-level rise of 0.5m or less... (Wilkinson 1996, p.555)

Such comments are often not based on any understanding of the diversity of reef islands or their morphodynamics, both of which need to be acknowledged in the vulnerability context.

For instance, the present research has confirmed that the islands of Eta atoll are small, are of low elevation and are mainly composed of unconsolidated sandy reefal sediments. There is no question that such islands are amongst the most vulnerable environments in the world to climate change and sea level rise, but whether they 'will become uninhabitable' is another question. Indeed, the proper question is: are all reef islands in the Maldives equally vulnerable? Based on the results of the present research the answer is likely to be no.

When vulnerability assessments of islands in the Maldives are carried out there should be some consideration of the conclusions of this research. For instance it is quite evident that island vulnerability would vary according to:

- The location of islands on the atoll (e.g. eastern or western sides; lagoonal or periphery);
- The nature of the reef platform (e.g. patch reef or faro; large or small reef platform);
- The size and shape of the island (e.g. large or small, circular or linear);
- The proportion of the reef platform occupied by an island (e.g. <10% islands unstable, >50% islands stable);
- Island elevation and topography (e.g. importance of height and continuity of marginal ridge in relation to wave-overtopping; basin-shaped islands more susceptible to flooding and saline intrusion than complex or dome-shaped islands);
- The nature of island sediments (e.g. islands with coral rubble more resilient than islands with sandy sediments);

- Presence/absence and location of lithified rocks (e.g. beachrock as indicator of shoreline erosion or of shore protection).

These few examples reinforce the view that all reef islands are not equally vulnerable and any assessment methodology should acknowledge that fact. Vulnerability will vary according to a number of factors, including the geographic and geomorphic properties of islands, which are emphasised above. It also confirms the earlier statement by Nurse *et.al.* (1998) and reproduced in Chapter 1 page 14 that lists nine 'internal' factors that will help determine how islands will respond to climate change and sea level rise. Reference should also be made to Chapter 9.5 which identifies some criteria that were used to distinguish 'stable' from 'unstable' islands in Eta atoll, and that could be used as 'guidance' in any vulnerability assessment undertaken in the Maldives.

Application of findings for management and strategic planning

Over a decade ago Pernetta and Sestini (1989) identified a number of current and prospective environmental problems in the Maldives. These they saw resulted '*in the large part from the high population density (650/km²) which is aggregated on to relatively few islands within each atoll*' as well as from '*unsound development*' which had '*been recently highlighted by the impacts of storm generated long distance swells which caused widespread flooding of reclaimed areas and weakening and/or destruction of coastal structures*'.

Problems that they listed relate to the:

- construction of coastal infrastructure including seawalls, jetties, breakwaters and harbours;
- land reclamation around islands;
- live coral mining;
- coastal erosion;

- tourist resort developments.

Similar problems exist on Eta atoll. For example, sand mining from the 'active sediment zone' is a common practice on many islands, reef flats have been reclaimed at Eydhafushi and Thulhaadhoo, harbours have been dredged at Dharavandhoo and Eydhafushi; tourist resorts have been developed on migrating islands (e.g. Fonimagoodhoo) on small patch reefs (e.g. Horubadhoo) and on small islands on faros (e.g. Dhunikolhu).

In all these instances problems have resulted or are anticipated in the form of accelerated coastal erosion, reductions in the protective and sediment-producing ability of reef platforms and increased maintenance and operation costs.

As Pernetta and Sestini (1989, p.2) have pointed many projects have gone ahead *'without prior investigation of local current patterns and patterns of erosion and deposition [which] not only increases their vulnerability but also the total capital investment which is at risk'*.

From this discussion it is evident that for island planning and management purposes there are some conclusions from this thesis that should be acknowledged. For instance there needs to be recognition that:

- The source of sediments for island building and accretion is from the adjacent reef and changes to the reef affect the island (see Figure 1.1).
- There is an 'active sediment zone' around each island (see Figure 3.10) that fluctuates horizontally by about 10-50m under normal circumstances during the year. Any disturbance to this zone will affect stability.
- The seasonal reversal of monsoonal conditions results in erosion, accretion and longshore sediment movements. Three patterns were

identified: Circulating, semi-circulating and oscillating, each of which was associated with a particular size/shape island.

- Islands on faros are more unstable than those on patch reefs. Permanent settlements on such islands would need to accept that protection and mitigation measures would be ongoing; proposals for new settlements on such islands may need to be reviewed.
- Islands undergo different equilibrium phases (growth, steady and 'degenerative') during their development. Normally greater changes occur in the growth and degenerative phases, than in the steady phase.
- Some islands have migrated towards the lagoon as a result of erosion on the more exposed side and accumulation to leeward on several islands. This process is continuing (e.g. Maaddoo, Kunfunadhoo).
- Few studies have been carried out on reef island morphodynamics and very little data and information is available for making 'informed' decisions about the future of the islands. Hence there is a need to undertake such studies and recognise their significance and role in strategic planning and management.

Implications of the findings for future research

The basic aim of this thesis involved a geomorphological examination of islands in Eta atoll and the development of models of reef island morphodynamics. This aim has been achieved. The geomorphological examination has identified the manner by which the islands were initiated and when, as well as how they subsequently developed. Models of island growth have been presented. An atoll-wide geochronology was developed that identified three main phases of island building. The more recent history of the islands over decadal to centennial scales was explored together with an assessment of seasonal and episodic-event changes. Relationships between geographic (locational), reef island and reef platform morphometric properties and morphodynamics were also established.

In spite of satisfying the primary objective of the research, this thesis has raised a number of questions that could be the subject of future research.

Sea level history. This study has not been conclusive about the role of sea level in reef platform and island formation. Although no evidence for a higher sea level was found, the timing of the earliest phase of island initiation on Eta atoll (over 4000 years B.P) coincides with a time when sea level was higher in many parts of the Pacific and Indian Ocean including Cocos (Keeling) Islands. Clearly there is a need to develop a Mid- to Late-Holocene sea level history of the region. Shallow drilling and stratigraphic studies are proposed for five islands on a north-south and east-west cross section of Eta atoll. These islands include: Funadhoo/Udoodhoo in the north, Mendhoo in the centre, Olhugiri/Maamaduvvari in the south, Hibalhithoo/Kunfunadhoo on the east and Fares on the west. Results from radiometric dating of core samples, reef platform surfaces and the basal sediments of reef islands at the five sites should enable a sea level history to be developed. Two other questions raised in this thesis could also be answered: that of a time lag between reef platform formation and island initiation; and the role of a high energy 'window' in island formation.

Phases of island building. The present study has indicated that for Eta atoll as a whole there have been three main phases of island initiation and island building. Whether these phases are applicable at an individual island level is uncertain, and this needs to be determined. Intensive morphostratigraphic and geochronologic investigations of several islands is required. Such a project should be undertaken at the same sites as suggested above, and the results would also serve to (a) establish whether the islands have accreted in a regular or episodic and (b) whether the simple island growth models suggested in Chapter 9.4.1 are valid or not. Alternative models may be developed.

Role of storms. Although the Maldives are not within a region of tropical cyclone (hurricane/typhoon) generation and are regarded as being relatively storm-free, this thesis has indicated that episodic storm and swell events do impact islands and reef platforms in Eta atoll. But the extent of those impacts and their role in island initiation and development remains rather ambiguous. More careful historical and archival research of records, both of events and impacts during the last 150 years is required. Additionally more detailed studies are needed of the nature, location, extent and age of coral rubble, boulder and block deposits on islands and reef platforms. Possible islands for this study could be Aidhoo/Maaddoo on the east and Maamaduvvari/Olhugiri in the south of the atoll.

Present reef platform sediments. A surprising result from the radiocarbon dating of contemporary beach deposits and *finolhu* (unvegetated sand islands) is that the ages are not modern, but rather they range from 920 to 1610 years B.P. While only five samples have been dated from these active environments (on four islands) the results raise the possibility that the present day reefal sediments comprise a mixture of both fossil and modern material, with a high proportion of the former. Note also that no sample from a vegetated island had a C^{14} age less than 1050 years B.P. An investigation of present day reefal sediments, including absolute dating of bulk samples and individual grains should shed some light on present day sediment production and reef productivity. A comparative study of an island that occupies a high proportion of the reef platform such as Maaddoo-hulhudhoo compared with a small island on a large reef platform like Nibiligaa could be conducted.

In addition to those suggested above, other related studies at a more island-scale level include:

- Comparative mapping of the 1969 and 1999 aerial photographs of the islands, with attention to higher resolution mapping of both reef and shore environments, using GIS technology.
- Selected island-wide studies of the seasonal erosion and accretion patterns representing the three types identified (circulating, semi-circulating, and oscillating), to be conducted on both lagoonal and peripheral islands over several years.
- Estimating the 'optimal' proportion of reef platform islands can occupy under 'normal' and higher energy conditions.
- Identifying potential sediment sinks on reef platforms that could be remobilised with enhanced energy conditions;
- Utilising the findings of this study as a baseline, the magnitude and extent of human impacts on island morphodynamics evident on inhabited islands.
- Given the consequences of climate change and sea level rise, a socio-economic/geographic study on resettlement experiences and issues for strategic planning considerations.

Stimulating these and other related studies/research would not only go a long way redressing the void in knowledge on the islands in the Maldives (Chapter 1.4), but provide better understanding of reef islands and their interrelationships with the boundary conditions specified in Chapter 1.3.

Hence, this study was carried out specifically in the belief that there is a need to understand reef island morphodynamics and that such understanding will assist in the sustainable planning and management of the islands in the Maldives. The future of these islands and their ability to continue providing for the benefit of their inhabitants depends to a large extent on the application of that understanding in the future planning and management of the islands.

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APPENDIX 1

Previous geomorphology-related research in the Maldives

This appendix presents some notes on relevant geomorphology-related work that has been carried out in the Maldives. As Stoddart (1966, p.2) observed in the mid 1960s that: *Several large expeditions have visited the Maldivian Islands reefs, yet paradoxically they remain one of the least known groups of atolls.* In relation to this observation, Woodroffe (1993) is of the opinion that little has changed even in the last 30 years.

The first detailed scientific account of the islands was made in the 19th Century, by Captain Moresby. With Lieutenant Powell and Riddel, he conducted extensive soundings, surveyed many islands and chartered the waters of the Maldives between 1834-37. Results of this work became the basis for the Hydrographic Charts published by the British Admiralty.

Although Darwin never visited the Maldives, he obtained detailed information on the geography, geology and geomorphological features and processes about the islands, from Moresby (see Darwin 1842). It was from Moresby's work that his theory of atoll formation (with reference to the Maldives) was promulgated. The origin of the ring-formed reefs (Darwin 1842) or faros (Gardiner 1903) was of particular interest and fascination for him. Darwin (1842 p.37) also postulated on the morphological development of Eta atoll as part of his account of Maalhosmadulu Atoll as well.

In 1899 Stanley Gardiner, a biologist from Cambridge University, undertook the most comprehensive biogeomorphological study of the Maldives to date and in particular of the study site. On his visit, Gardiner described the geomorphology and other salient features on almost all the islands of Eta atoll. Extensive dredging and marine biological sampling throughout the Maldives was carried out. Alexander Agassiz followed visiting the Maldives

in late 1901 to early 1902 while working on his theory of atoll development. During this time he visited most of the atolls in the Maldives, from Addu (ψ) in the extreme south to Ihavandhippolhu (α) in the extreme north.

The John Murray Expedition of 1933-34 led by Sewell visited the Maldives in March and April 1934, to study Goidu Atoll (K), including changes since Gardiner's work, and gravity surveys were conducted on four other islands in Eta atoll (Sewell 1936b). In addition, this expedition visited Addu Atoll (ψ), to describe the changes there since Gardiner's visit (Sewell 1936a).

Twenty years after Sewell's visit, Fosberg visited the southern Maldives and documented the vegetation there and in Male' (Fosberg 1957; Fosberg Groves and Sigee 1966), followed by The Yale Seychelles Expedition or 'Xarifa Expedition', led by Hans Hass in 1962. Hass (1962) proposed the 'central subsidence' theory of atoll formation, after observations from the Maldives. In 1964, Stoddart led an expedition to Addu Atoll (ψ), the southernmost atoll. Here detailed studies of reefs, corals, sediments and vegetation types were undertaken (Stoddart 1966; Davies *et al.* 1971). Cousteau's research vessel *Calypso* came to the Maldives in 1967 and for the first time conducted underwater observations. Evidence of subaerial reef exposure of surfaces now some 50-60 m below water was described (Cousteau and Dirole' 1971).

A set of aerial photographs of the entire Maldives was taken by the Royal Air Force in 1969, which were used for revising the navigation charts and now serves as a good basis for comparative and other relevant studies of the islands. The same year, extensive studies of corals in Ari Atoll (Ξ) were conducted by Scheer (1969, 1971, 1974), which resulted in identifying new species of corals and extended his concept of phytosociology species associations of corals, based on work conducted in Rasdu Atoll (ν).

The subsurface geology was investigated for the first time by the Deep Sea Drilling Project in 1972. In 1974 a French petroleum company, sank an industrial multichannel seismic well in North Male' Atoll (λ) to 47m depth, as part of a drilling operation prospering for oil. In 1990, under the Ocean Drilling Project, on Leg 115, two sites were also drilled in the northern part of the Maldives. The combined results enabled an understanding of the sedimentation patterns and rates, the type of environment, geochronology and other information on the platform on which the islands occur (see Kidd and Davies 1978; Droxler *et. al.* 1990; Duncan and Hargraves 1990; Malone *et. al.* 1990; Aubert and Droxler 1992; Purdy and Bertram 1992).

A detailed soil and water quality study of the islands in the Maldives was undertaken by Butany (1974) to assess the agricultural potential of the islands.

Table A1.1 lists some of these general works and contributions from expeditions and individual workers up until 1980s.

Table A1.1 Major geomorphology-related work undertaken in the Maldives.

Year(s)	Expedition/ worker(s)	Contribution
1834-37	Moresby	Soundings, surveyed many islands and chartered the waters of the Maldives.
1899	Stanley Gardiner	Biogeomorphological study of the Maldives.
1901	Agassiz	Geomorphology and other salient features on islands of Eta atoll. Dredging and marine biological sampling throughout the Maldives. Worked on his theory of atoll development.
1934	John Murray Expedition led by Sewell	Changes on Goidu Atoll ($\bullet$), and Addu Atoll ($\bullet$), since Gardiner's visit. Gravity surveys in Eta atoll.
1957	Fosberg	Vegetation study.
1962	'Xarifa Expedition' led by Hans Hass	'Subsidence' theory of atoll formation.
1964	Addu Atoll (ψ) expedition led by Stoddart	Accounts of reefs, corals, sediments and vegetation types.
1967	Cousteau	Underwater observations and accounted glacial sea level fall evidences.
1969	Scheer	Phytosociology associations of corals species in Ari Atoll (Ξ).
1972	Deep Sea Drilling Project	Submarine subsurface geology of reef platforms.
1974	Butany	Soil and water quality assessments.

In addition, from the 1980s, several workers have conducted very specific environment-related studies in the Maldives. Purdy (1981) studied the evolution of the Maldives with particular attention to the local variations of atolls and the nature of reef development.

With the projected consequences of sea level rise, the Government of Maldives initiated a few studies at the macro level. Most of these studies were aimed at a policy or management level (e.g. Edwards 1989; Woodroffe 1989).

Reef studies, particularly associated with environmental problems, were conducted too (see Brown and Dunne 1988; Edwards and Clark 1992; Clark and Edwards 1995). Woodroffe (1993) conducted radiocarbon dating of Holocene material for the first time. These results are presented in Table A1.2.

Table A1.2 Radiocarbon datings undertaken in the Maldives on λ , τ , χ and ψ atolls

ANU Lab no.	Coral Material	Atoll	Location	Elevation Depth(m) w.r.t MSL	Conventional radiocarbon age (yrs. B.P)	Environmentally corrected radiocarbon age ¹
6861	Faviid	λ	Conglomerate exposure on reef flat near Huraa	+0.5 $\pm$ 0.2	1160 $\pm$ 70	710 $\pm$ 80
6862	<i>Acropora</i>	ψ	1.5m depth in pit in centre of Feydhoo	-0.5 $\pm$ 0.2	3600 $\pm$ 80	3150 $\pm$ 85
6863	Faviid	τ	boulder conglomerate beach on south side of Veymandoo	+0.8 $\pm$ 0.3	2300 $\pm$ 70	1850 $\pm$ 80
6864	<i>Heliopora</i>	ψ	In situ reef exposed by sand erosion on Feydhoo	0.0 $\pm$ 0.3	3160 $\pm$ 80	2710 $\pm$ 85
7166	sand	χ	0.9m depth in pit in centre of Foammulah	0.0 $\pm$ 0.3	1620 $\pm$ 160	1170 $\pm$ 165
7167	sand	ψ	1.5m depth in pit in centre of Feydhoo	-0.5 $\pm$ 0.2	5730 $\pm$ 90	5280 $\pm$ 95
7748	Faviid	λ	1.2- 1.3 in borehole for harbour extension	-0.8 $\pm$ 0.5	3710 $\pm$ 70	3260 $\pm$ 80
7749	Faviid	λ	5.8m in borehole for harbour extension	-5.3 $\pm$ 0.5	4140 $\pm$ 70	3690 $\pm$ 90
7750	<i>Acropora</i>	λ	11.2m in borehole for harbour extension	-10.7 $\pm$ 0.5	5620 $\pm$ 110	5170 $\pm$ 115
7751	<i>Acropora</i>	λ	17.7m in borehole for harbour extension	-17.2 $\pm$ 0.5	6410 $\pm$ 110	5960 $\pm$ 115

Source: Woodroffe (1993)

¹Environmental correction for ocean reservoir effect of minus 450 $\pm$ 35 years following the correction for marine shell adopted by Gillespie and Polach (1979).

From the numerous works undertaken in the Maldives, those of particular relevance to this study include Darwin (1842), Gardiner (1903 and 1931), Agassiz (1902,1903), Sewell (1936a, b), Stoddart (1973b), and Woodroffe (1993).

The descriptive and analytical work on the Maldives in general by Woodroffe (1993) is especially applicable in this study since he first summarised the latitudinal variations of atoll characteristics and island types were identified. In addition, the chronological nature of island formation and development was outlined for the first time, based on radiocarbon datings of island sediments.

The important observations made by various authors regarding islands in the Maldives are summarised and presented in brief form below with specific reference to: (1) island and atoll characteristics; (2) island formation and development; and (3) processes-related comments.

1- Island and atoll characteristics:

- Islands are placed on the eastern side on the northern atolls, and on the south eastern side on the southern atolls;
- more continuous reefs on southern atolls than those of northern ones.

(Darwin 1842)

- Islands in the northern banks situated on the smallest rather than the largest of the lagoon shoals;
- land on rim-reefs is more common on the east than the west of atolls; islands on the centre banks (lagoonal) vary;
- different changes and conditions exhibited by each bank.

(Gardiner 1903)

- Lagoon depths vary with atoll size and location, and no obvious explanation exists for this phenomenon,

- many atolls in the Maldives are symmetric, being in the area of monsoon reversals,
- the atoll rim is broken down into a series faros, in the northern Maldives,
- the continuity of the peripheral reef round each atoll lagoon increases from north to south.

(Stoddart 1973b)

- Seasonal reversal in monsoon winds 'complicate' the location of islands on reef platforms;
- little is known of sand cays within lagoons, which have not yet been studied.

(Stoddart and Steers 1977)

- reef islands on atolls in the Maldives differ from those on other coral atolls.

(Woodroffe 1993)

2- Island formation and development:

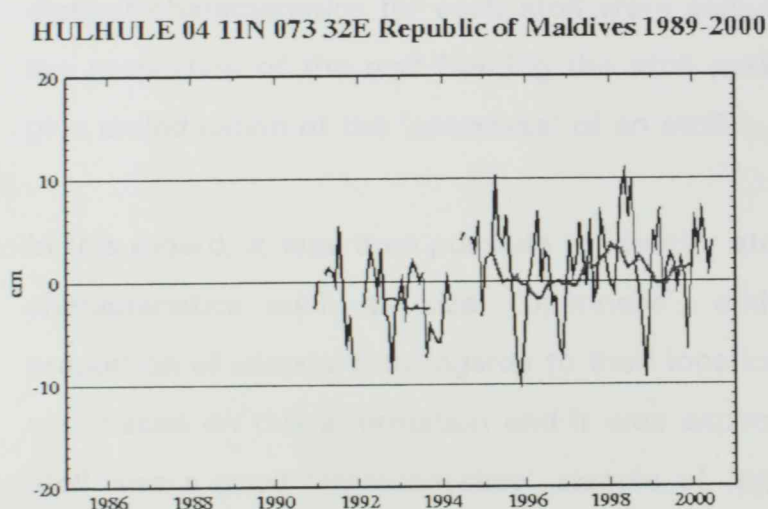
- The islands formed by material thrown up from the outside and not from the interior of the lagoons (Darwin 1842).
- Islands formed due to lowering of sea level (Gardiner 1931).
- Possible existence of a higher sea level on Kunfunadhoo (Agassiz 1903).
- Sand and coral fragments might have been thrown up and formed part of the reef surface;
- islands in the north were positioned more east to south-east on the reef platforms, east, through to north-east in the south;
- islands were building out lagoonwards;
- migration of islands across the reef flat may go to push them into the lagoon (Sewell 1936a, b).
- Islands were formed immediately after reefs caught up with sea level;
- reef growth and island formation may differ in detail from atoll to atoll (Woodroffe 1993).

3- Processes-related remarks:

- Westerly winds are the strongest;
- the work of destruction (erosion) completed in ten years (*Darwin 1842*).
- the strongest and heaviest winds and seas from the west, which either pile up coral to form land or wash it away; islands on the rim reef were washing away on their seaward and growing lagoonwards (*Gardiner 1903*).
- Effects of south-west winds are considerably greater than the north-east winds (*Sewell 1936a*).
- The contrasts in morphology from north to south suggest different factors have been and still may be controlling related aspects of the islands;
- different processes control island development in the relatively storm-free Maldives setting (*Woodroffe 1993*).

Recent sea level history

The recent sea level history in the Maldives as recorded from tide gauge data from Hulhule' indicates a fluctuation of $\pm 10\text{cm}$ between 1991 and 2000.



Source: <ftp://ilikai.soest.hawaii.edu/woce/gifd/m0108w.gif> (1/11/2000))

APPENDIX 2

Quantitative characteristics of atolls and reef platforms in the Maldives

The morphometric and reef platform characteristics of the 26 geographic atolls of the Maldives presented in this appendix were examined using the British Admiralty charts for the Indian Ocean, Maldives sheets 1011 and 1012 (1992) and Sheets 1013 and 1014 (1993) at 1:300,000.

Initially, the morphometric parameters such as the perimeter, length and width of the atolls were measured using MapInfo software. The number of reef platforms and islands associated with them were later identified.

Aspects of the reef platforms such as the numbers that occur on the atoll periphery and those in the lagoon of atolls were identified. The presence/ absence of islands on these reef platforms was examined in relation to their numbers and location. Based on this information, distinct characteristics for each atoll were calculated. These include the proportion of the reef forming the atoll periphery, which would give an indication of the 'openness' of an atoll.

In this regard, it was then possible to identify atolls that have similar characteristics such as size, 'openness', and the absolute and proportion of islands with regards to their location. The site selection was based on this information and it was expected that the chosen atoll was a good 'representative' sample of 'typical' atoll from the Maldives.

atoll	area (km ²)	perimeter (km)	number of passages	proportion of passages	number of reef platforms	number of peripheral reef platforms	% peripheral reef platforms	number of lagoonal reef platforms	% lagoonal reef platforms	total reef platforms with islands	% reef platforms with islands	% of reef platforms with single island	no. of peripheral reef platforms with islands
α	278	68	9	29.2	17	9	52.9	8	47.1	13	76.5	84.6	9
β	3818	377	75	54.0	152	76	50.0	76	50.0	141	92.8	92.2	68
γ	134	65	3	3.2	26	3	11.5	23	88.5	2	7.7	50.0	2
δ	3	8	0	0.0	1	0	0.0	0	0.0	1	100.0	0.0	0
ε	1157	153	40	40.4	155	41	26.4	114	73.5	91	58.7	95.6	35
ζ	134	52	15	39.6	15	14	93.3	1	6.7	12	80.0	91.7	11
η	924	122	33	40.7	90	35	38.9	55	61.1	50	55.6	88.0	28
θ	686	113	26	20.5	46	25	54.3	21	45.6	23	50.0	60.9	21
ι	8	11	0	0.0	1	0	0.0	0	0.0	1	100.0	0.0	0
Κ	109	43	1	4.4	11	1	9.1	10	90.9	1	9.1	0.0	1
κ	84	36	2	1.7	12	2	16.7	10	83.3	1	8.3	0.0	1
λ	1561	160	36	25.7	252	38	15.1	214	84.9	34	13.5	85.3	12
μ	3	7	0	0.0	1	0	0.0	0	0.0	1	100.0	0.0	0
ν	65	29	4	5.6	10	4	40.0	6	60.0	3	30.0	33.3	3
ξ	530	93	22	18.6	153	21	13.7	132	86.3	17	11.1	76.5	11
Π	2334	210	56	43.7	253	76	30.1	177	69.9	77	30.4	74.0	45
Ο	1103	164	50	11.8	233	48	20.6	185	79.4	18	7.7	88.9	12
π	48	25	1	0.6	1	1	100.0	0	0.0	1	100.0	100.0	1
ρ	593	94	20	20.3	86	20	23.3	66	76.7	20	23.3	95.0	12
σ	997	136	22	8.2	130	23	17.7	107	82.3	10	7.7	70.0	9
Σ	729	104	15	19.0	101	19	18.9	82	81.2	26	25.7	80.8	11
τ	1694	156	17	8.8	125	19	15.2	106	84.8	19	15.2	63.2	15
υ	885	127	7	5.2	55	6	10.9	49	89.1	9	16.4	44.4	6
φ	3287	245	41	15.8	227	41	18.1	186	81.9	75	33.0	81.3	28
χ	7	12	0	0.0	1	0	0.0	0	0.0	1	100.0	0.0	0
ψ	148	57	4	6.6	16	4	25.0	12	75.0	4	25.0	50.0	4

APPENDIX 3

Comparative mappings of 1969 and 1999 aerial photos

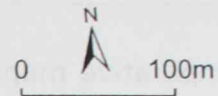
A comparative mapping of selected islands in Eta atoll was done using the 1969 aerial photos of the atoll taken by the Royal Air Force (UK), and those taken by the Ministry of Construction and Public Works in January and February 1999. The mapping was carried out to determine the trends and magnitude of changes that may have taken place over this 30-year period, in order to generalise any spatial pattern that may be evident from these maps.

Although the photos were not photogrammetrically corrected, a qualitative analysis of the changes and trends that may have take place on the islands is possible. The salient features of the islands, such as the extent of vegetation, beach, beachrock outcrops and other geomorphological features that may be present on islands can be utilised for this analysis.

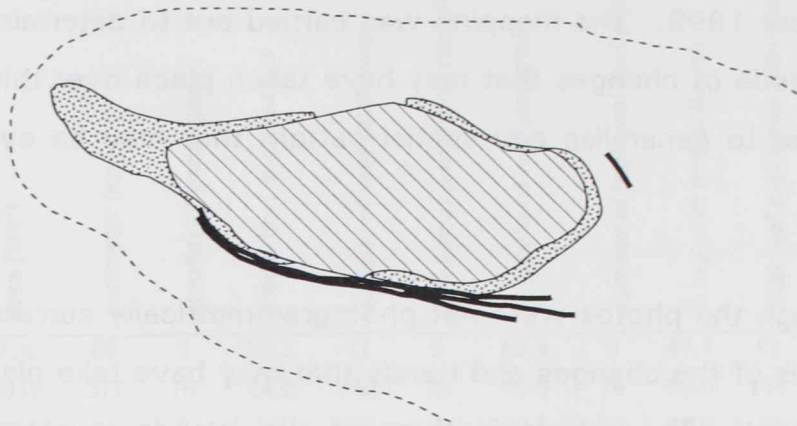
The comparative mapping of the islands were presented in Chapter 7, where it was discussed in relation to the relevant characteristics, factors and conditions related with the islands. The purpose of presenting this information here is to give the reader the opportunity to explore in more detail the features, and aspects of relevance of the islands that may not be easily discerned from the figures presented in Chapter 7.

Maps of the islands in this appendix are presented in alphabetical order from Aidhoo to Ufuligili.

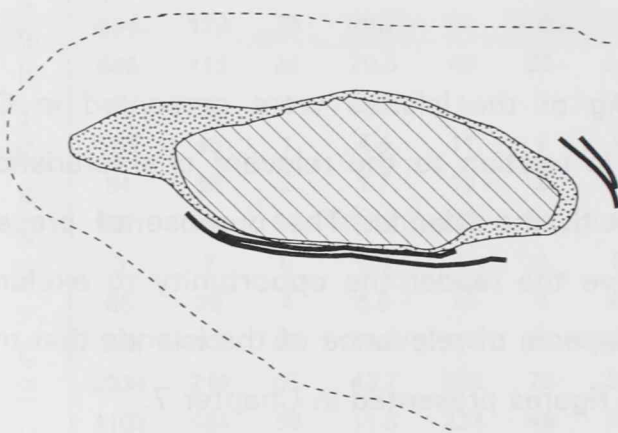
Aidhoo



1969

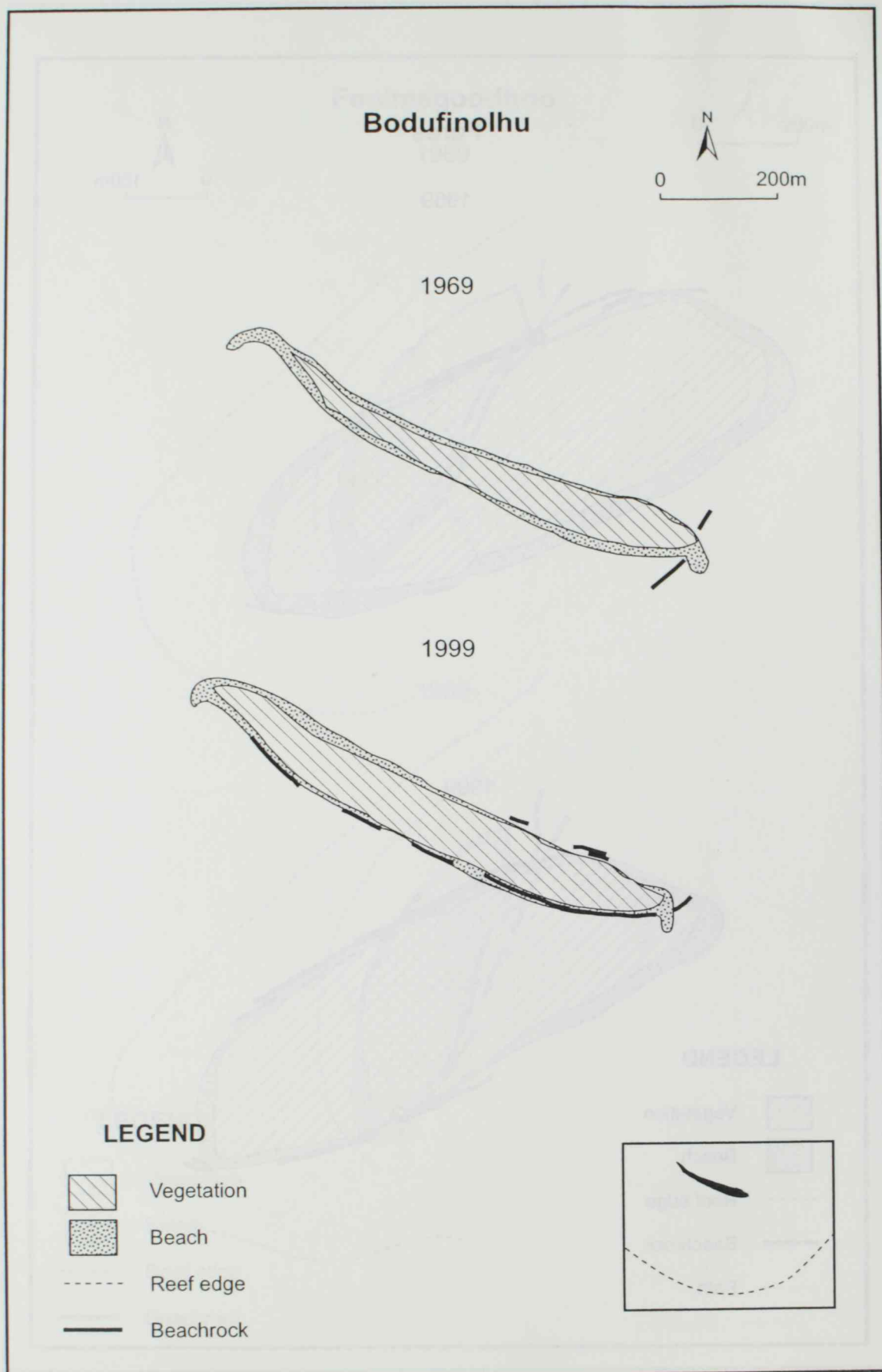


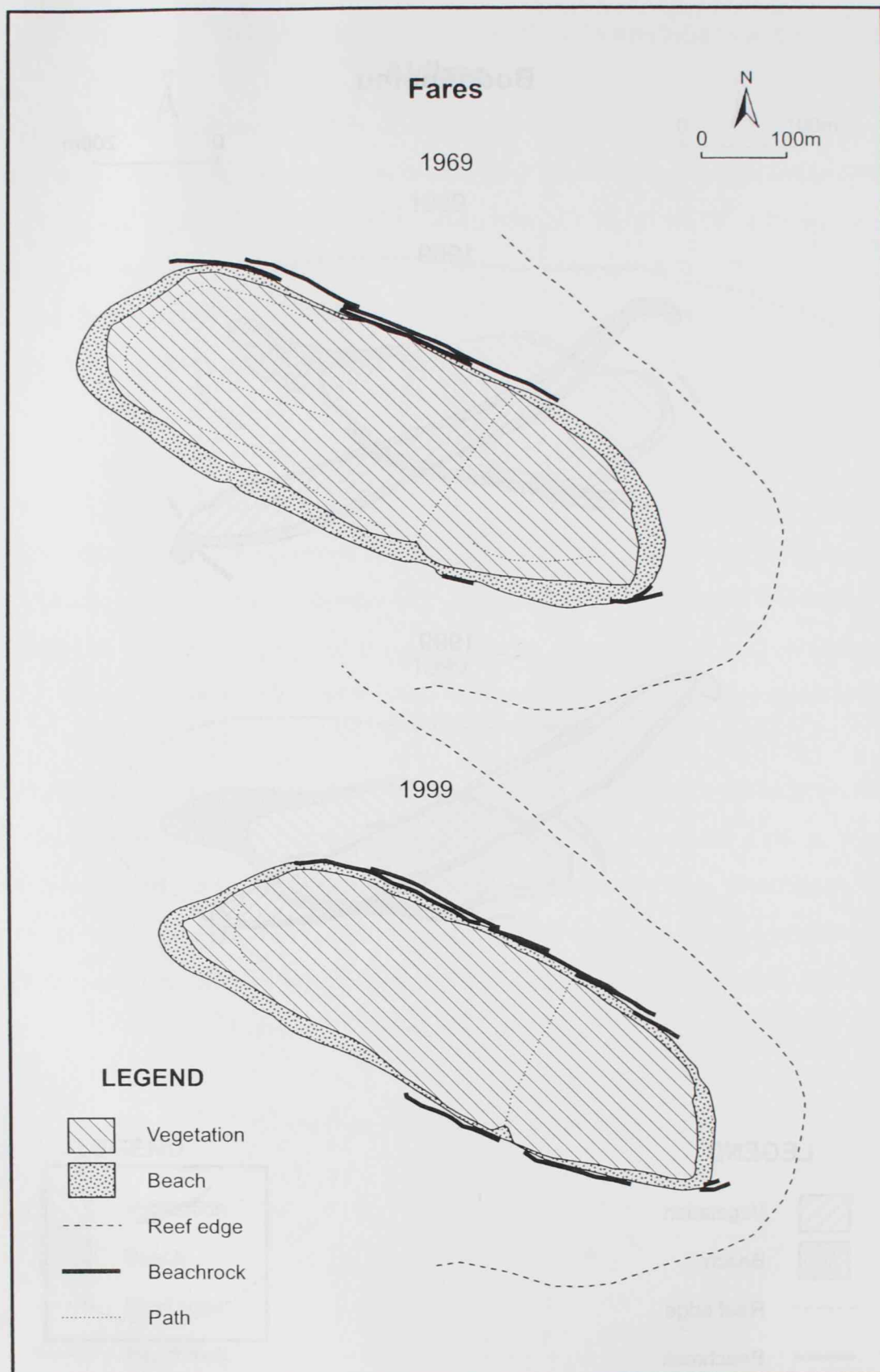
1999



LEGEND

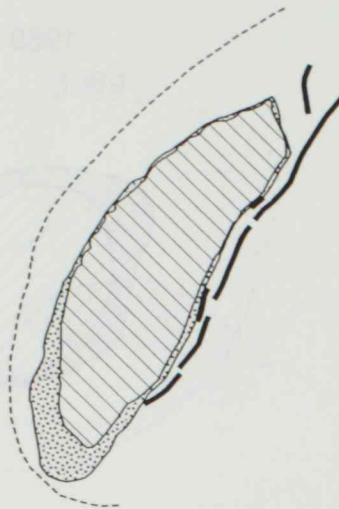
-  Vegetation
-  Beach
-  Reef edge
-  Beachrock



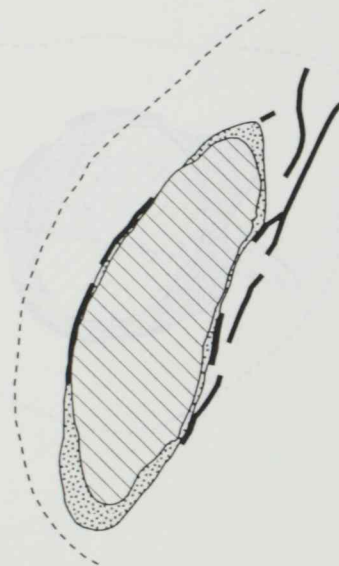


Fonimagoodhoo

1969

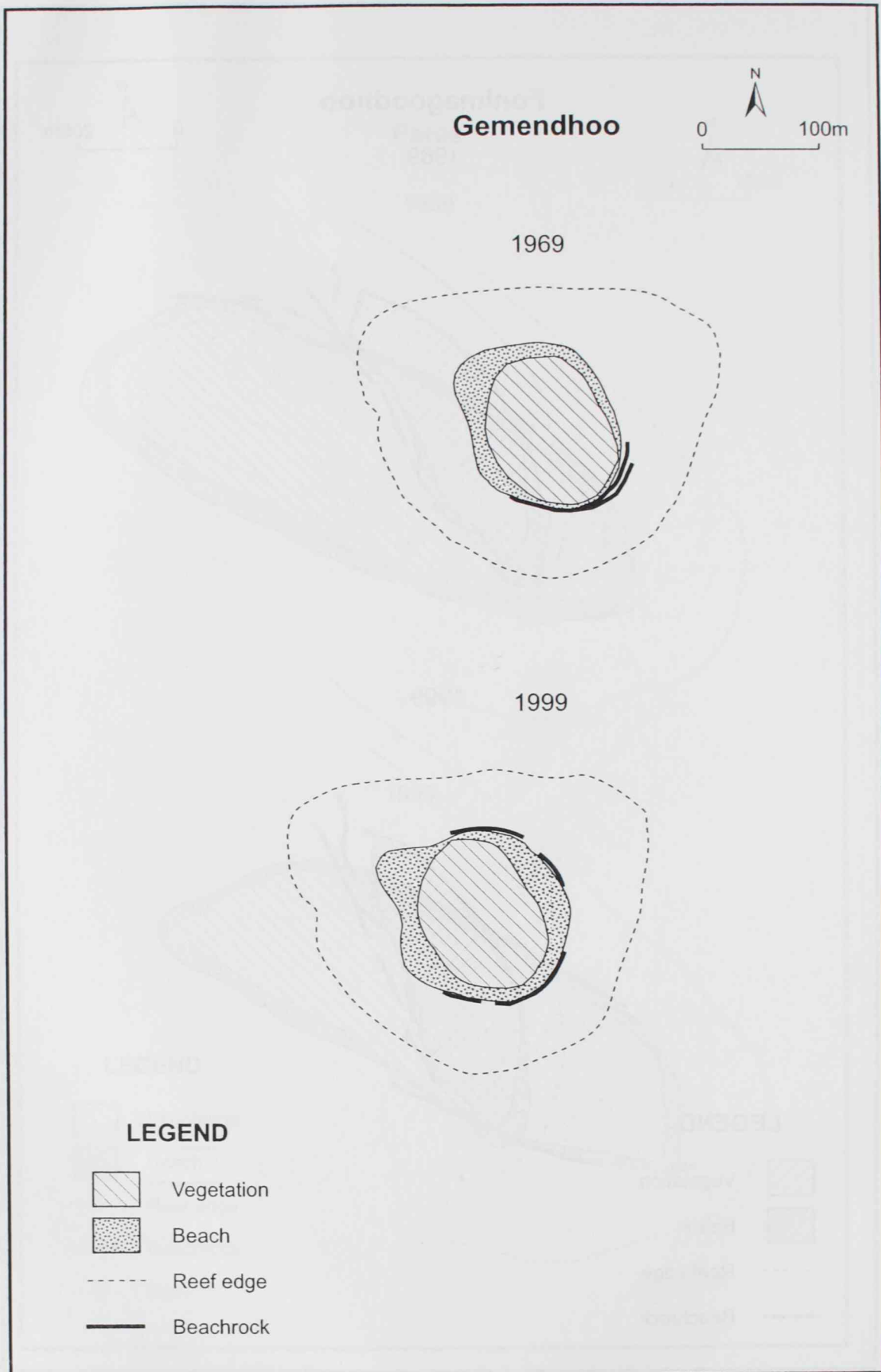


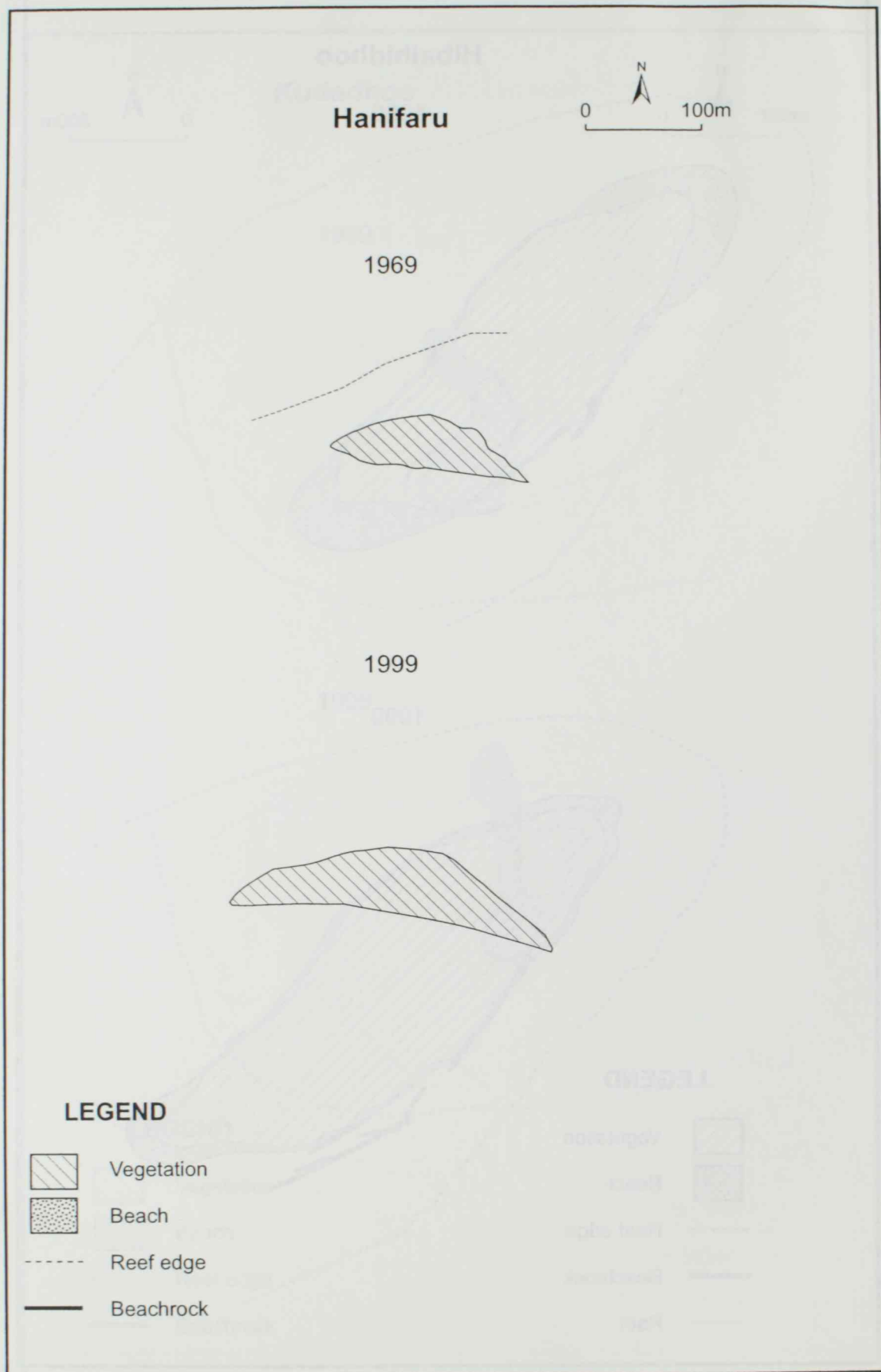
1999

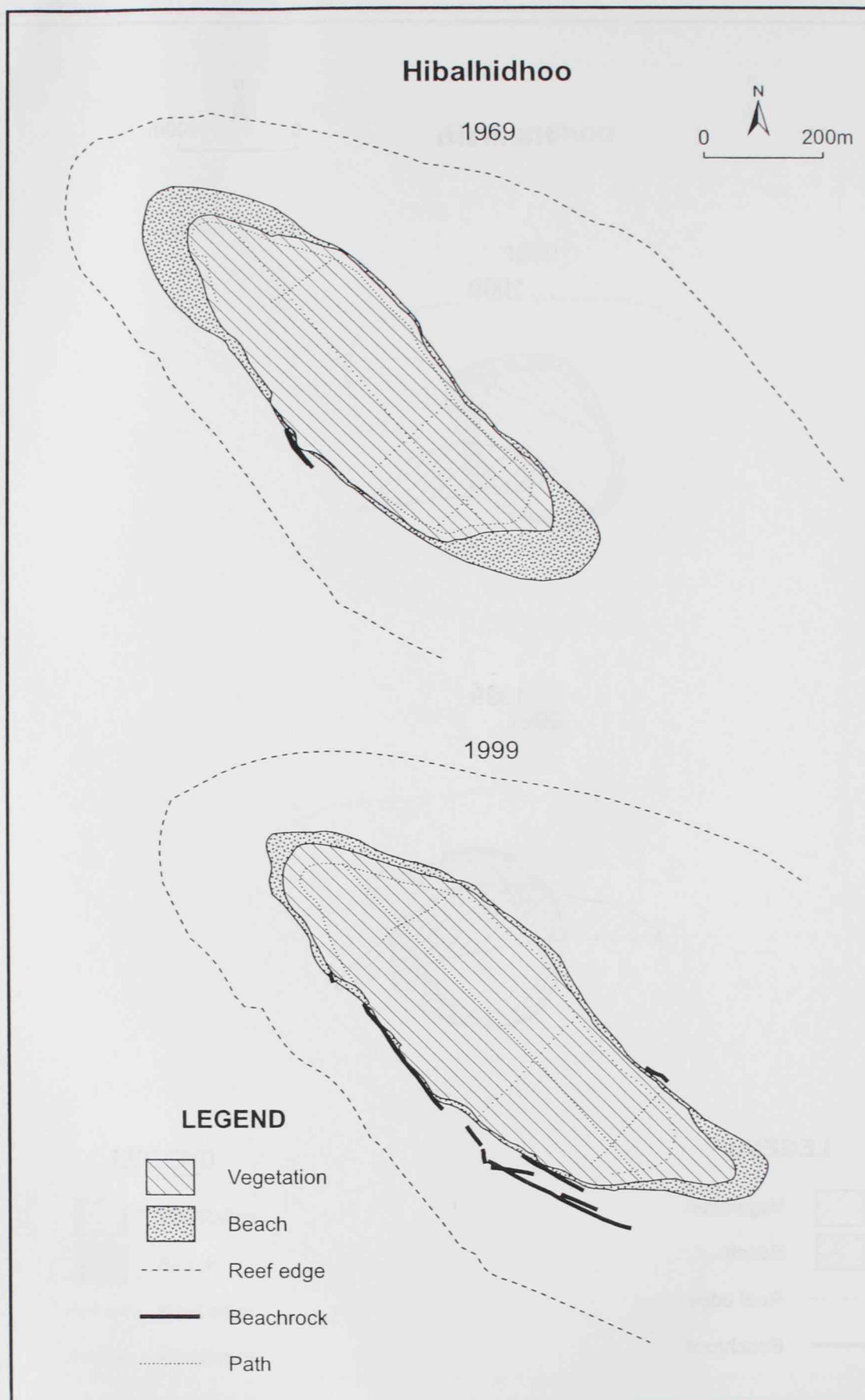


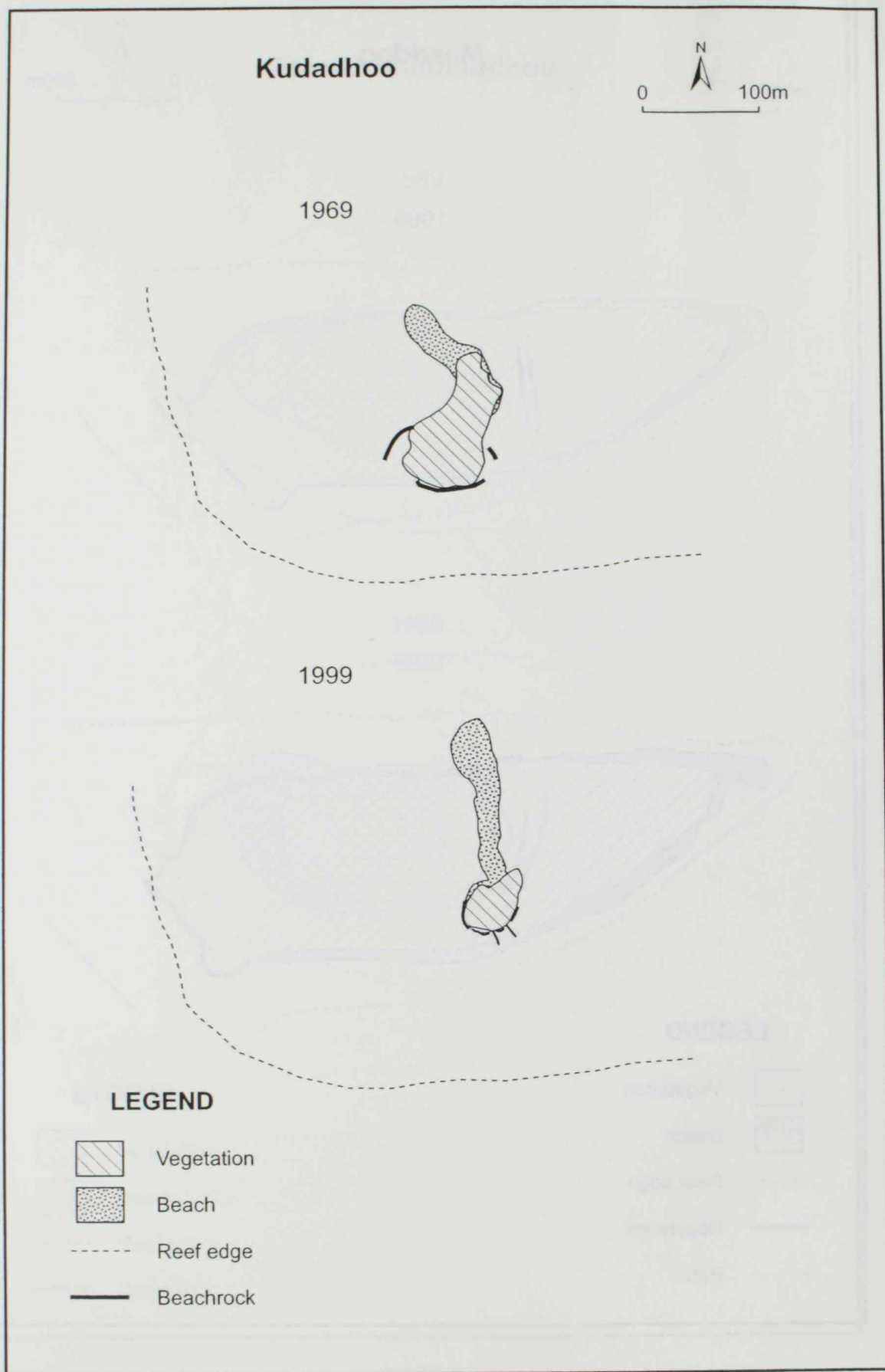
LEGEND

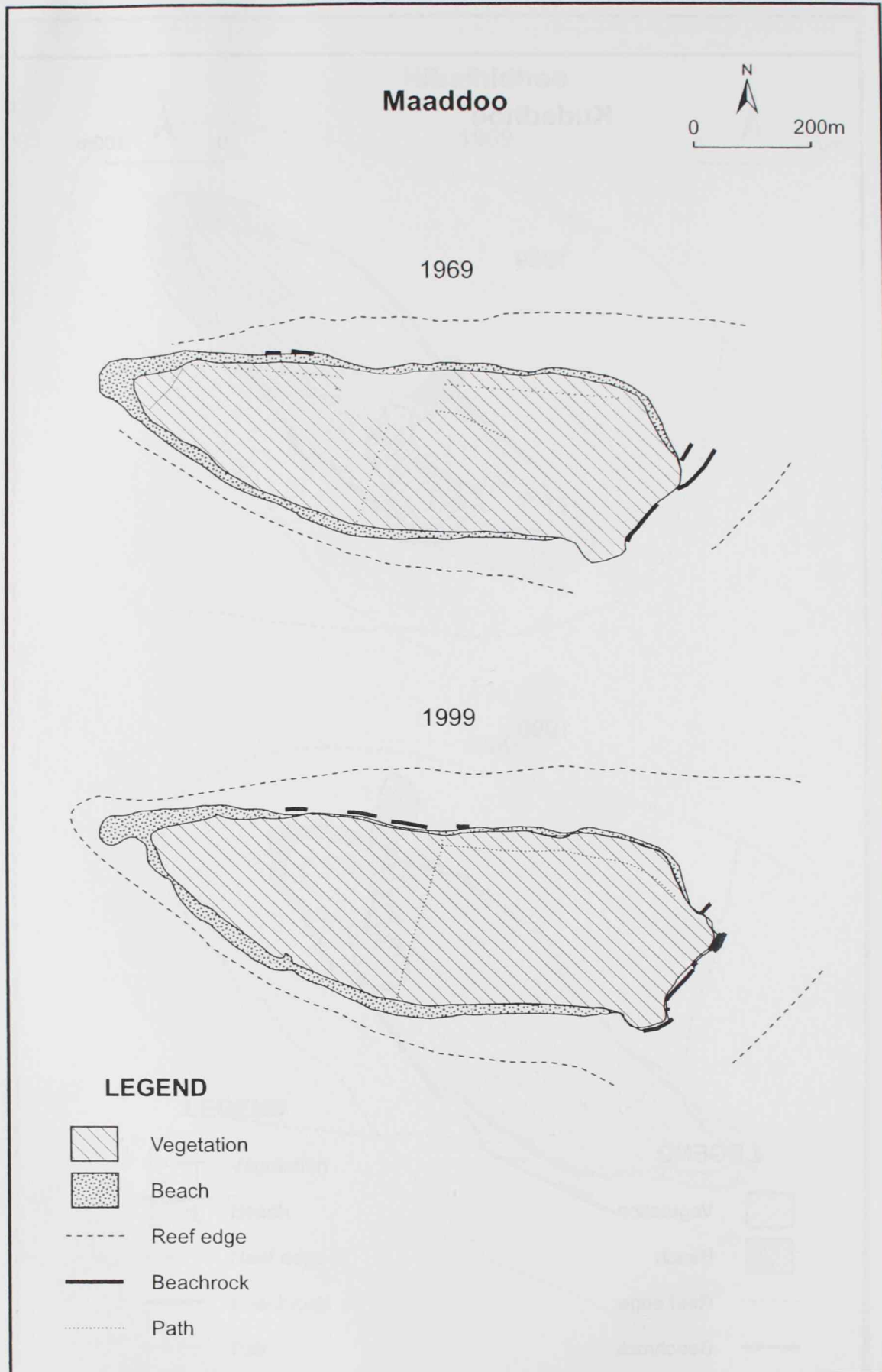
-  Vegetation
-  Beach
-  Reef edge
-  Beachrock

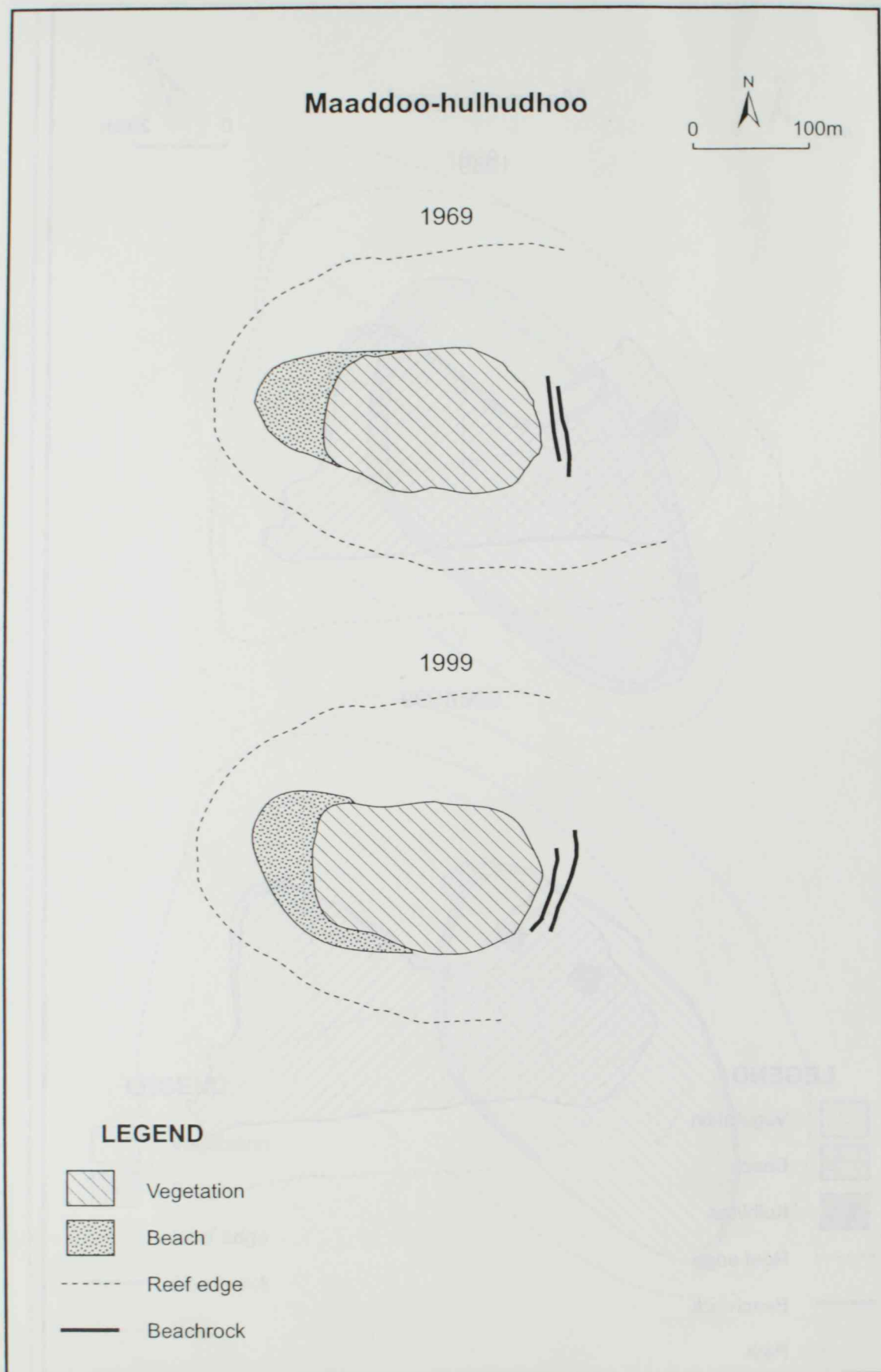


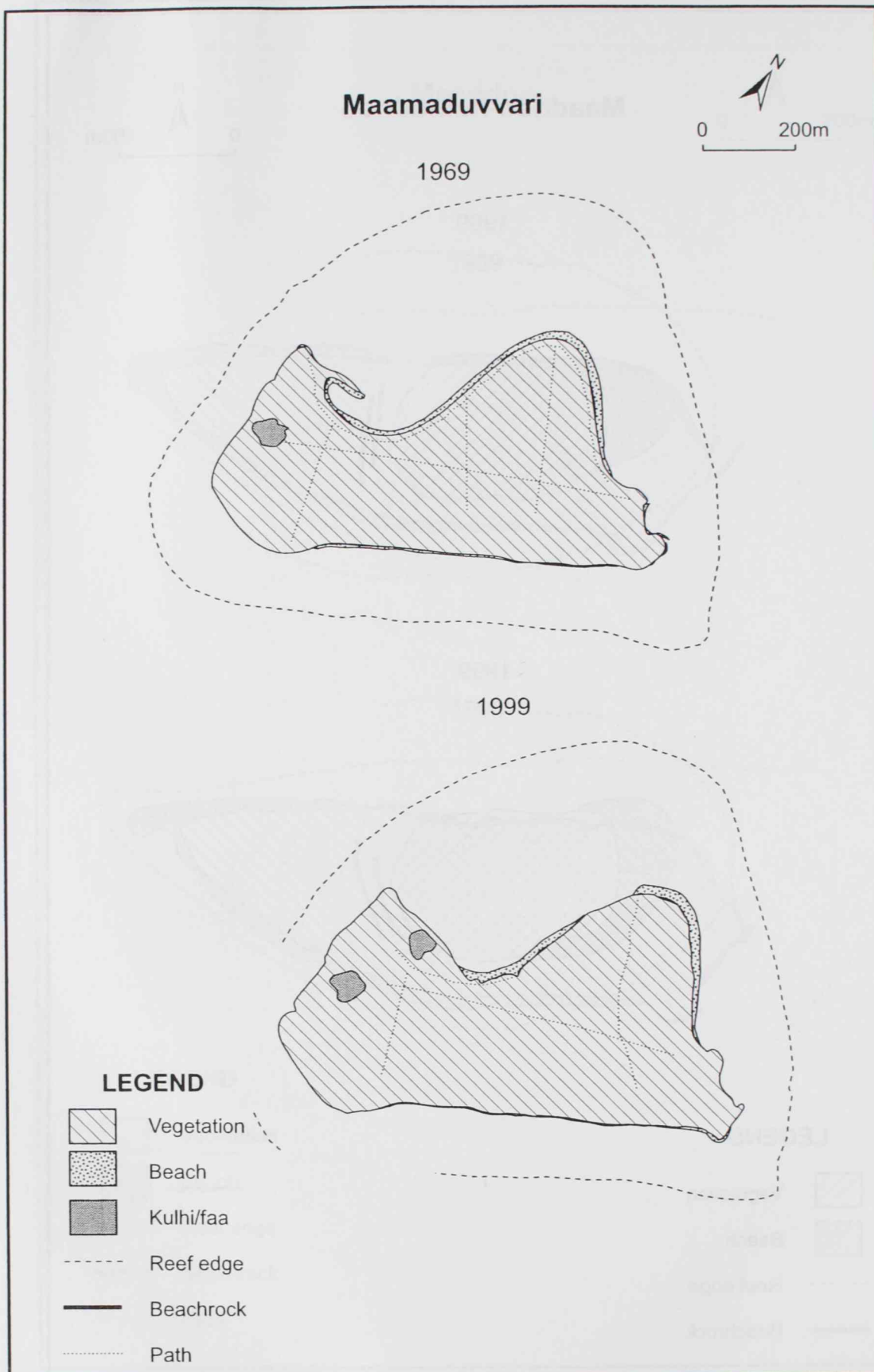


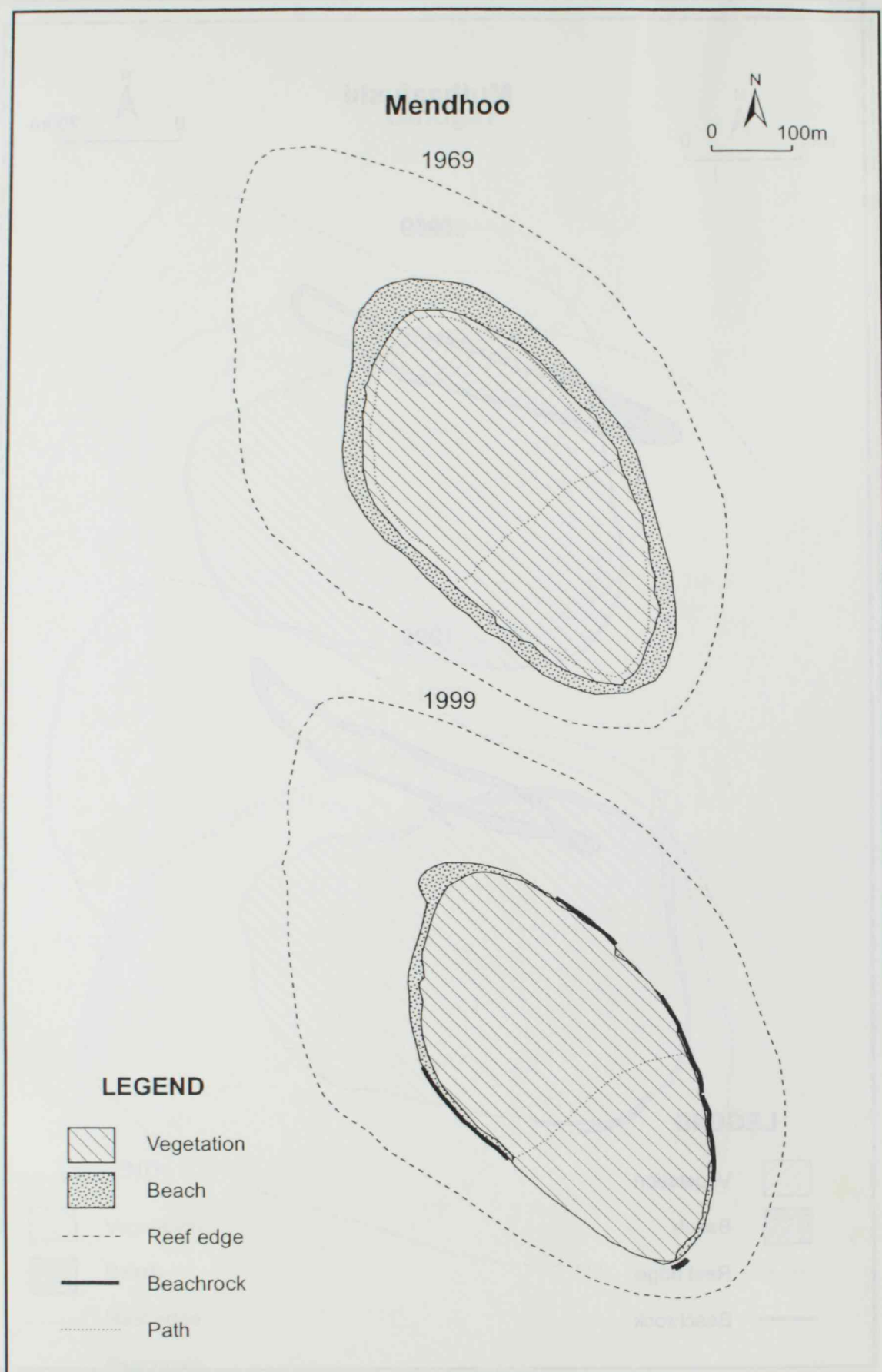


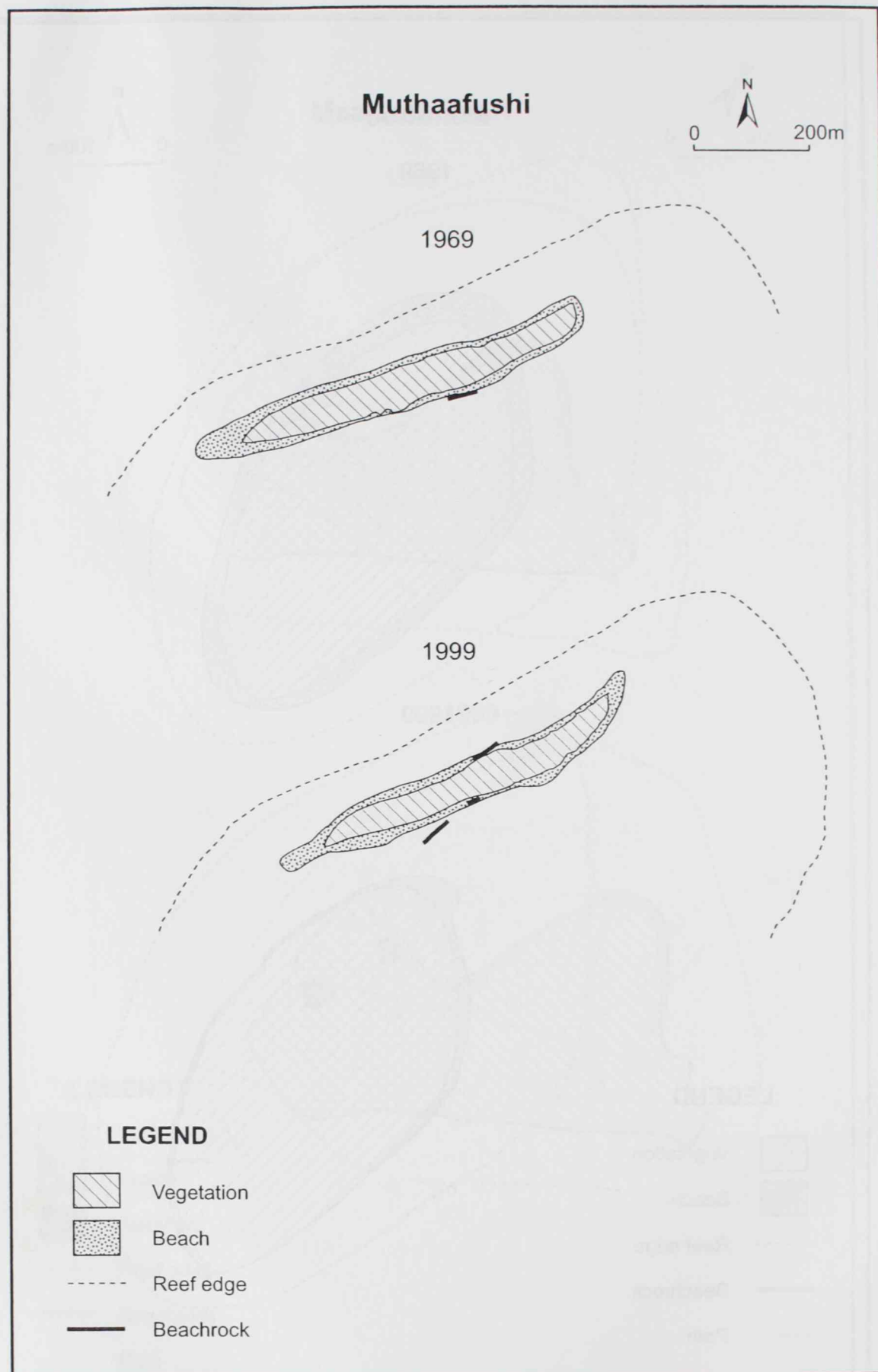


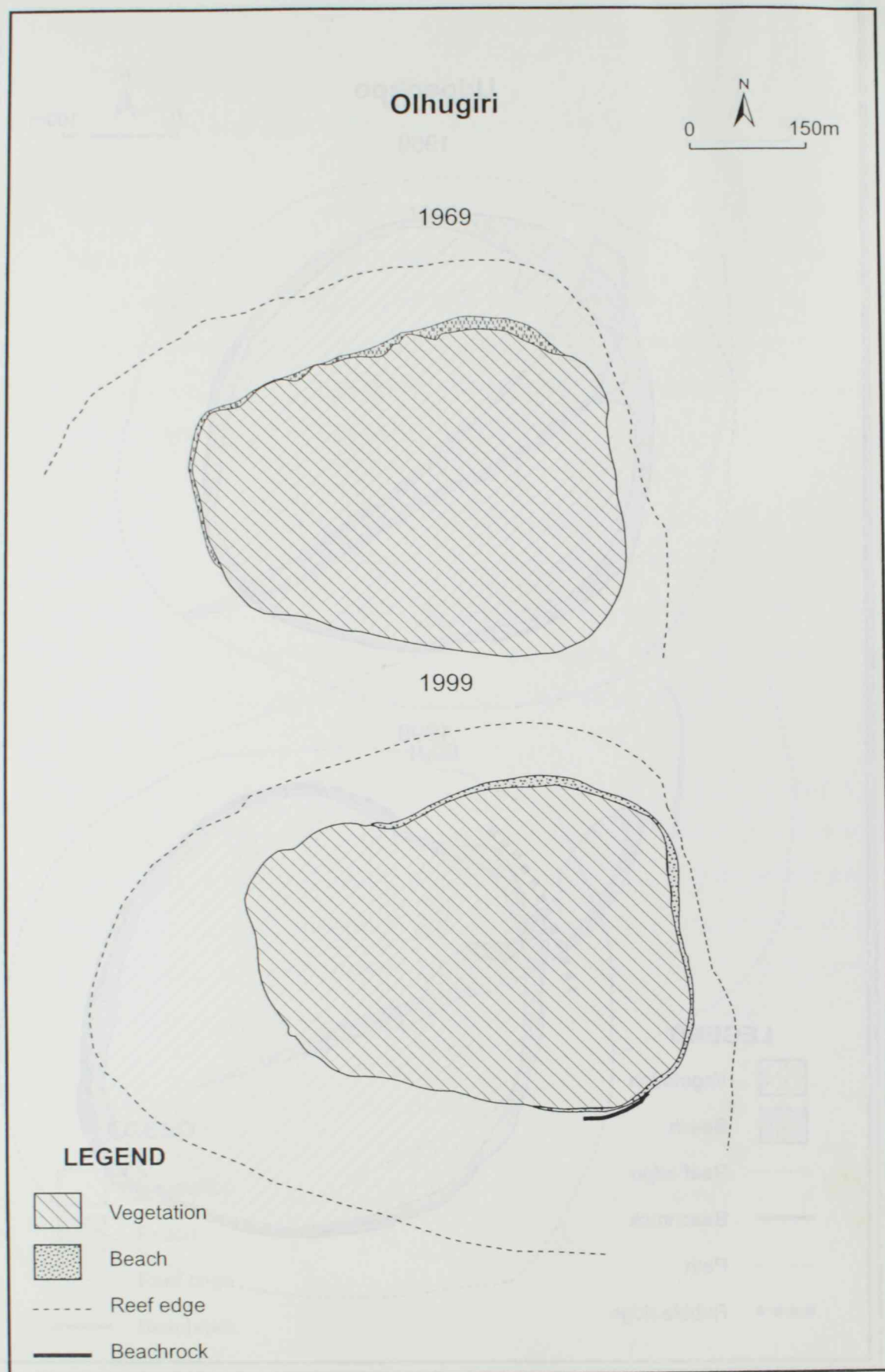


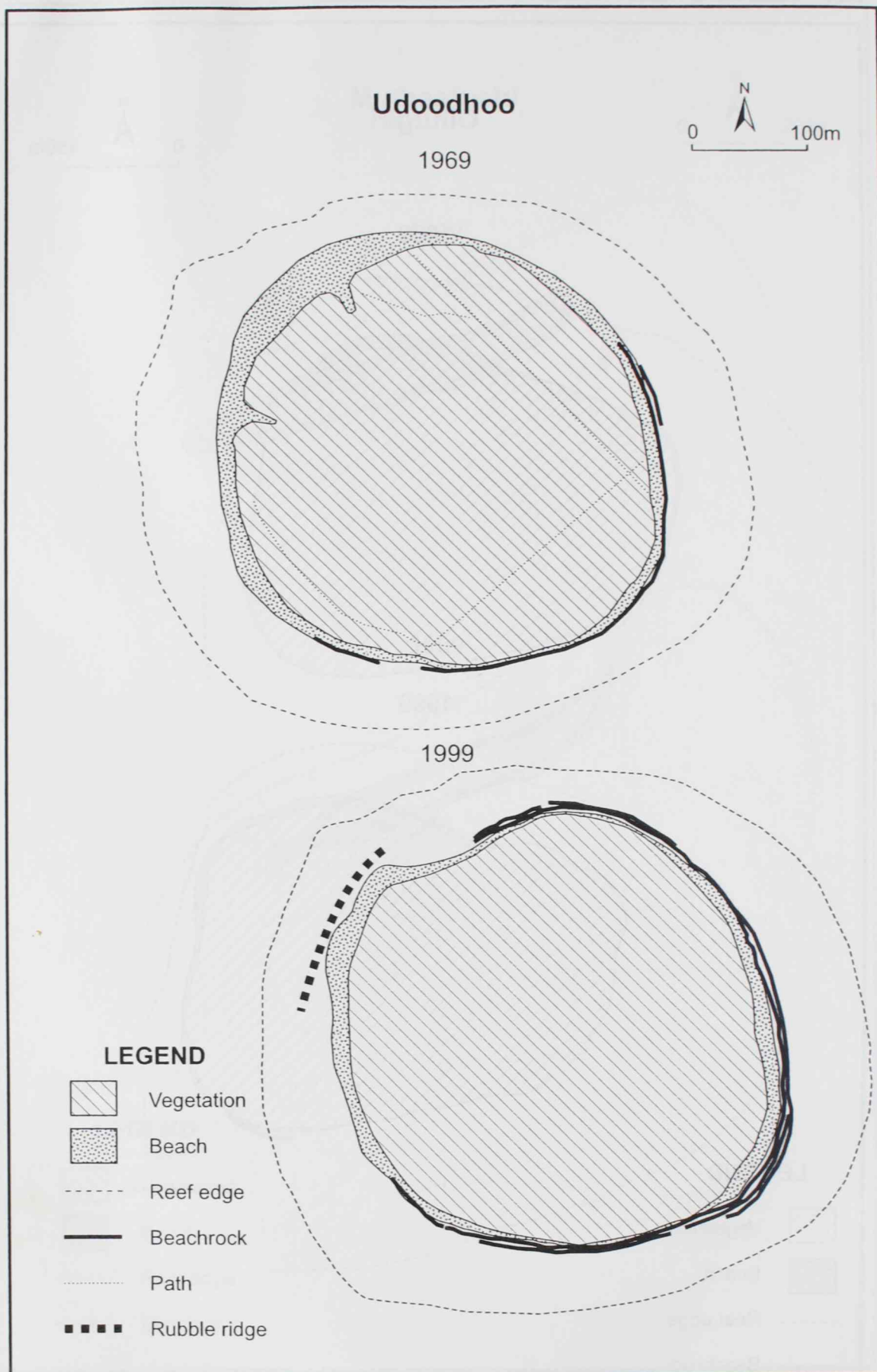






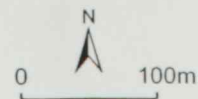




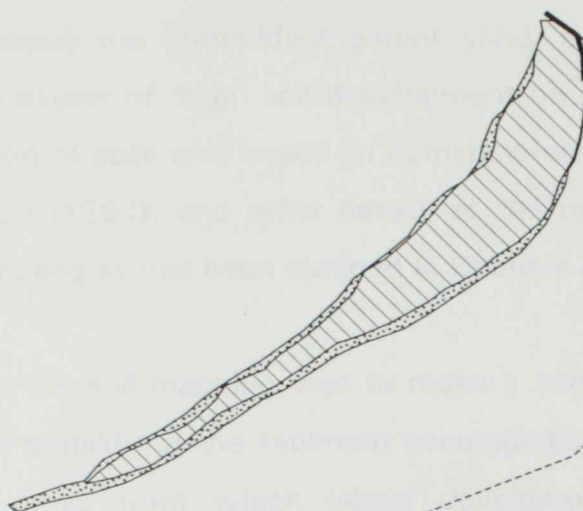


APPENDIX 4

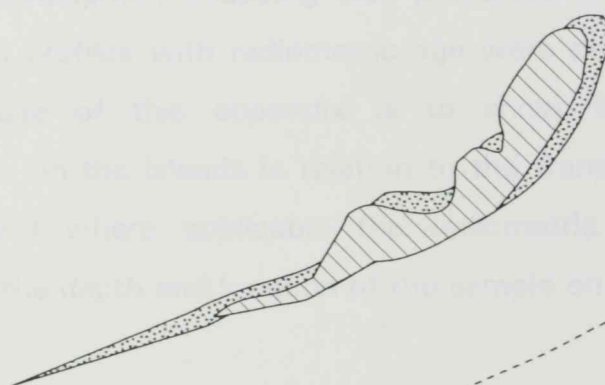
Ufuligili



1969



1999



LEGEND



Vegetation



Beach



Reef edge



Beachrock



APPENDIX 4

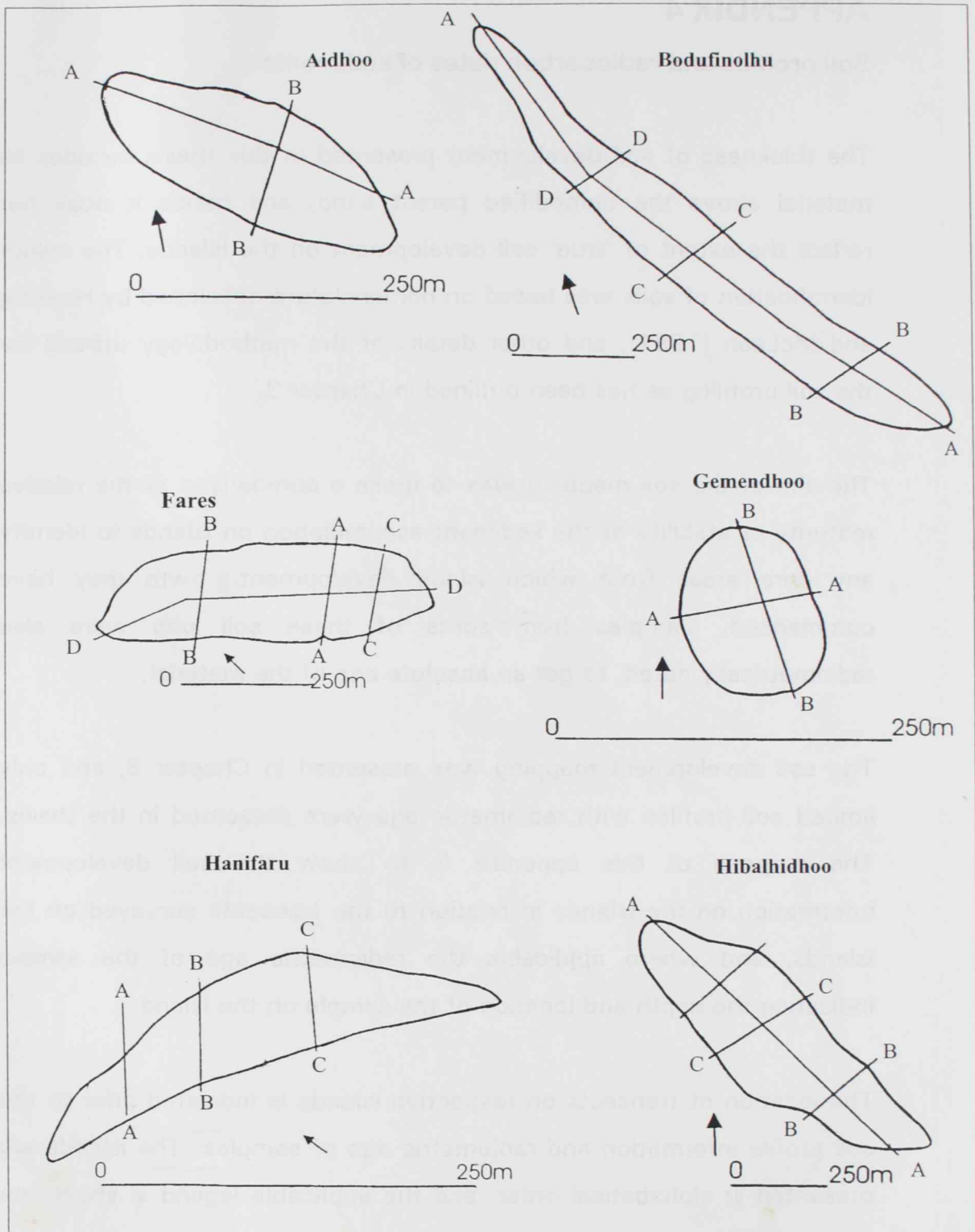
Soil profiles and radiocarbon dates of sediments

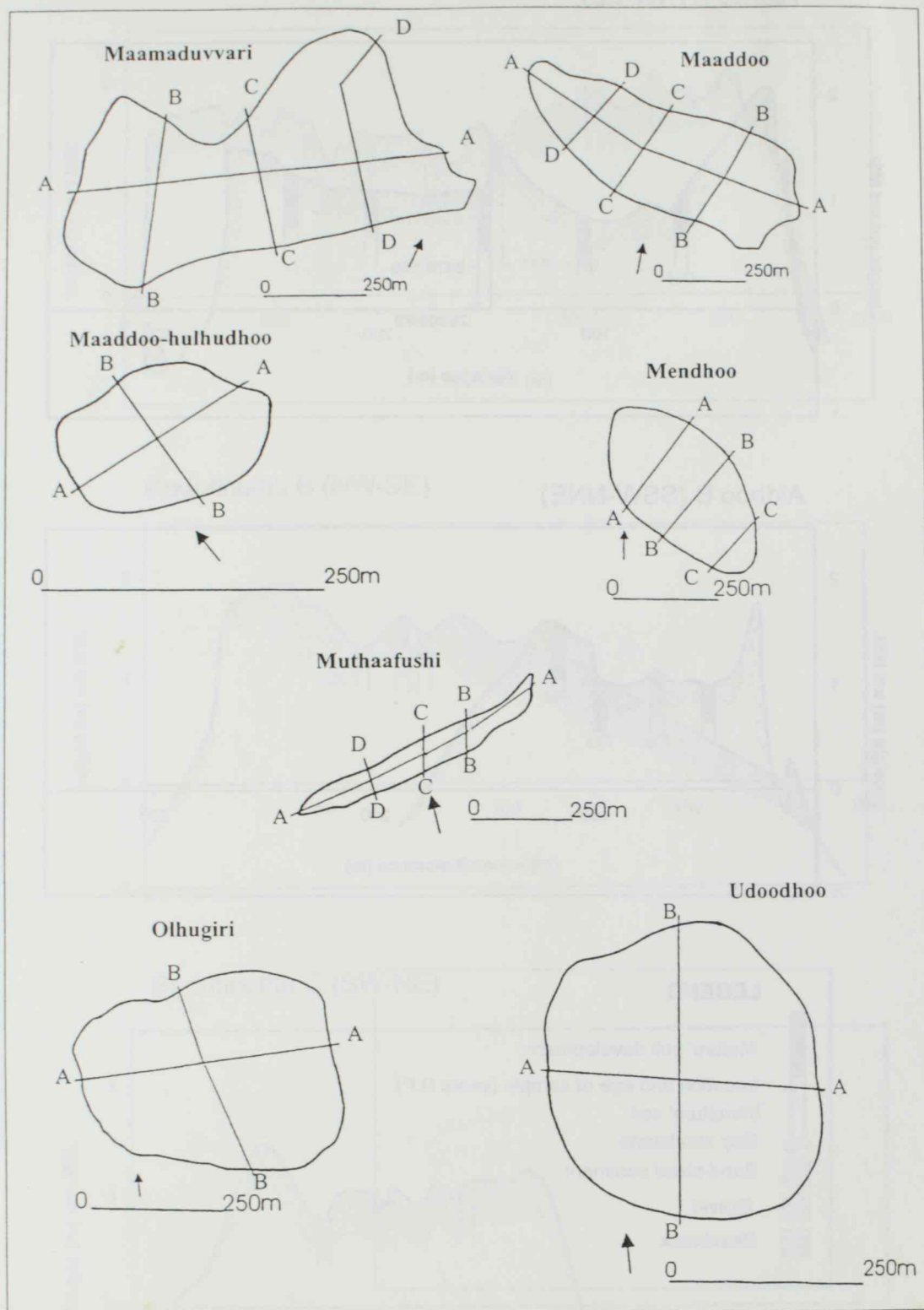
The thickness of soil development presented in this thesis includes all material above the unmodified parent sand, and hence it does not reflect the extent of 'true' soil development on the islands. The colour identification of soils was based on nomenclature developed by Hosking and McLean (1991), and other details of the methodology utilised for the soil profiling as has been outlined in Chapter 3.

The aim of the soil mapping was to make a comparison of the relative maturity or stability of the sediment accumulation on islands to identify any core areas from which island development/growth may have commenced. Samples from some of these soil pits were also radiometrically dated, to get an absolute age of the material.

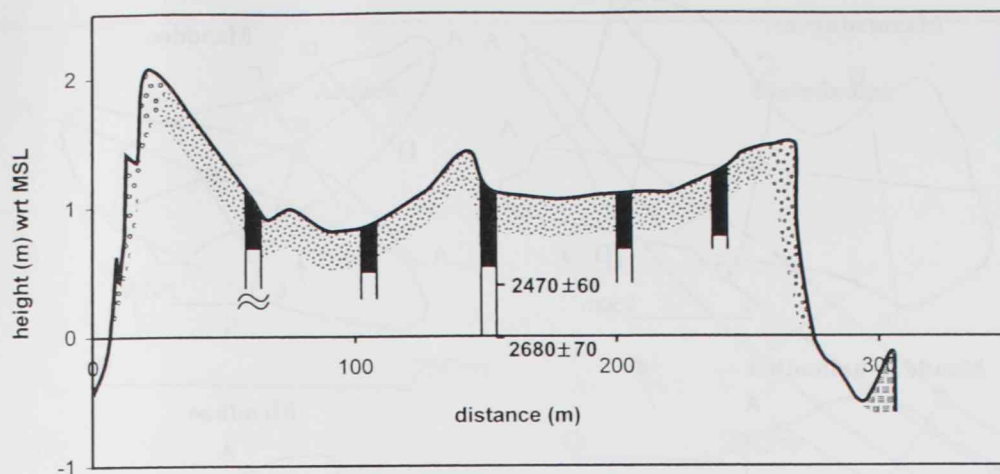
The soil development mapping was presented in Chapter 8, and only limited soil profiles with radiometric age were presented in the thesis. The purpose of this appendix is to show the soil development information on the islands in relation to the transects surveyed on the islands, and where applicable the radiometric age of the sample indicating the depth and location of the sample on the island.

The location of transects on respective islands is indicated prior to the soil profile information and radiometric age of samples. The islands are presented in alphabetical order, and the applicable legend is shown on page A32.

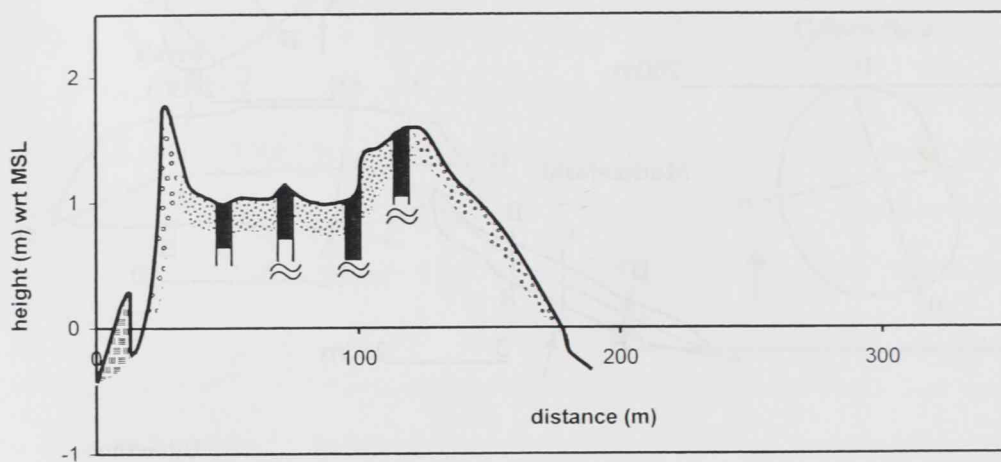




Aidhoo A (NW-SE)

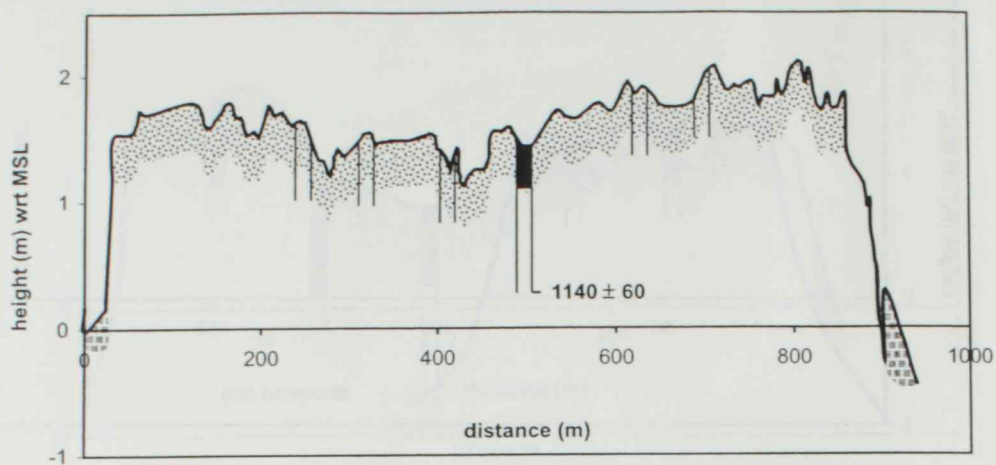


Aidhoo B (SSW-NNE)

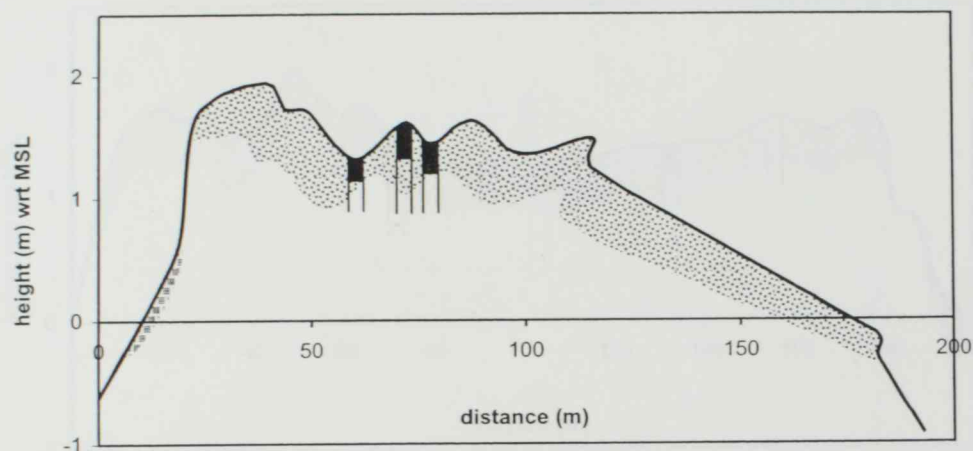
**LEGEND**

-  'Mature' soil development
-  Location and age of sample (years B.P)
-  'Immature' soil
-  Cay sandstone
-  Sand-sized sediment
-  Gravel
-  Beachrock

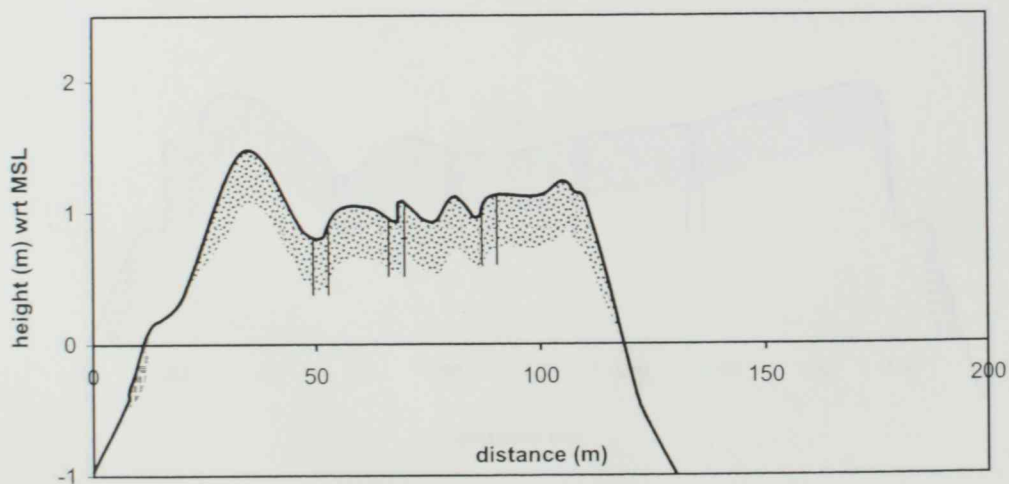
Bodufinolhu A (NW-SE)



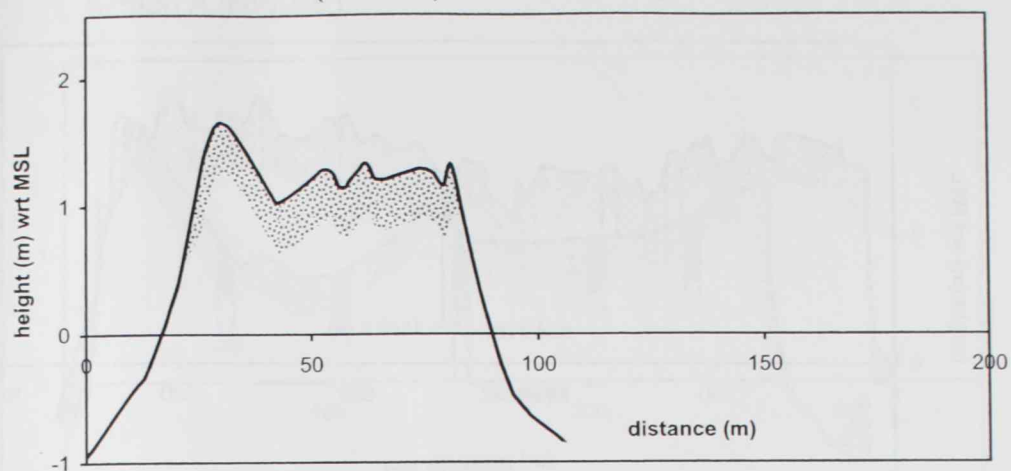
Bodufinolhu B (NW-SE)



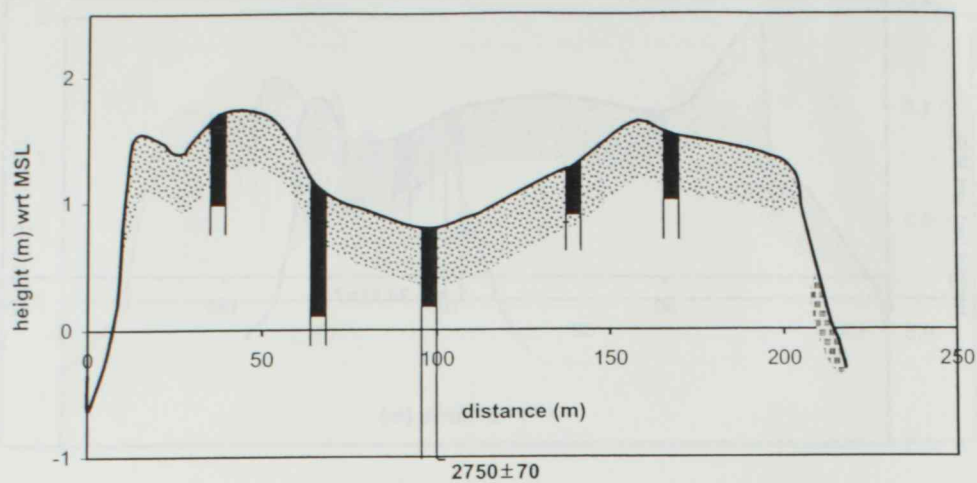
Bodufinolhu C (SW-NE)



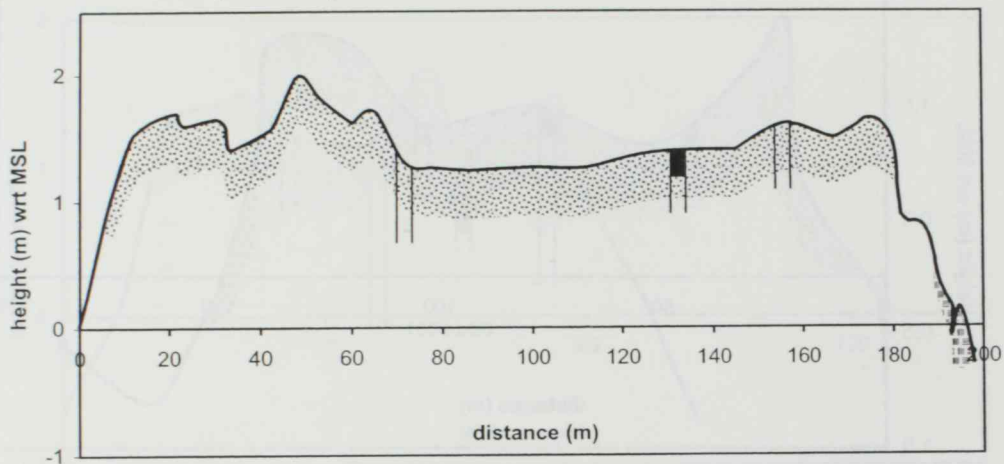
Bodufinolhu D (SW-NE)



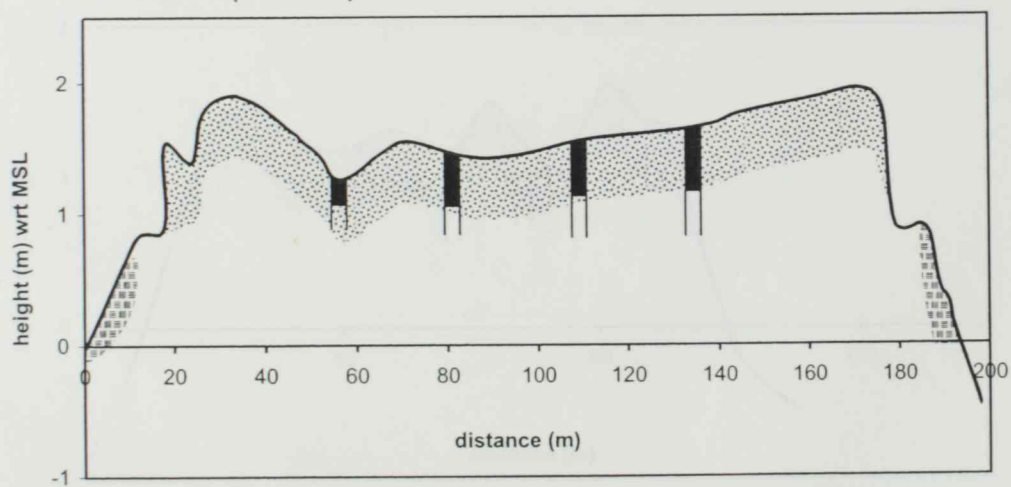
Fares A (SW-NE)



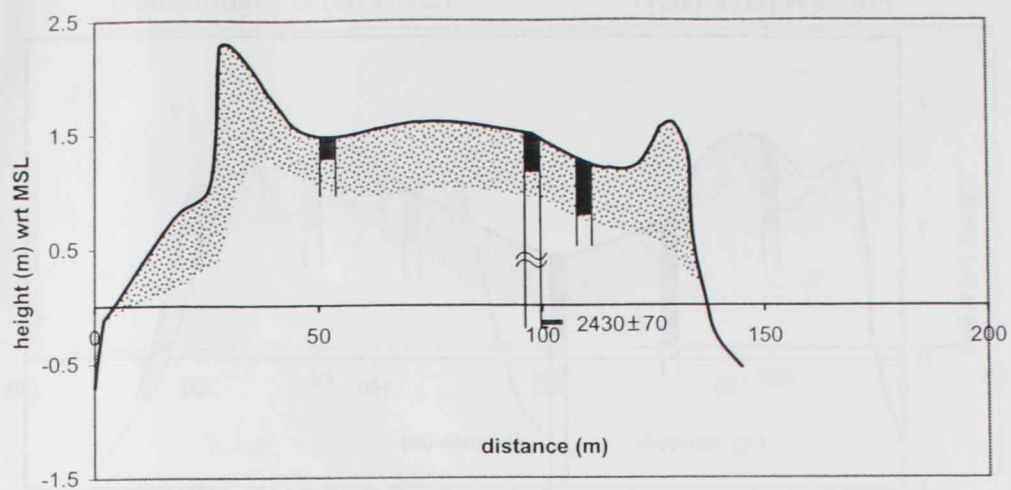
Fares B (SW-NE)



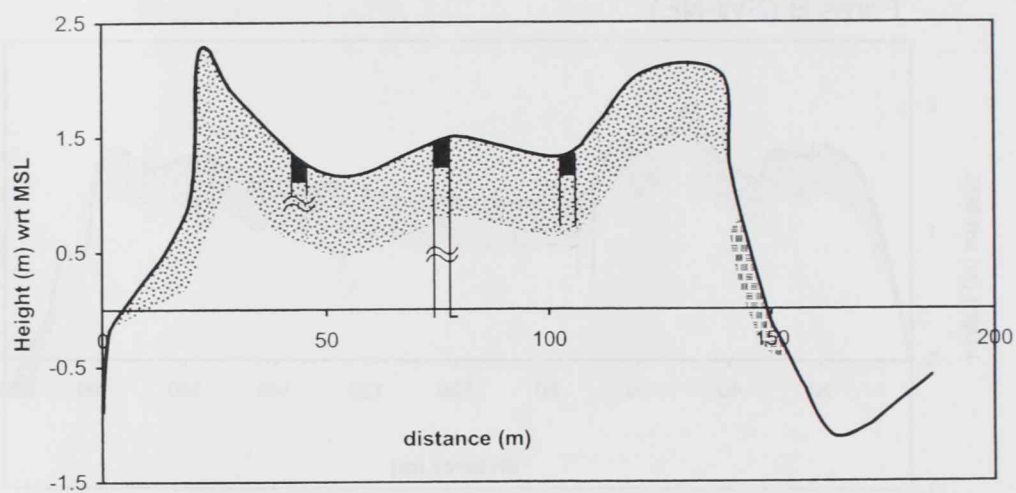
Fares C (SW-NE)

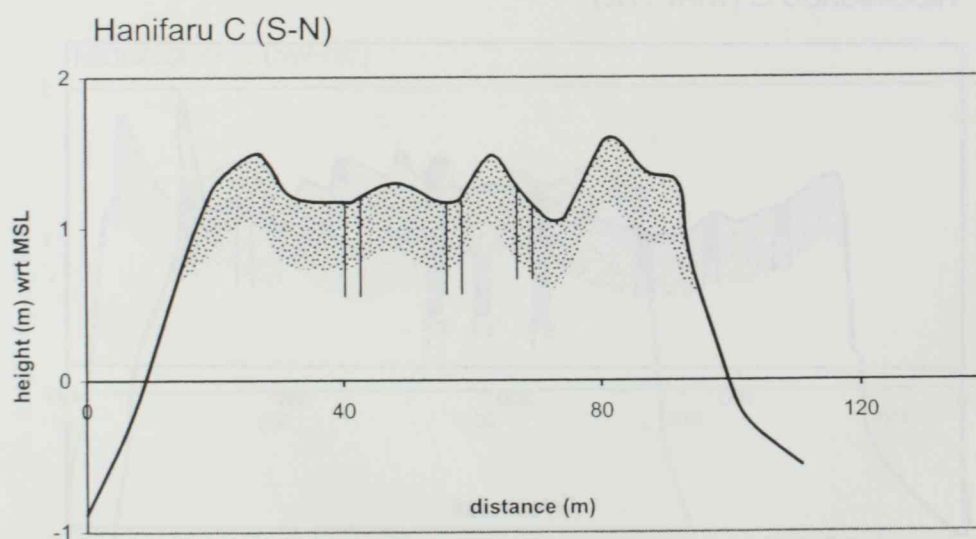
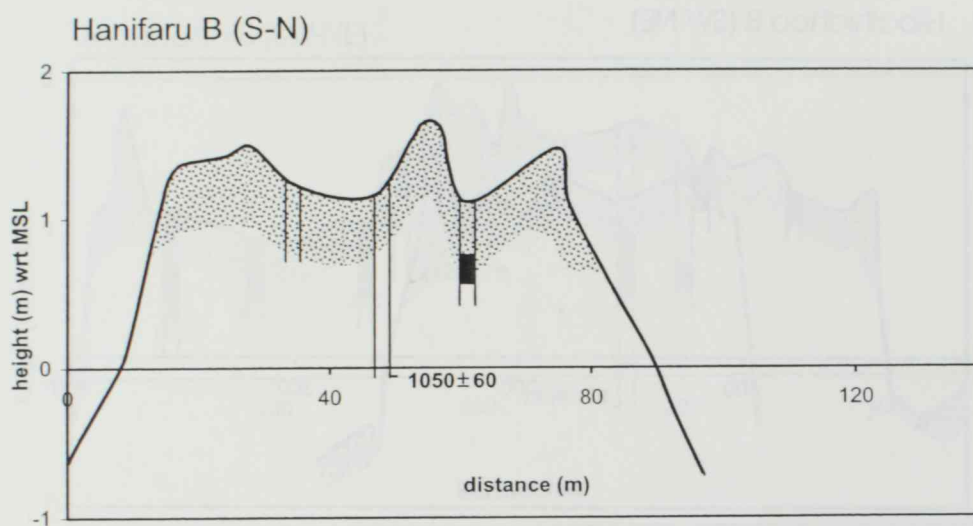
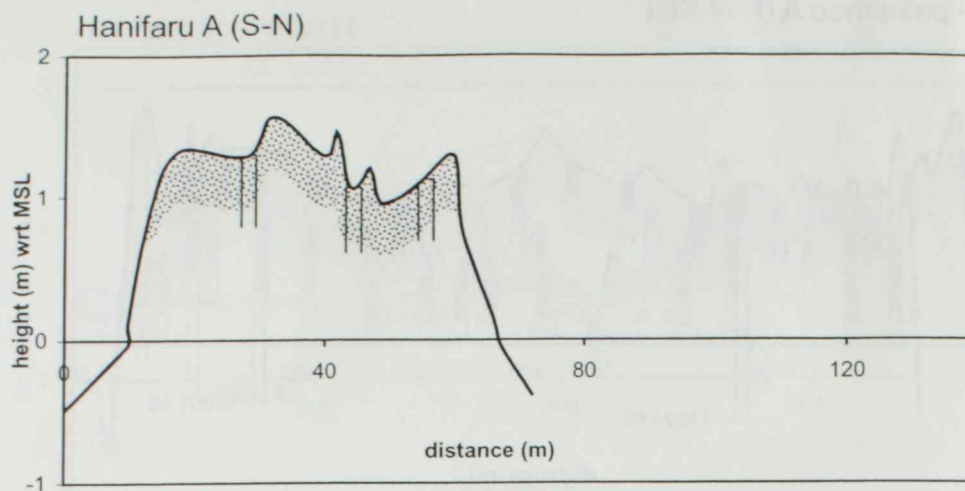


Gemendhoo A (WSW-ESE)

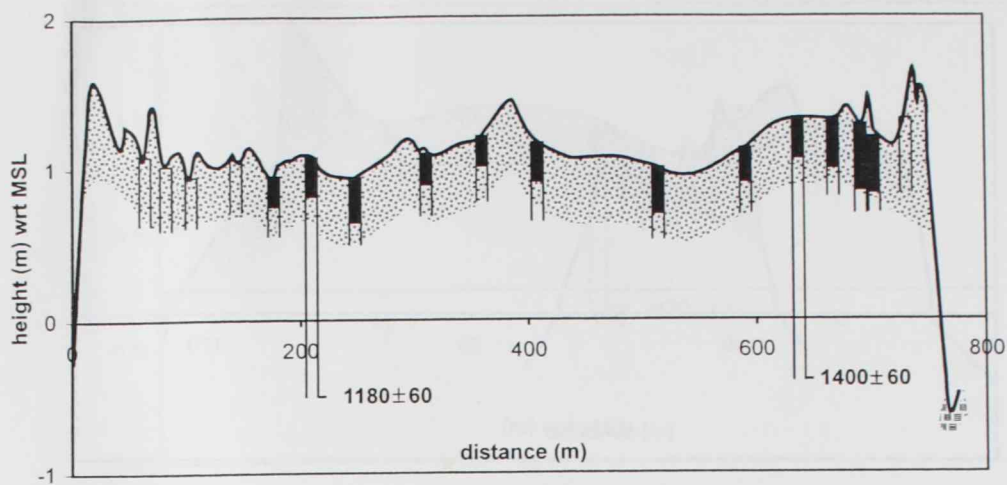


Gemendhoo B (NNW-SSE)

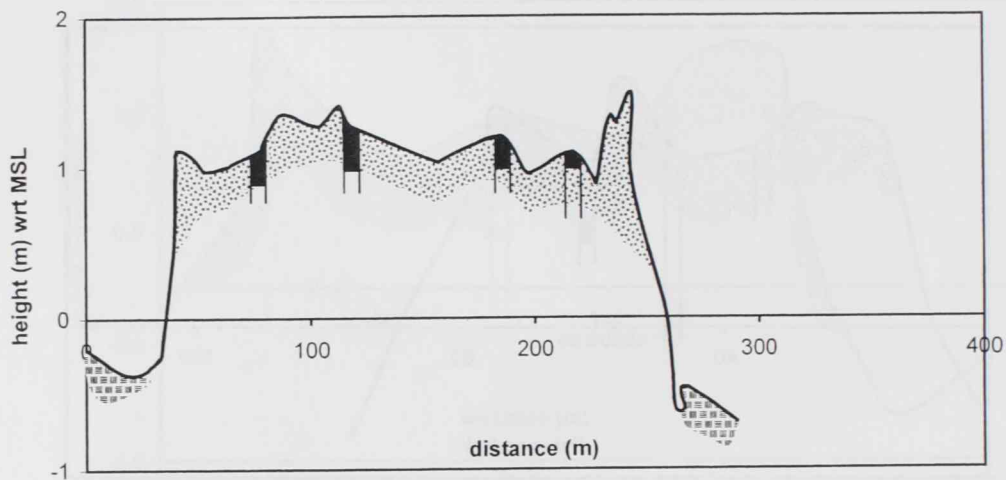




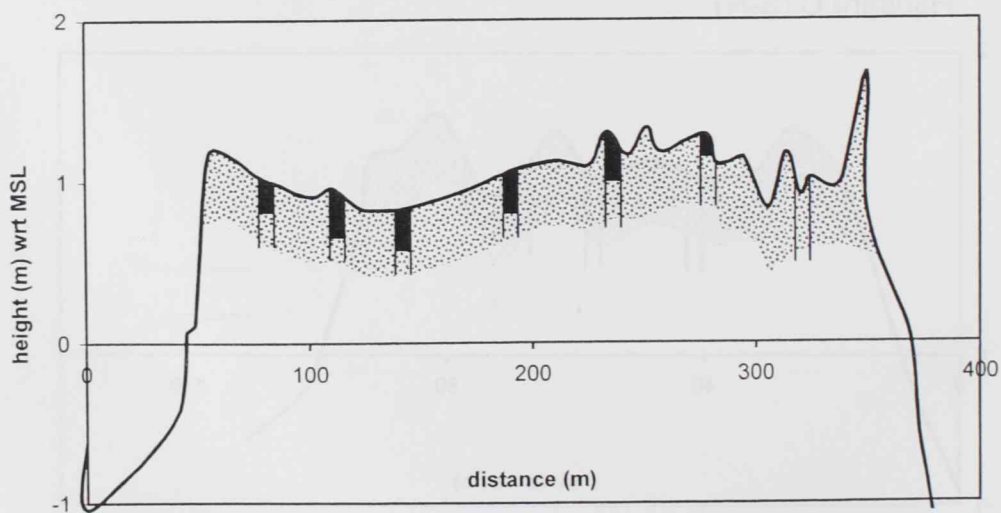
Hibalhidhoo A (NW-SE)



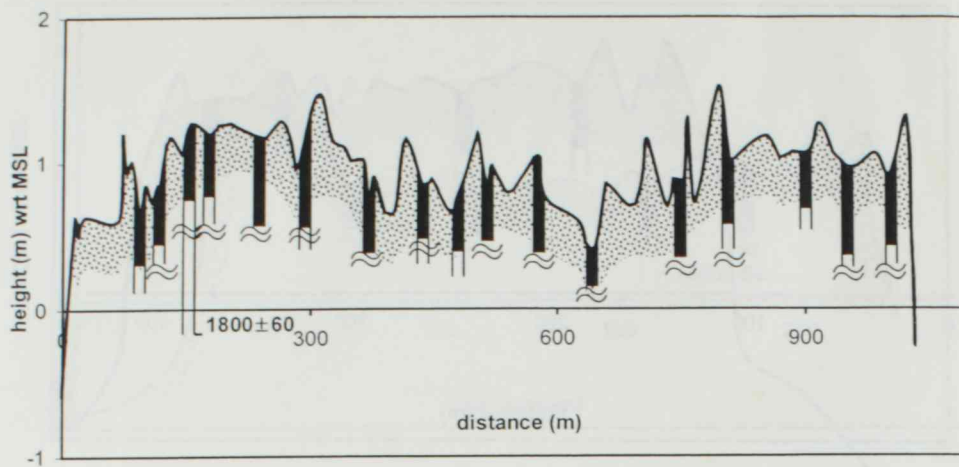
Hibalhidhoo B (SW-NE)



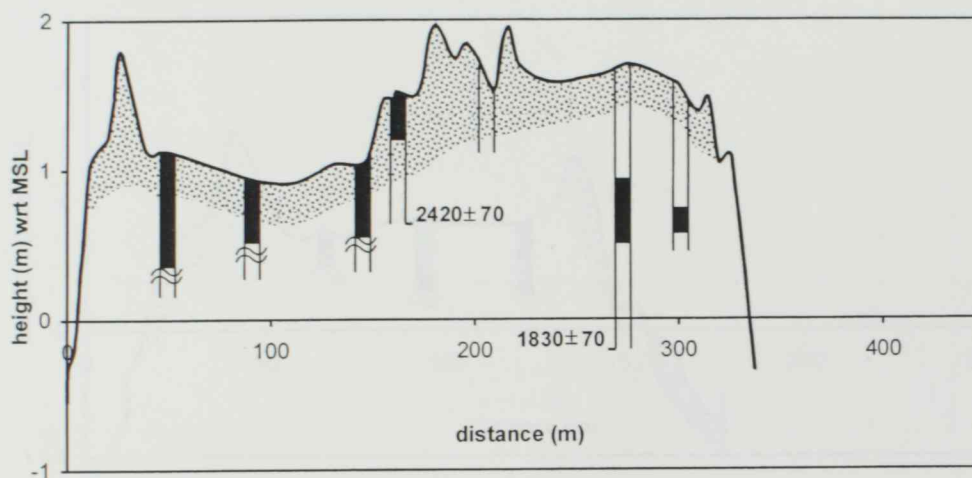
Hibalhidhoo C (WSW-ENE)



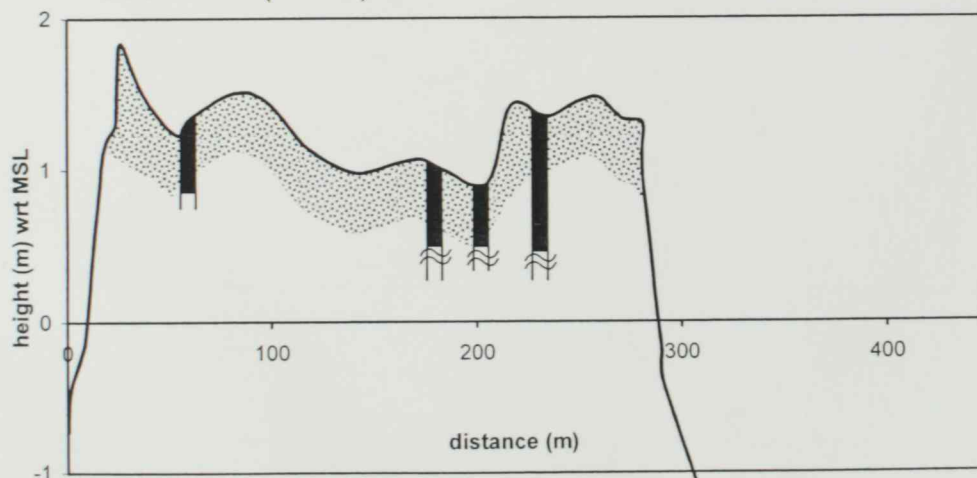
Maaddoo A (NW-SE)

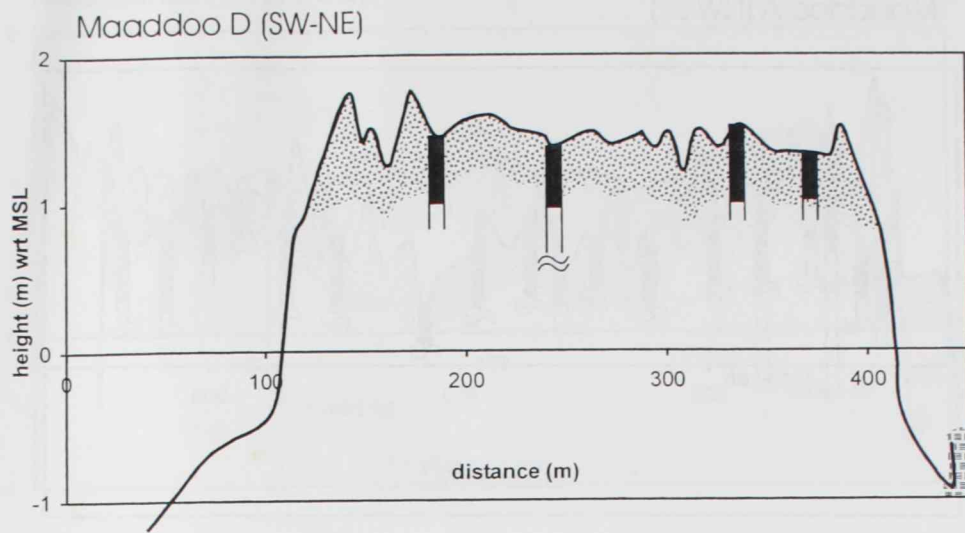


Maaddoo B (SW-NE)

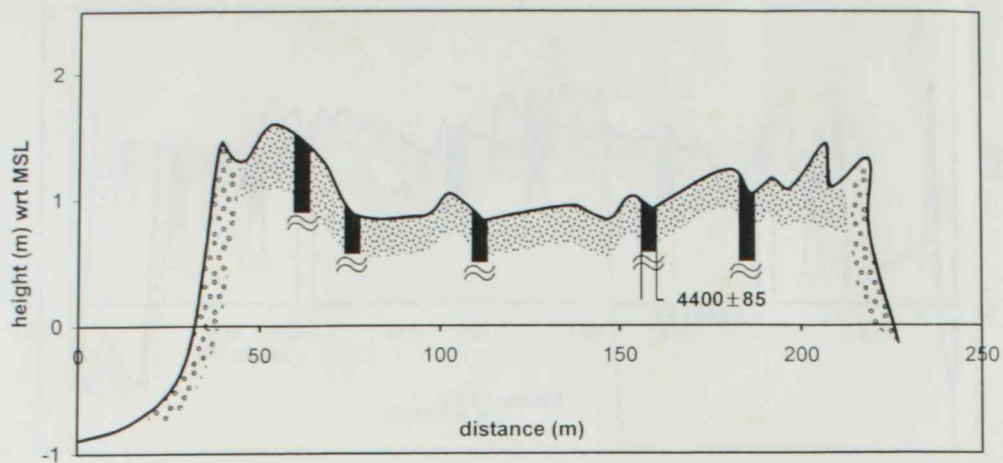


Maaddoo C (SW-NE)

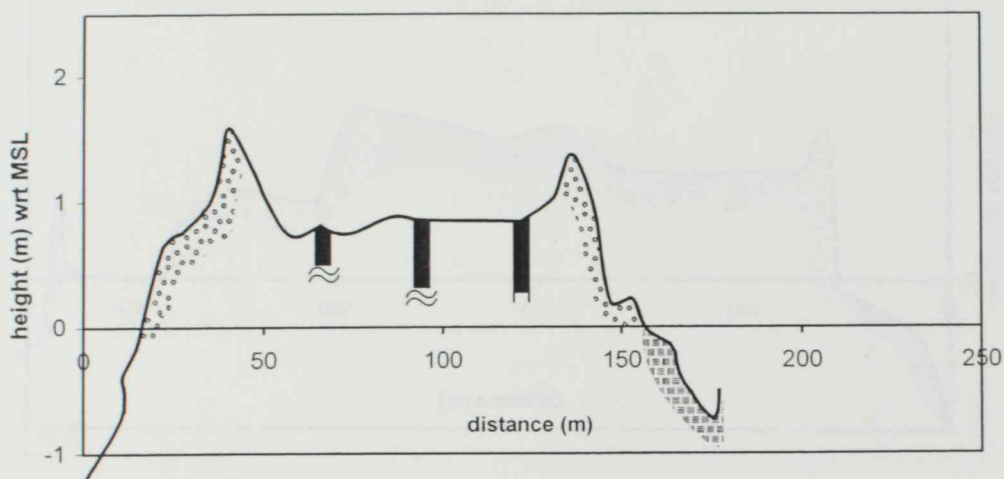




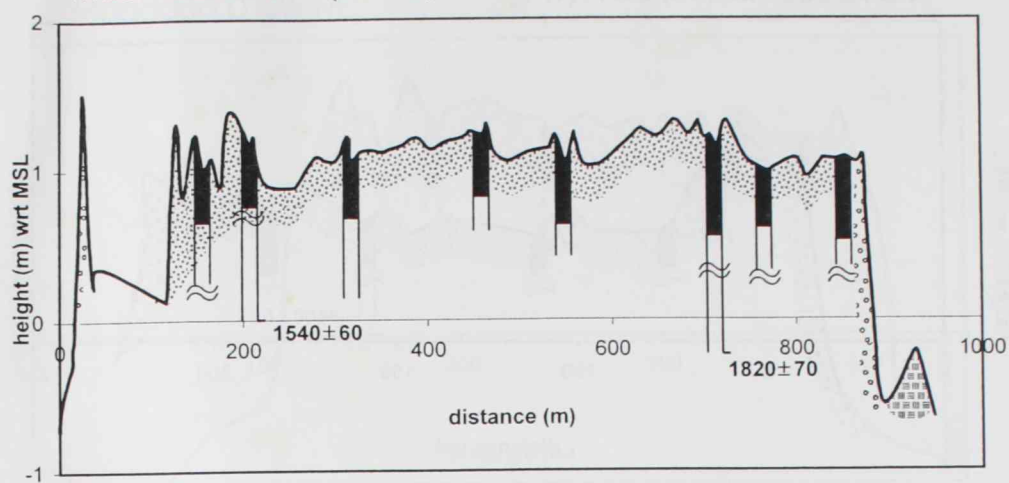
Maaddoo-hulhudhoo A (W-E)



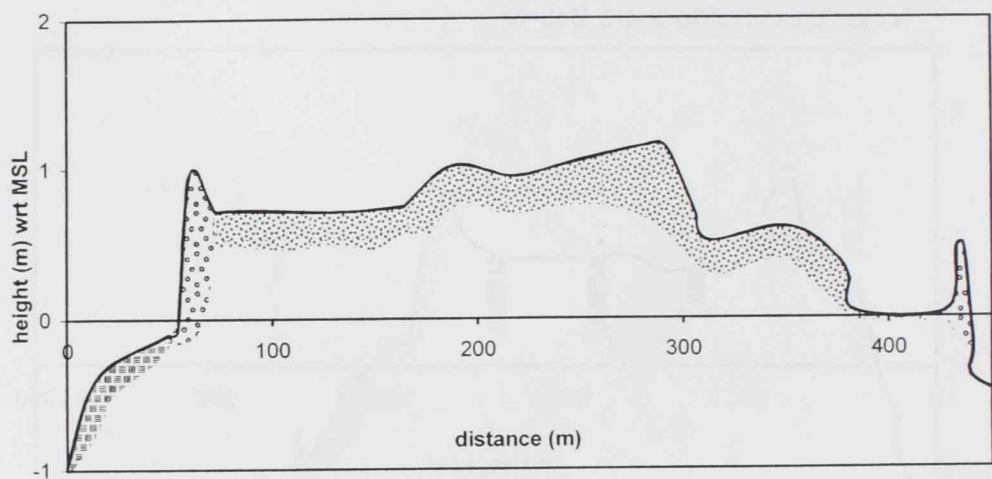
Maaddoo-hulhudhoo B (S-N)



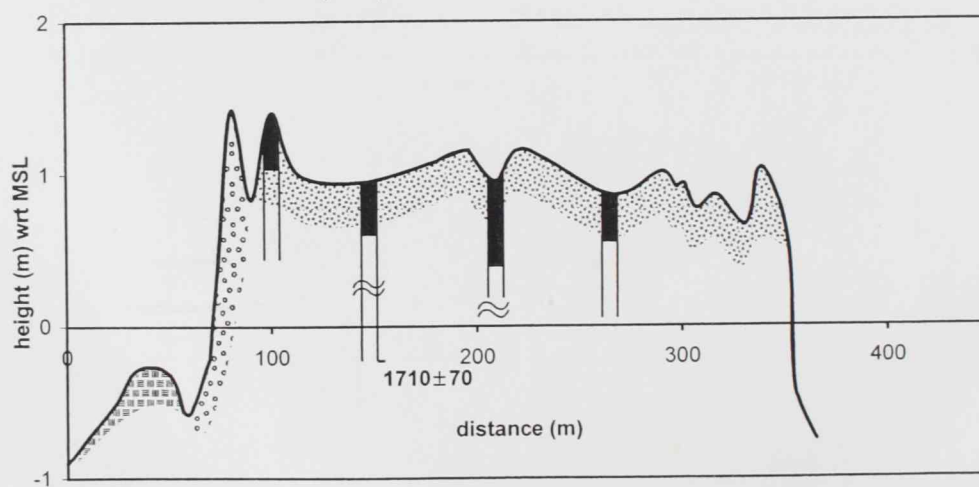
Maamaduvari A (SW-NE)

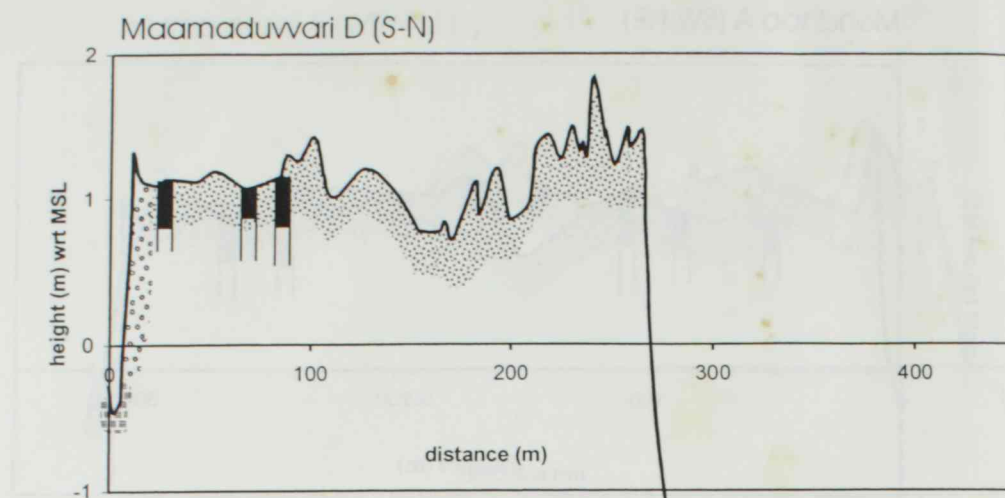


Maamaduvari B (SW-NE)

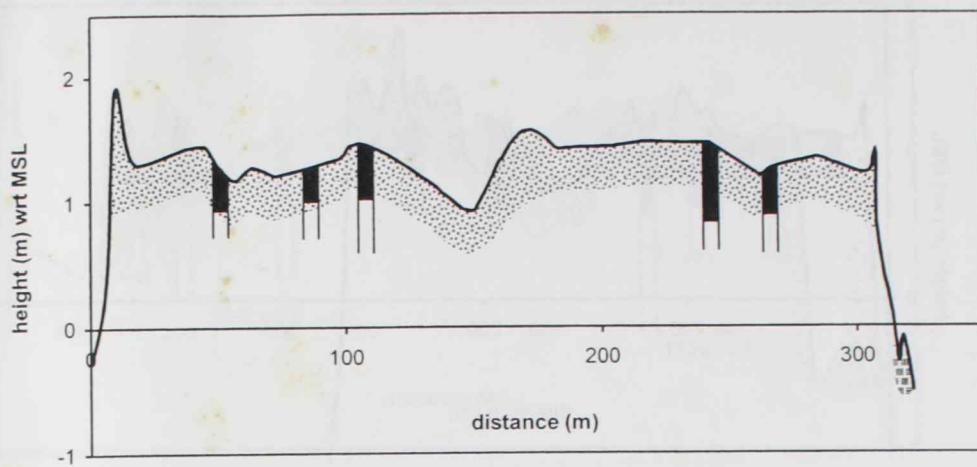


Maamauwari C (S-N)

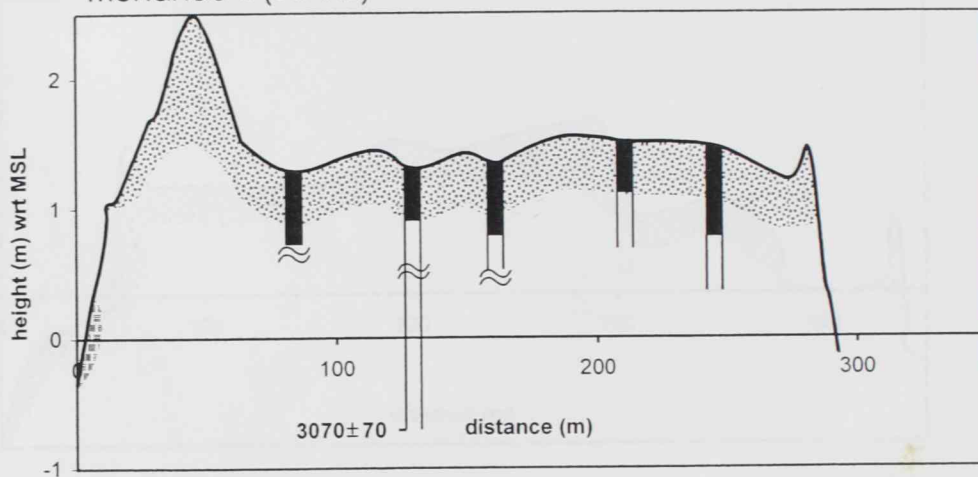




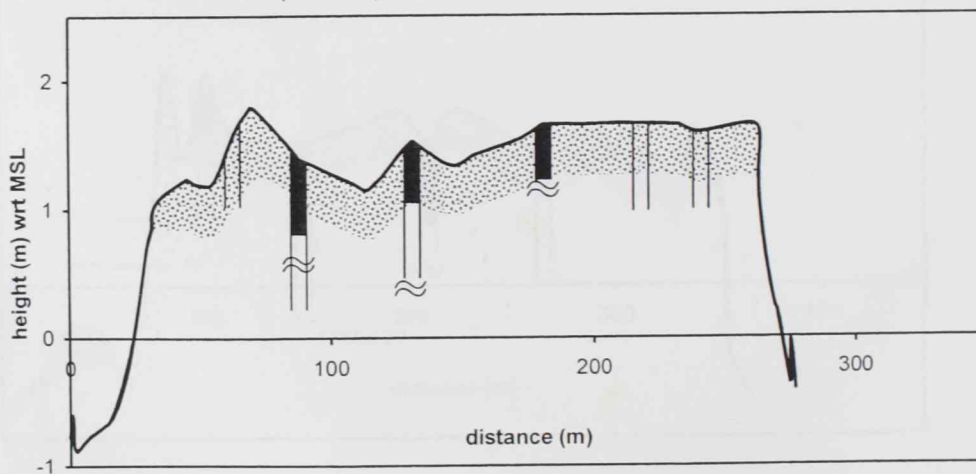
Mendhoo A (SW-NE)



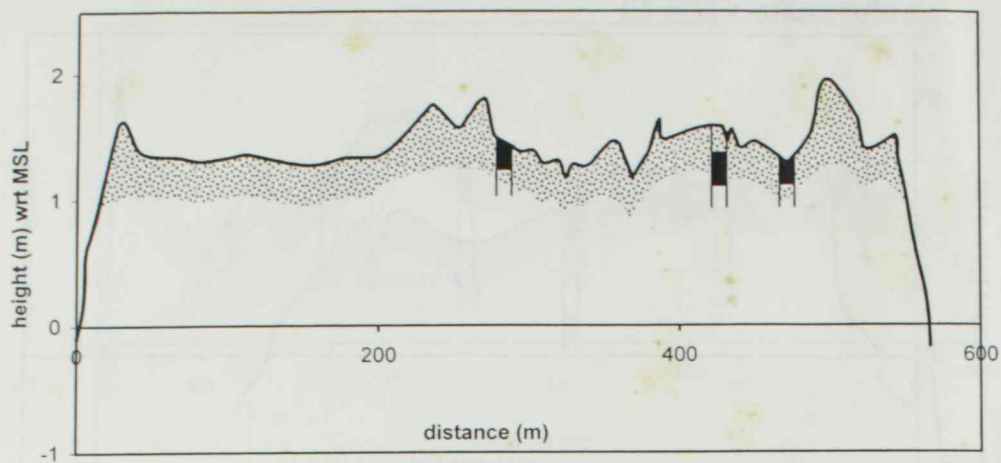
Mendhoo B (SW-NE)



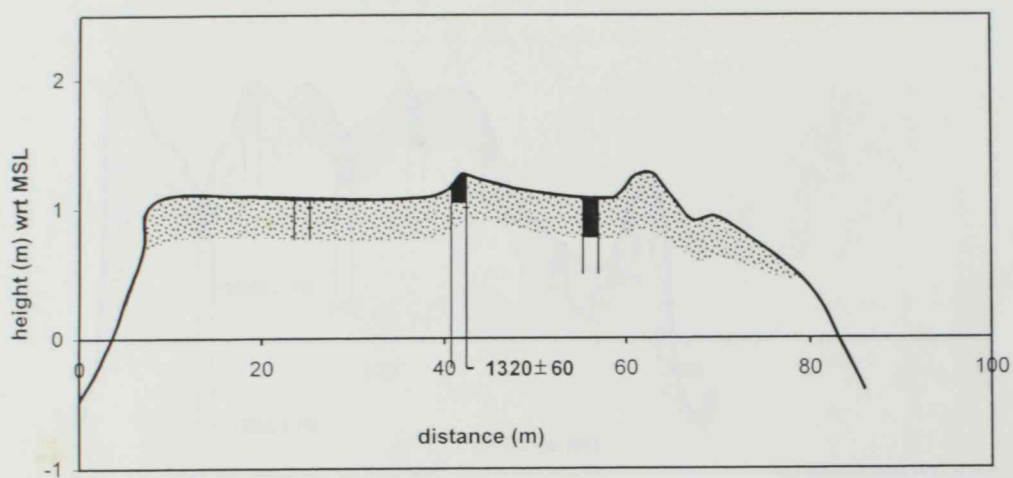
Mendhoo C (SW-NE)



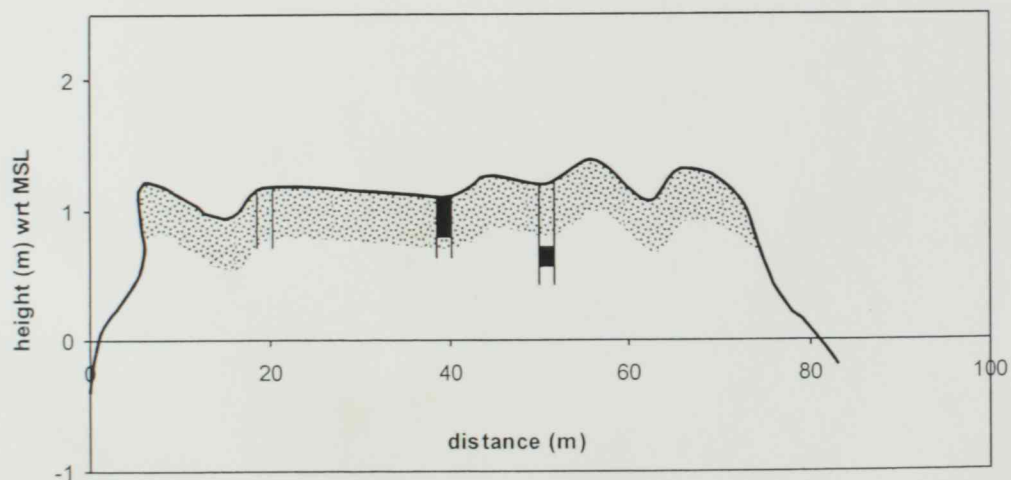
Muthaafushi A (WSW-ENE)



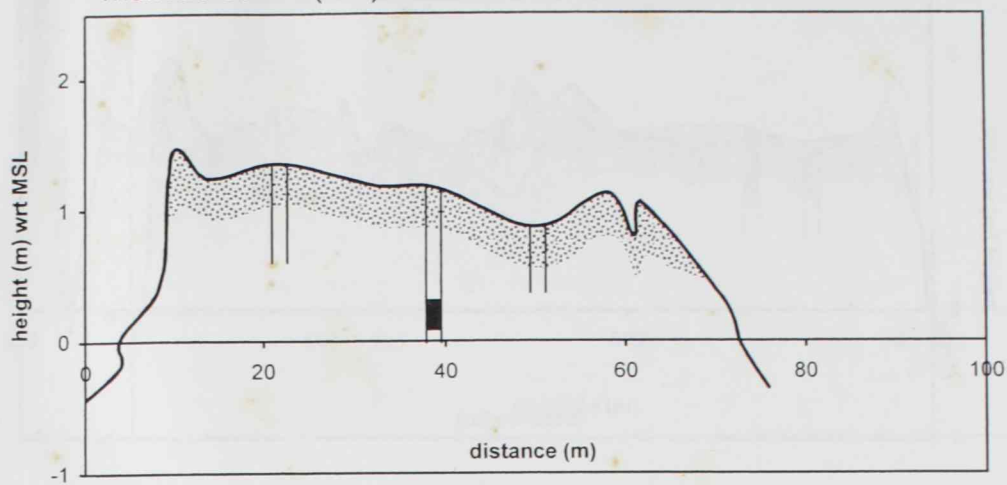
Muthaafushi B (S-N)



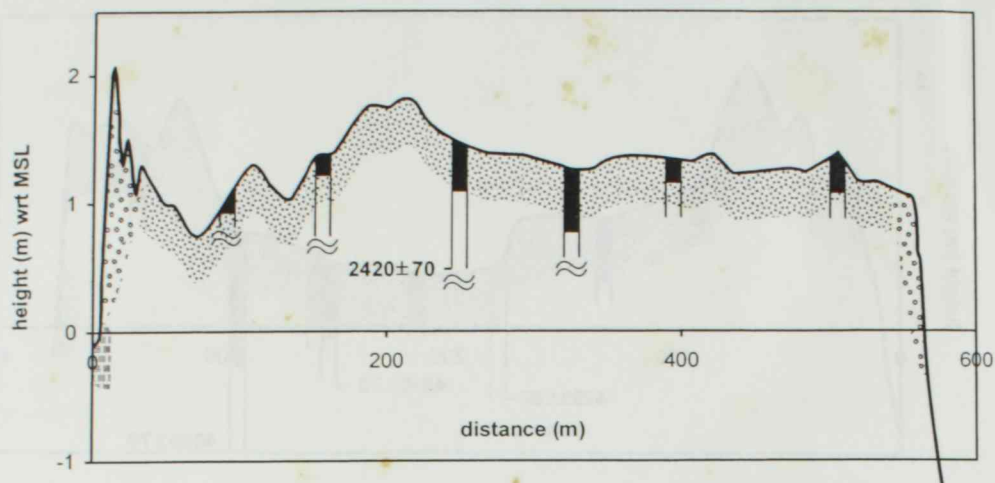
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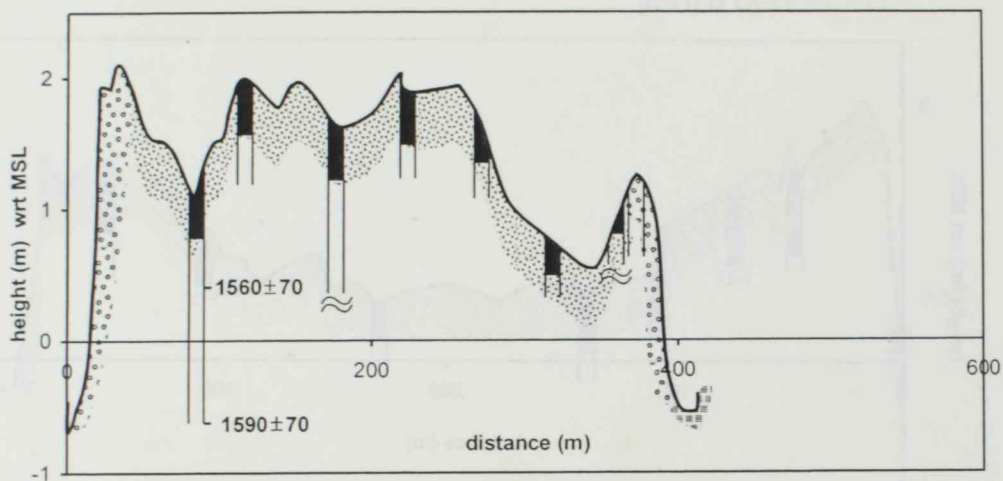
Muthaafushi D (S-N)



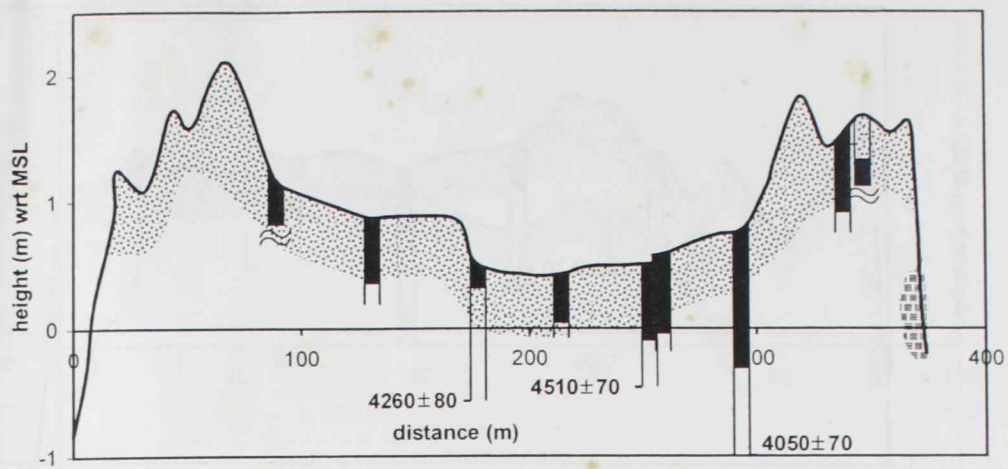
Olhugiri A (WSW-ENE)



Olhugiri B (SSE-NNW)



Udoodhoo (A) W-E



Udoodhoo B (N-S)

