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THE GEOMORPHOLOGICAL AND ZONATIONAL DEVELOPMENT OF MANGROVE SWAMPS IN THE TOWNSVILLE AREA, NORTH QUEENSLAND

VOLUME I

Thesis submitted by

ANTHONY PHILIP SPENCELEY BSc *Aberd* MSc *NE*

in July 1980

For the Degree of Doctor of Philosophy in

the Department of Geography at the

James Cook University of North Queensland

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A.P. SPENCELEY

8 July 1980

ABSTRACT

Research was undertaken in three mangals in the Townsville area. Two were located on an open accreting coastline and the third on an estuarine coast. Mangals on the lee-side of Magnetic Island and Orpheus Island were examples of an open accreting coastline whilst the mangal at Saunders Beach, on the right bank of Althaus Creek, was an example of an estuarine coast. Because of ease of access, the first and last sites were studied intensively. The aims of the project were:

(i) to investigate factors that influence mangrove zonation;
(ii) to investigate the role mangroves play in the sedimentary processes operating on the intertidal slope; and
(iii) to investigate the evolution of the swamps.

The soil chemical characteristics of an open accreting coastline were found to be different from those of an estuarine coastline. The chemical data from Magnetic Island displayed a marked spatial trend but, on the whole, lacked a temporal variation. At Saunders Beach, the soil chemical data displayed significant variations both in time and space.

Statistical analysis of the data using factor analysis revealed a basic similarity in the underlying structure of the data sets. Over 50% of the covariance was explained in terms of a salt factor and a pH factor. Grouping the zones together according to their soil chemical characteristics produced a contrary picture. Stations from within the *Rhizophora* zone on Magnetic Island were not grouped together, nor were the stations within the *Ceriops* zone. However, stations within a particular zone at Saunders Beach were grouped together. The reverse situation occurred on the bare or sparsely covered areas on the upper intertidal slope. Zones on Magnetic Island were grouped together but those at Saunders Beach were not. Consequently the zonation of mangroves in the Townsville region cannot be adequately explained in terms of the soil chemical variables that were analyzed.

Two types of salt flats were identified, relict and contemporary. Relict salt flats were caused by a relative fall in sea level whilst the contemporary salt flats were caused by a break in the vegetation canopy. Consequently they need not be part of the usual vegetational sequence in seasonally dry climates.

It was found that maximum bed load was transported in the seaward or creekward section of the swamps declining landward. However, above approximately mean high water spring tides (MHWST) amounts of bed load increased. A similar trend was observed in the pattern of accretion. Greatest variations in erosion or deposition were seen in the seaward or creekward margins of the swamps declining landwards to approximately MHWST, beyond which the variations again increased. The increases on the upper part of the intertidal slope were due in part to particle size differences. Other controlling factors that may be important are the initial rippling wavelet on the flood and ebb tides; overland flow from the terrestrial environment; intercepted rain water streaming down tree trunks and being concentrated between buttress roots; intercepted rain water dripping off the tree trunks, concentrating its energy on a small area.

Series of grids were used to simulate pneumatophores. It was found that the grid spacing directly influenced the rate of accretion. The experiment reinforced the idea that mangroves stabilize the intertidal slope sediments, the fine rootlets binding the soil particles. Electrolytic and chemical factors may also be associated with the increase in cohesion of the sediment.

The evolutionary history of the swamps was described. Each swamp had a different sequence of development. Coupled with a different set of species being present, each mangal has developed a unique vegetational pattern in response to the continually changing environmental conditions. Interactions that operate within mangals of the Townsville area have been incorporated into a model of mangal development. Mangal development and the distribution of species within mangals are seen as a reflection of the species pool available for colonization, geomorphological history of the area, soil type and the changing environmental conditions which affect the normal interspecific competition.

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CHAPTER ONE

RESEARCH PROBLEM AND METHOD OF ANALYSIS

General Introduction

Mangals (MacNae, 1968) occupy about one-quarter of the world's tropical coastline (Johannes in Krishnamurthy, 1975). For centuries they have been exploited as a source of building timbers, firewood and dyes (Watson, 1928; Walsh, 1977; Bird, 1978). Today, they are recognized increasingly as an essential part of the nutrient chain in tropical and sub-tropical environments. A study of mangals in Puerto Rico found them to be a more fertile environment than most marine and terrestrial communities (Golley *et al.*, 1962). Mangals also provide important fish breeding grounds (Carter *et al.*, 1973). However, there are still large deficiencies in fundamental information concerning the operation and function of mangals as a community. This has received some attention with the publication of three highly significant reports. The first of these was an ecosystem analysis of the Big Cypress Swamp, Florida (Carter *et al.*, 1973). As a result of this report and associated research programmes the importance of this ecosystem was realised. Subsequently the decision to build an international airport on the eastern edge of the Big Cypress Swamp was shelved.

The second report was in the proceedings of a conference on acid sulphate soils which was published in the same year (ed. Dost, 1973). The conference dealt with the recognition, distribution, processes and problems associated with acid sulphate soils. The last and probably most important publication is the two-volume proceedings of an International Symposium on Biology and Management of Mangroves, held in Hawaii in 1974 (ed. Walsh *et al.*, 1975). Divided into six sections: Biogeography; Biology, Geomorphology and Soils; Anatomy and Physiology; Micro-organisms; and the Effects of Man, the two volumes provide, to date, the most comprehensive statement of knowledge on mangroves. Even so, many gaps in that knowledge still remain, particularly on the physical environment where the interaction of the plants with the land surface is poorly comprehended. Since copies of the reports were not received until mid-1976 they could not be used as background information in the initial development of the project. However, they are of great value in assessing the results.

Mangroves are located in a dynamic environment, a constant interaction occurring between the mangroves growing on the intertidal slope (Davies, 1972) and the local and regional marine processes. The effect that mangroves have on sedimentary processes across the intertidal slope has been commented upon for several decades. Mangroves are thought either to assist in the accretionary processes by initiating the formation of islands (Vaughan, 1909) or to be able to establish themselves only after the land surface has reached a suitable height (Watson, 1928; MacNae, 1968). However, such a discussion of these finer points ignores the fundamental problem associated with the sedimentation processes in mangals. It has been assumed that the roots of mangroves actively trap sediment (e.g. Walsh, 1974:66). However, although macro-organic matter is found lodged between prop roots and pneumatophores, the exact role that these physiological adaptations play in the sedimentary processes has not been demonstrated. The fact that mangals are thought of as the tropical equivalent of the mid and high latitude salt marshes (Steers, 1959) may have led researchers to presume a sedimentary role for mangroves similar to that of salt marsh species. That the two communities have different physiognomic characteristics and occupy different portions of the intertidal slope seems to have been ignored.

A comparable situation appears when the causes of plant zonation are considered. Similar controlling factors have been suggested for salt marshes (Adams, 1963) and for mangals (Clarke and Hannon, 1967; MacNae, 1968). Walsh (1974) produced a comprehensive review of the arguments. The crux of the problem is that although a relationship has been determined between plant zonation and various physical factors, no direct *causal* relationship has been demonstrated; it has only been inferred. Since such relationships have been challenged in other coastal vegetation communities, such as in sand dune swales (Jones, 1972a, b), it is probable that factors other than physical controls are important in determining mangrove zonation across the intertidal slope.

The evidence that has been put forward to explain the present day distribution of mangroves across the intertidal slope has relied basically upon data concerning contemporary phenomena. Since the nature of the environment within which mangals exist is dynamic, the inputs, throughputs and outputs of energy and matter associated with that environment must be constantly changing both in time and space. As a result, the rates of various processes operating in mangals should show a variation parallel to that of the environmental fluctuations. The extent of mangals and the distribution of species within these communities are therefore viewed as a result of the sum of all past and present processes. Therefore in order to reach a meaningful understanding of the pattern that exists today within a particular swamp, it is probably as important to comprehend its evolutionary history as to be aware of the present day processes operating within that swamp.

The object of this study is to investigate the dynamic relationship between mangals and the processes operating on the intertidal slope and high tide flat in the Townsville area. This will be achieved by considering

(i) contemporary factors that may influence mangrove zonation
(ii) the role mangroves play in the sedimentary processes operating on the intertidal slope
(iii) the evolutionary history of the swamps.

Factors Influencing Mangrove Zonation

Most mangals display a distinct pattern or zonation of species from the seaward to landward edge of the swamps, the zonation essentially paralleling the direction of the coast. Local deviations from this trend are apparent on creek banks and in complex deltas. MacNae (1968) suggested that an ubiquitous floral assemblage can be identified across the intertidal slope to which causal factors can be ascribed. A basic pattern in the Indo-West Pacific from sea to land is a pioneer fringe of *Sonneratia* spp. and *Avicennia* spp., followed by zones of *Rhizophora* spp., *Bruguiera* spp., *Ceriops* spp., and a landward fringe that may be forested or colonized by *Avicennia* spp. and by halophytes. Such a scheme identified by MacNae is typical of many areas, for instance South Africa (MacNae, 1963; MacNae and Kalk, 1962), Bombay, India (Navalkar, 1951), north Queensland (MacNae, 1966) and Malaya (Watson, 1928). The full zonation occurs only in areas which have a high rainfall all year round. The landward zones become more complex in composition depending on the local species pool. Genera such as *Aegiceras*, *Aegialitis*, *Lumnitzera* and *Xylocarpus* are associated with this zone although there are variations in their frequency of occurrence. With an increasing length of the dry season, both the number of species present and the number of zones decrease. Bare saline flats occur with an increasing frequency and extent as the dry season becomes longer. *Avicennia* sp. and samphire species are found in the landward zones under such conditions (e.g. Baltzer, 1969; Walter, 1971; Thom *et al.*, 1975; Spenceley, 1976).

A number of subsidiary species may also be present in each zone, the number of species tending to increase in a landward direction. This trend is more apparent in swamps that have developed either under a high rainfall regime or where seasonally high fresh water discharges from neighbouring creeks and rivers occur.

The zonation of mangroves across the intertidal slope and high tide flat has been likened to a succession (Davis, 1940; Chapman, 1944; Richards, 1952). This view has been challenged by Clarke and Hannon (1969) who considered the zonation of mangroves and halophytes at Sydney to be related in part to the micro topography. The view that the disposition of mangroves is related to the geomorphological process-response system rather than actually being a succession, has also been advocated by Thom (1967, 1975; Thom *et al.*, 1975). Since the salt affected areas are still subjected to environmental, geomorphological and micro climatological changes, a stable self-perpetuating climax vegetation community does not exist. Thus in such an area it is misleading to equate the zonation of mangroves with a succession since no climax community exists. Instead there are concomitant changes in plant/land surface environments. These perpetuating changes are reflected in the variety of species associations and patterns observed in mangals.

Controls of Zonation

Building on ideas developed by Watson (1928) and De Haan (1931), MacNae (1968) suggested three fundamental determinants of the zonation within mangals. They are:

(i) Frequency of flooding;
(ii) Salinity of soil water;
(iii) Waterlogging of the soil.

All of these may be influenced by the presence of creeks, gullies, rivers and channels. Factors two and three will also depend upon (a) rainfall and/or the supply of fresh water, (b) evaporation and transpiration, (c) the nature and quality of the soil. The channels, if large enough, may influence the type of material deposited. The increased discharge, resulting from rains associated with cyclones, may contain a different load characteristic from that usually carried. Coarser material may be entrained and deposited within the mangal. This in turn may influence the distribution of the mangroves (Baltzer, 1972).

Other parameters have also been suggested as contributing to the zonation of mangals. The amount of light in an area was thought to be important for seedling establishment and growth of light-demanding species (Baltzer, 1969; Clarke and Hannon, 1971; Chapman, 1975). Although no characteristic zonation was identified on the Island of Madagascar (Hervieu, 1968), zonation there was thought to be due in part to local hydrodynamic characteristics. It was considered that the development of intermediary zones depended on the rapidity and progression of sedimentation in any one area; the more rapid the sedimentation the less likely that the mangrove zonation would be fully developed. This was because the faster growing species would initially invade the area excluding the slower establishing and growing plants. An imbalance in numbers and distribution of the species would therefore ensue. However it was believed that differences noted above were not sufficient to explain the disparities between the various mangals. Progressive embankment of tidal channels which increased emergence of areas was also thought to be important. Changes in plant zonation were thought to develop with increased salinity and aridity inland (Hervieu, 1968).

Weiss and Kiener (1971) also used salinity values to explain the mangrove zonation at Tulear (south west Madagascar) even though significant differences were also noted in the chemical analyses of water samples which were collected from various zones in the swamp. Likewise on New Caledonia Baltzer (1969) reasoned that the level of sea water and ground water salinity values were prime causal factors for mangrove zonation. Each species was thought to have limiting conditions of tidal immersion. Water greater than particular critical depths inhibited successful seedling establishment. A correlation was found between species distribution and ground water salinity.

The preference of particular species for certain salinity levels was noted also by MacNae (1968). Barbour (1970) indicated that most mangroves are faculative not obligate halophytes which attain maximum development in fresh to brackish water (0-10ppt). However, he did acknowledge the fact that it was difficult to relate the results of laboratory experiments to conditions in reality. Many experiments involving plant growth have been reported but the conditions under which the experiments have been conducted were different from each other as well as from field conditions.

Salinity of water and soil solution; tide; water level, whether caused by tides, rainfall or drainage from the interior; and soils were thought to be the major environmental factors controlling plant distribution across the intertidal slope in Florida (Davis, 1940). Variables such as climate, aeration, and drainage were thought to be of lesser importance. This opinion has been challenged by Egler (1952) who suggested that a quite different set of factors was responsible for the zonation. These were the effect of fire and hurricanes in conjunction with a recent rise in sea level.

In an attempt to formalize the causes of zonation, Clarke and Hannon (1969) produced what they termed the halocoenotic complex in mangroves and salt marshes of the Sydney district, N.S.W. (Figure 1.1). The basis of this complex was that the plant-soil-climate interrelationship is dominated by the phenomenon of tidal inundation, salinity of soil water, and extent and nature of plant cover. In the interpretation of the relative importance of these three factors, the type of vegetation present at Sydney must be considered. The zonation from sea to land was A—*Avicennia marina* var. *resinifera, Aegiceras corniculatum* sometimes present; B—*Arthrocnemum australisicum, Sporobolus virginicus, Samolus repens, Triglochin striata, Suaeda australis;* C—*Juncus maritimus* var. *australiensis, Cladium junceum, Phragmites communis*; D—*Casuarina glauca* and *Melaleuca quinquenervia*. That is with only one zone of mangrove present. Under those circumstances it is difficult to recognize the universal application of this scheme to mangroves in general without much more field investigation.

Clarke and Hannon, however, have made a valuable contribution to the study of salt marshes and mangroves. They have highlighted many areas of concern and stimulated the inquiry into mangrove zonation. The formal recognition that ground water salinity is related to plant cover, not just to the nature of the soil, rainfall and evaporation as has been generally accepted, adds a new dimension to the understanding of zonation and in particular to the causes of bare patches.

A linkage that is not included in the complex is the one between tidal inundation and drainage and aeration. This is important since significant variations occur in the rate of soil chemical reactions concomitant with changes in tidal exposure of the intertidal slope (Moorman and Pons, 1975). In spite of the disregard of soil as an important variable in causing zonation (e.g. Davis, 1940; Clarke and Hannon, 1969) this factor may hold the key to the question of plant zonation in mangals (Baltzer and Lafond, 1971).

Such a suggestion has also been advanced by Thom (1975). He suggested that patterns in swamps were seen as a response of plants to habitat changes which have been primarily induced by geomorphic processes. Thus, given any particular climatic and tidal environment and an assemblage of mangrove species, the responses of those species to the particular geomorphic environment will determine which species will successfully establish themselves and consequently the distribution pattern of the mangroves. At Tabasco, Mexico, the interaction of certain habitat characteristics, such as water regime and substratum properties, with the various species present produced particular patterns in the vegetation community (Thom, 1967). *Rhizophora* trees preferred lower sites because of a higher degree of water saturation, low salinities and chemically reduced conditions. *Avicennia* species, in contrast, preferred higher, drier habitats with higher salinities (often greater than 40ppt), and oxidized soils. *Laguncularia* had less stringent requirements but displayed a general dislike for relatively dry compact soils. Short term and long term seral changes were noted. On actively accreting mudflats, in the short term, changes occur as a response to the interaction between geomorphic and biotic processes. Long term trends were conditioned by continually changing physiographic processes on the deltaic plain which influenced phenomena such as water saturation of the soil, salinity of ground and surface water, soil type and drainage of the surface. Time lags, however, did occur between landform and vegetation changes.

By comparing situations on the Ord River and the low wooded islands in the northern section of the Great Barrier Reef, Thom and his co-workers (Thom, 1975; Thom *et al.*, 1975) have shown that various plant habitats were affected by geomorphic processes. These processes in turn affected the habitat's topographic form, the frequency of tidal inundation, the sediment type, the salinity of soil water and degree of aeration. The interaction of these environmental factors may also affect the patterns of mangrove associations and physiography. Such ideas were also inherent in Gledhill's work (1963) on the ecology of Aberdeen Creek mangrove swamp, Sierra Leone, where he noticed distinct floral, sedimentological and geomorphological associations.

The essence of Thom's argument allows a reassessment of work by Walter and Steiner, and by Bünning. Walter and Steiner's classical work on East African mangroves was completed in 1936 and a resume was given by Walter (1971). One of the main conclusions of this study was that zonation of mangroves was a direct consequence of competition between species present. The competitive ability of individual species was itself influenced by their responses to three environmental factors:

(i) frequency and duration of flooding by sea water;
(ii) consistency of soil : sand or clayey mud deposits;
(iii) the degree of admixture with fresh water at the mouth of rivers and the concentration of brackish water.

Likewise Bünning (Ding Hou, 1958) considered that zonation of the mangroves was caused primarily by the soil types (their mineralogical and physical condition) not by salinity. Moorman and Pons (1975) have shown that soil chemistry is affected by exposure which, indirectly through frequency of inundation, affects the processes acting on the intertidal slope and therefore the particle size distribution. The reversible oxidation-reduction reactions that take place in waterlogged soils have been described by van Beers (1962), Ponnamperuma (1972), and Moorman and Pons (1975). The latter authors distinguished two major phases of soil formation: pedogenesis in the reduced muds and changes which take place upon aeration and oxidation of the sediment. In the reduced phase there is an accumulation of secondary organic matter mainly from roots. Under anaerobic conditions, decomposition and mineralization of soil organic matter is low. The amount of organic matter in the soil depends upon the rate of sedimentation and the type of mangrove present; densest organic mats being found, in West Africa, under stands of *Rhizophora* spp. (Hesse, 1961b; Giglioli and Thornton, 1965).

Elemental reduction is generally due to microbial activity, e.g. *Sporovibrio desulfuricans* (Vieillefon, 1969). The source of oxygen for their activity is derived from oxides (such as that of iron) and from sulphates, whilst the energy required is derived from the decomposition of organic matter (Moorman and Pons, 1975). Upon aeration oxidation is initiated. Again microbial activity, e.g. *Thiobacillus ferro-oxidans* (Hart, 1959) and *Thiobacillus thio-oxidans* (Thornton and Giglioli, 1965) is important. Oxidation becomes dominant where tidal flooding diminishes. With increased emersion and loss of plant cover, soil forming factors dominate pedogenetic activity.

The concept of soil ripening (Pons and Zonneveld, 1965) summarizes the wide range of processes that take place on aeration. Processes include physical ripening, related to the dehydration and compaction of the sediments with particular reference to changes in water content, volume, consistency and structure of the soil; chemical ripening, comprising all chemical and physio-chemical changes which sediments undergo; and biological ripening which reflects processes influenced by organisms (Pons and Zonneveld, 1965).

Soil ripening as a concept provides a good methodological framework. Field studies in mangals, however, suggest that the intensity of the processes may vary between sites. Diemont and Wijngaarden (1975) have demonstrated that significant differences exist between two types of coastlines that they defined as an estuarine and an open accreting coastline:

(i) Soil types in an estuarine system change abruptly whereas those in an open accreting coastal system change gradually. This is due to the physiography of the system.

(ii) Morphological features of the systems differ in colour and organic content. Estuarine soils are brown and have a high content of organic matter. Open accreting coastal systems' soils are greenish and low in organic matter.

(iii) Water movement in reduced estuarine soils is good, whereas there is hardly any water movement in soils of an open accreting coastal system.

(iv) Differences in water movement are confirmed by differences in pH and HCO_3^- concentrations between soil and open water. In estuarine systems the pH difference is zero and the HCO_3^- difference is less than 10mmol/l. In open accreting coastal systems the pH difference is approximately 1 unit and the HCO_3^- difference is 15-25mmol/l.

(v) In estuarine systems the oxidizable sulphur content is 1.52% or more in reduced soils whereas in open accreting coastal systems the content is 0.5% or less.

(vi) Oxidation in an estuarine system begins in the levees at mean high water. The highest basins are above mean high water springs and reduced. In an open accreting coastal system oxidation begins at mean high water.

(Diemont and Wijngaarden, 1975)

The differences listed above, however, related to broad areal characteristics. No information was given about trends across the intertidal slope.

Although the occurrence of any species has been commonly explained in terms of the external physical or biotic media, the physical environment must also impinge upon the metabolic processes that result in growth and reproduction (Chapman, 1966). Thus Lugo *et al.* (1975) working in the mangrove forests of south Florida concluded that the zonation of mangroves also involves zonation in their rates of photosynthesis, respiration and transpiration. Clarke and Hannon (1971) have shown that the mangrove and salt marsh species were able to compete against one another with varying degrees of success depending on the shade, salinity and waterlogging conditions.

The ideas suggesting controls of mangrove zonation can be put into one of two categories. On the one hand there are papers which argue the case for salinity, exposure and competition as being the most important factors. On the other, it has been pointed out that there are significant changes in soil chemical processes which could affect rates of mangrove transpiration, respiration and productivity.

There is evidence that suggests further inquiry into the status of some elements in the soil would be useful. Navalkar and Bharucha (1950) made a study of the exchangeable bases of mangrove soils in India. Three distinct soil/vegetation types were distinguished. *Avicennia alba*'s soil was dominated by Ca-Mg, *Acanthus ilicifolius*'s by Ca-Na and *Suaeda fruticosa*'s by Ca-K. One qualification exists however. When soils from beneath *A. alba* were considered, samples were only collected from one area. Soil from different locations along the coast were sampled in the case of the other species. Thus the soil chemical status under different vegetation cover in the same locality has not been analyzed. Differences in soil characteristics may therefore result as much from different parent materials and fresh water flushing as from variations which relate to vegetation changes.

Two studies of more local interest were those conducted in Auckland, New Zealand, by Davison (1950) and Chapman and Ronaldson (1958). Seasonal variations of several elements were considered beneath a salt marsh and mangrove (*Avicennia officinalis*) cover. Seasonal trends were found for chloride, sodium, calcium and potassium. The variations in chloride, sodium and calcium were directly related to changes in precipitation as well as to the presence of shell layers in the case of calcium. No reasons were given for variations in potassium although it was noted that maximum values were found in sandy layers in association with shell bands.

In a pedogenetic study of soil types under a mangrove forest in south west Senegal, Vieillefon (1969) identifies seven vegetation zones. *Rhizophora racemosa* and *R. mangle* were located on the edge of the river followed by a wide zone of *R. mangle*; a zone of *R. mangle* with a herbaceous layer of *Paspalum vaginatum*; a zone of *Avicennia nitida* with some undergrowth of *Scirpus littoralis*; similar to the last zone but with a sparser undergrowth of *Sporobolus robustus* and *Sesuvium portulacustrum*; a bare zone; and a zone covered with a herbaceous layer comprising *Heleocharis mutata* and *H. carribea*. Great variation in the organic matter of the soils depended on the surface vegetation. *Rhizophora* spp.'s prop roots produced a more extensive organic mat than the lateral roots of *Avicennia* sp.'s. On exposure to the air oxidizing conditions were created and the roots of dead trees were rapidly broken down. Because of the type of soil changes Vieillefon considered that the soils under each vegetation zone did not constitute a soil catena but rather a chronosequence. That is, their juxtaposition related to a long evolution which was conditioned by the presence of particular species.

Generally his results showed a decrease in pH and an increase in salinity inland. There was also a decrease in surface water content which is a function of the frequency of immersion and the presence and type of vegetation cover. A 30% shrinkage in volume on drying of mangrove muds was noted in comparison with 10% on the bare flat. There was an inverse density relationship with water content and the quality and amount of organic matter. pH values were found to be lower in the *Rhizophora* than on the bare flat. Likewise the oxidation-reduction potential was slightly higher in the bare flat than under *Rhizophora*. Accumulation of sulphur in the swamps on a seasonal basis was noted. This was due to desiccation, moisture levels and movement of the water table. Variations were greatest under *Avicennia* and bare areas, and least under *Rhizophora*. Trends were also distinguished with the concentrations of soluble ions.

Thus a variety of trends were observed in the chemical data from the sea to the land in association with a changing vegetation cover. However, it is not apparent whether the data pertains to a single reading or to average values. This reduces the value of Vieillefon's study. Thornton and Giglioli (1965) and Giglioli and King (1966) also found a series of trends in the Gambian mangals. Salinity was least under *Rhizophora* and greatest under the bare Tebebe flat. Highest values of free sulphur were noted under *Rhizophora*. Using air dried samples they found that concentrations of soluble sulphate were highest under *Avicennia*.

The papers cited above suggest that there are identifiable soil/plant relationships within mangals, in particular between the soluble and exchangeable ions and the overlying vegetation. Although seasonal trends in chloride and sulphate have been considered, scant attention has been paid to variations in other ions such as calcium, magnesium, sodium and potassium. Consequently a number of questions can be posed:

(i) Is the vegetation/soil relationship postulated by Navalkar and Bharucha (1950) valid or is it a fortuitous relationship due to the sampling technique that was employed?

(ii) If Navalkar and Bharucha's vegetation/soil relationship is correct does a similar relationship exist for both an estuarine situation and an open accreting coast?

(iii) Irrespective of a spatial trend, do temporal variations also exist in the ionic concentrations?

(iv) Can the observed ions satisfactorily explain the distribution of species across the intertidal slope?

(v) How are bare salt flats formed in mangals? Can it be assumed that they are part of the "normal" zonational sequence, especially in seasonally dry climatic areas?

These questions were considered in this project with respect to mangals in the Townsville area. Sites, which represent the range of conditions experienced in the Townsville area, had to be designated and a suitable sampling programme devised.

Experimental Design

Successful resolution of the questions posed above depends upon the choice of sites, sampling in the field and the chemical and statistical techniques employed in the laboratory to derive and explain the results. Two sites were chosen in the Townsville area, Magnetic Island and Saunders Beach, for intensive study. A further site on Orpheus Island was investigated when it became possible to get limited access to the island. The rationale for choosing these sites is given in Chapter Two. At each site initial surveys were conducted to identify the main zonational patterns within the mangals. Most vegetation zones formed narrow belts running parallel to the coast or creek. The zones tended to be monospecific with respect to the dominant species, although other less frequently occurring species were present. Because of the narrowness of the zones, only one station was set up within them. Where a zone became wider more than one station was located within it.

Short term changes in some of the soil chemical attributes of the mangal on Magnetic Island were monitored primarily because the vegetation zones extended from just below mean low water neaps to the extreme high water mark. The extent of the mangrove distribution means they cover a variety of micro-environmental conditions which could influence the vegetation cover. Sampling was undertaken at monthly intervals from November 1973 to December 1975 inclusive, as near as possible to the highest spring tides. This meant that the maximum number of stations were covered by tidal waters. Ground water samples were taken from the selected stations, along a transect through the mangal. Salinity or the amount of sodium chloride concentration (Metson, 1971) was obtained from these samples using a Hamon temperature/salinity bridge.

A different time period was employed at Saunders Beach and Orpheus Island. During 1974 Saunders Beach was sampled on a seasonal basis. However, starting in January 1975 the site was sampled every three months up to and including January 1976. Limitations of access restricted visits to Orpheus Island to three occasions, December 1973, September 1974 and February 1975, i.e., during two wet seasons and the intervening dry season.

Soil samples were obtained from Magnetic Island and Saunders Beach sites during 1975. Each station was sampled at three depths, 0cm, surface; 10cm; and 30cm. These depths were chosen for a number of reasons. They represent that part of the soil which is penetrated by plant roots during seedling establishment. From field observation the depth to 30cm appears to be the region of greatest root density. Lastly, as the depth of sampling increases in such a dynamic environment, the "noise" element will also increase due to sedimentological conditions unrelated to contemporary conditions. The exceptions to this sampling programme were at the front of the mangal on Magnetic Island. Here the sediment depth was too shallow to obtain a sample from 30cm below the surface.

Soil stations were taken from stations on Magnetic Island every month during 1975 and five samples, taken three months apart, were obtained from the Saunders Beach stations, starting in January 1975. No soil samples were taken for analysis from Orpheus Island because the island was visited before and after the soil sampling programme was undertaken. Therefore no temporal data could be obtained for comparative purposes.

Fourteen discrete soil chemical variables were considered, although two were not detected in the analyses. Those variables measured included:

(i) pH measured in a KCl solution
(ii) pH measured in a distilled water solution
(iii) water soluble carbonate
(iv) water soluble bicarbonate
(v) water soluble chloride
(vi) water soluble sulphates
(vii) soluble sodium
(viii) soluble potassium
(ix) soluble calcium
(x) soluble magnesium
(xi) exchangeable sodium
(xii) exchangeable potassium
(xiii) exchangeable calcium
(xiv) exchangeable magnesium

These particular elements are important to plants in a number of different ways. They are essential for the development of a variety of plant components, for example proteins, vitamins, enzyme activities, maintenance of cells and photosynthesis (Richardson, 1968). However, these macronutrients tend to be in relatively shorter supply than the micronutrients required by plants in environments located at the marine/terrestrial interface (Ranwell, 1972). Consequently the availability of macronutrients is more likely to be a limiting factor to the distribution of plants across the intertidal slope. For this reason the macronutrients tend to be the elements most frequently considered in such a study (e.g. Navalkar and Bharucha, 1949, 1950; Davison, 1950; Chapman and Ronaldson, 1958; Durand, 1960; Weiss and Kiener, 1971).

Laboratory Methods

The soil samples were placed in plastic bags. On return to the laboratory the samples were divided into two. One half of the sample was maintained in its field condition and was used for determining pH. The second half was air dried at a temperature of 25^{o}C (Hesse, 1971). The dried samples were stored in plastic bags. The techniques used for the elemental analyses of each dried sample are described in Appendix 1. Soluble and exchangeable sodium, potassium, calcium and magnesium were analyzed using a Varian Atomic Absorption Spectrophotometer AA-5. Water soluble carbonates, bicarbonates and chloride were determined by titration (Hesse, 1971; Metson, 1971) and water soluble sulphate was determined using a Hitachi spectrophotometer, the results being based on the optical density of a barium chromate reaction (pers. comm. Dr W.D. Johnson, University of New South Wales, 1975). As a means of checking the variability within the machine for the latter experiment, one sample from the first batch was re-analyzed on each run. Less than 10% variation was observed in the results. The water soluble results were based on a 1:5, soil:water solution. A similar solution was used in the pH determination. Solutions were made up with KCl and distilled water for this latter analysis. Navalkar and Bharucha (1949) considered that the results of the KCl solution represented the background pH values whilst the results from the distilled water related to seasonal fluctuations.

Two factors probably influenced the pH readings. The pH electrode malfunctioned. Consequently the first six months' values had to be recalibrated. A delay existed for some of the samples between being sampled and the readings being taken. It is possible that if drying out of the samples had occurred, especially with those having a high organic and sulphur content, lower pH readings would have been produced due to the development of sulphuric acid (Hesse 1961a, b).

Problems also occurred when collecting the ground water samples. Sediment on the mangal fringe and lower intertidal slope was shallow and was affected by burrowing animals. Therefore it was not quite apparent what was being sampled, sea water or ground water. Sampling from these two stations was discontinued for this reason. At Saunders Beach it was found that the sub-surface water level responded very quickly to changing tidal levels. Often it was found that by the time the stations were accessible, the water level had fallen too low to be sampled. Sufficient numbers of samples were collected, however, to give an indication of the general trends in the data.

Statistical Analysis

Use was made of computer packages for the various statistical techniques used in this study. These include the Statistical Package for the Social Sciences (SPSS-10) issued by the University of Pittsburg, version 6.01.1 (1975) and the Biomedical Package (BMD). Three statistical techniques were utilized to analyze the data. These were discriminant analysis, factor analysis and multiple regression analysis. The techniques were described in Appendix 2.

The three analytical procedures were utilized to consider different aspects of the mangal environment. It has been previously postulated that with an increase in height of the land surface, soil forming factors would also vary. Consequently, it may be postulated that the soil chemical characteristics may change from the sea to the land. These changes may or may not be associated with an observed vegetational change in the same direction.

Factor analysis was used to explain the relationship amongst the variables considered in this study (Overall and Klett, 1972). The technique was used to try and identify any underlying trends within the data which could suggest possible causes for the identified pattern. This idea was extended using discriminant analysis. Assuming that there was a relationship between the soil chemical characteristics and the overlying vegetation, this technique was used to indicate the degree of similarity between stations along the transects. By comparing the groupings suggested by the discriminant analysis with the overlying vegetation groupings, an indication of the relationship between soils and vegetation can be outlined. The relationship between ground water salinity and the degree of tidal exposure, precipitation, height of the surface and distance seaward from the landward fringe was assessed using multiple regression analysis.

Sedimentation in Mangals

The investigation of contemporary processes on the intertidal slope can be approached in two ways. Initially sedimentary processes may be monitored across an area influenced by tidal waters, but lacking a vegetative cover. The results obtained from such studies could be compared with results from sites where a vegetation cover exists. To date more work has been published concerned with the former situation than a vegetated surface.

Sedimentation Processes on the Intertidal Slope

The manner in which particles are eroded, transported and deposited across the intertidal slope is related to two concepts, that of scour lag and settling lag (van Straaten and Kuenen, 1958; Postma, 1961, 1967). Scour lag is related to the differences in maximum velocity allowing sedimentation of suspended particles and the minimum velocity required to erode the same material from the bottom. The smaller the grain size, the greater the difference between the two velocities. The concept of settling lag is also important. Particles settling from a slackening tide are not deposited vertically below the place where they start to fall from suspension, but are carried along some distance before reaching the bottom (van Straaten and Kuenen, 1958). By this mechanism a particle is picked up, transported landward and deposited. At a later stage this particle may be resuspended and undergo the same motions except that it may be carried back out to sea. However, it is highly unlikely that it will be resited at its original position. In this manner a particle is continuously transported in a criss-cross motion across the flat until it is finally deposited in an area where the critical erosional velocity needed for transportation is not exceeded by future water immersions. Van Straaten and

Kuenen (1958) emphasize that their treatment of lag effects is based purely on competency of the currents and not on capacity. Since only small amounts of material are released by the passage of water, capacity is not viewed as a limiting factor.

The advantages of the two concepts are their simplicity. However problems arise when considering the boundary conditions of sediment erosion and transportation. Sediment can be divided into two basic units depending on the particle sizes. Cohesionless material is primarily made up of sand and gravel whilst cohesive material comprises finer particles, silts and clays. Cohesionless sediments resist erosion by the submerged weight of the individual particles. Resistance to erosion by cohesive particles is far more complex. Depending on the mineralogical characteristics of the fine sediment and the dissolved ions in the water, the resulting interaction between particles may be attraction or repulsion. If attracted, flocs are formed. As a consequence both the particle shape and its hydraulic characteristics are altered. It is because of these features and the complexity of their combinations and permutations that there is a basic lack of knowledge of the hydrodynamic aspects of erosion and deposition in cohesive sediments (Partheniades, 1971).

Dunn (1959) considered that shear strength of the substratum was the most important factor. This was dismissed by Partheniades (1965) who found that provided flow does not induce stresses of an order higher than the order of the macroscopic strength of the bed then minimum scouring shear stresses and erosion rates are independent of the shear strength of the bed material. On deposition, a group of flocs will consolidate with time. Physico-chemical bonding forces resisting erosion will therefore increase with consolidation. Although erosion and deposition of cohesive sediment are controlled by the bed shear stress (Partheniades, 1971), the stability of these materials varies with parameters such as type and amount of clay content, clay mineral orientation, sample bulk density, antecedent water conditions and temperature of eroding water. An increase in the water temperature decreases the sediment stability (Grissinger, 1966; Partheniades, 1971).

An experiment which attempted to test the relationship between water content of sediment samples and the critical erosional velocities was discussed by Postma (1967). It was found that with a decrease in water content, the critical erosional velocities increased. How valid these observations are is open to question as eddy currents which could be caused by the instrument design may bias the results. Lower water concentrations were achieved by varying the length of time sediment had been allowed to consolidate. However, consolidation also occurs naturally by desiccation (Thompson, 1968; Pestrong, 1972; Anderson 1973).

Thompson (1968) observed that portions of the intertidal slope on the Gulf of California were not covered by tidal waters for varying lengths of time. The desiccation effect caused by exposure had a marked consequence on the critical erosional velocities required to pick up material. He found that for material 8 microns in size and a settling time of 3, 16 and 40 hours the critical erosional velocities were 12-17cm/sec, 23cm/sec and 39cm/sec respectively. Anderson (1973) noted that on the New Hampshire marshes desiccation of even a few hours between tidal cover was enough to affect the amount of material transported across the intertidal slope. Thus he found that more material was transported on the ebb tide than on the flood tide. Pestrong (1972) working near San Francisco found that more material was transported on the flood than on the ebb tide. Both researchers did agree, however, on the role of waves on sediment transportation on intertidal slopes. Both considered that most material was resuspended by wave action rather than by tidal currents on the flat (Anderson, 1972; Pestrong, 1972). Pestrong, through observation, and Anderson (1973) from samples collected by a suction pump concluded that it was the initial rippling waves that cross the flat that caused the most change, especially in the flood, but also on the ebb tide. The rate at which the initial wavelet advanced was partly governed by the tidal range for that section of the tidal cycle and the gradient of the intertidal area.

Effect of Mangroves on Sedimentary Processes

The relationships and influences that exist between mangroves and the sedimentary environment have been discussed in general terms by various researchers. Two trends are apparent in the literature. Mangroves are thought either to have a land building capability or to have a process modification role (Carlton, 1974). With particular but not sole reference to southern Florida, it has been suggested that mangroves have a land building capability and even play an active role in the creation of islands (e.g. Vaughan, 1909). This is achieved either by the establishment of mangroves which then create different environmental conditions which restrict the movement of sediment across an area, or by a slow build up of the surface by the continuous input of organic detritus to form a peaty environment. The processes may be assisted by the presence of algal mats which are able to bind the sediment. The alternative hypothesis, that of process modification, suggests that mangroves cannot establish themselves until the land surface has reached a particular, but unspecified relative depth beneath the surface waters. Having become established, mangroves will then play a decisive role in influencing and modifying the rate of geomorphic processes. This is clearly indicated by the change in underlying sediment characteristics from a coarse to a fine sediment which often accompanies the establishment of mangroves.

The importance of relative depth of water overlying the sediment is not clear. Other more influential parameters may be locally responsible for mangrove establishment and development. This problem can be exemplified by Australian examples. Thom *et al.* (1975) showed that on the Ord River mangroves occupied a height range from approximately +3m to +8m. The spring tidal ranges for Lacrosse Island and Wyndham, 84km inland, are 6.39m and 7.49m respectively. Burgis (1974:23) however, reported that at Broad Sound, Queensland, with an approximate spring tidal range of 11m, mangroves were established only between +10m and +11m. This contrasts with the Townsville situation where mangroves are established from about +1m to +3.8m relative to tidal datum. The spring tidal range is 2.5m.

Although many authors have alluded to the ability of mangroves to build land or to trap material, few have made any attempt to verify their opinions. Writing about the importance of pneumatophores Hamilton (1919:470) stated: ". . .they collect a considerable quantity of detritus and play a prominent part in the uplift of the marsh." MacNae and Kalk (1962:29) wrote: "Once established, the pneumatophores interfere with the circulation of tidal water and silt falls and accumulates around them." More recently Lugo and Snedaker commented on the fact that: "The low velocities of the incoming and retreating tides and the dense, well developed root system entrap all but the smallest organic fibres" (1974:45). These three papers epitomise the attitude which is prevalent in many research contributions. Even in 1940 Davis stated: ". . .Their descriptions are nearly all written without either a thorough study of the general ecology of mangrove vegetation or enough field and experimental work to verify their conclusions about the land building role of mangroves" (1940:309).

Factual information concerning contemporary sedimentation rates and processes operating in mangrove swamps was not available until 1971 when a short paper was published by Bird (1971a). He studied a mangal, composed solely of *Avicennia marina*, at Yaringa, Victoria. During this project Bird conducted three accretionary experiments using a number of different techniques. In January 1968 he set up a network of 12 bamboo canes at various sites in front of the swamp on the bare mudflat. Stakes were inserted so only 20cms remained exposed. Monthly measurements were taken. At the end of an eleven month period seven sites showed accretion (max. 2.8cm). Within the mangal vertical accretion was measured with respect to a layer of brick dust, scattered over ten sites. After three years the amount of accretion at the various sites were measured. Deposition rates of up to 0.7cm (landward), 2.4cm (centre) and between 0.4cm and 4.6cm (outer fringe) were recorded. The effect of pneumatophores was simulated by inserting a grid of pegs into the mud, on the seaward side of the mangal. At the end of one month 0.3cm of sediment had been deposited within the grid. The material was subsequently eroded when the pegs were extracted. However, such a sequence of erosion and deposition may occur normally as a seasonal pattern on the intertidal slope. Such sequences of cut and fill have been recognized on beaches (Davies, 1972). From his experiments Bird concluded that pneumatophores influenced the pattern of sedimentation by causing a calm water environment conducive to the deposition of muddy sediment that would otherwise be kept in suspension or carried away; and the pneumatophores were responsible for trapping and fixing sediment that would ordinarily remain in motion.

Two problems, however, remain as a result of Bird's study. First, unlike the monthly measurements of the stakes, no such readings are available for the brick dust experiment. Therefore it is not known if the reported figures represent part of a seasonal pattern of accretion and erosion or represent a continuous sequence of deposition. Second, no mention is made of the size of the grids used to simulate pneumatophores. This is particularly important since a dense network of pegs may cause interference to the flow of water. Turbulence might be induced causing local scouring and erosion. However, a scattered network of pegs may have little or no effect.

In a contemporary study in the Bahamas, Scoffin (1970) investigated the sediment binding ability of prop roots, sea grasses and algal mats. Data on tidal velocities, 15cm above the sediment surface, were obtained by noting the time taken for a sample of dyed water to travel a set distance; wave height and length were estimated; water depth at high water, sediment thickness and depth to bedrock at high tide were measured; and the amount of material less than 63 microns in size was obtained by wet sieving. Scoffin was able to generate artificially tidal currents of varying intensity by using an underwater flume. From the results obtained in this study Scoffin concluded that the presence of vegetation promoted stability of the ground surface and offered resistance to erosion. Those parts of the plants which protruded above the sediment/salt water interface acted as a baffle thereby reducing tidal velocity. At the same time the root system bound the sediment grains. This feature was related, in part, to the density of the vegetative cover. A dense vegetation cover may protect the surface from erosion whilst a sparse vegetation cover may actively promote erosion and transportation by the generation of local eddy currents.

The net effect probably depends on the local tide velocity and hence energy conditions as has been demonstrated by the temporary storage ability of sea grasses (Mitchell-Tapping, 1975).

Over all, results from experiments conducted by Scoffin suggested that prop roots and fine rootlets of *Rhizophora* were the most successful sediment binders followed in decreasing order of importance by sea grasses and algal mats. The effect of these structures on the rate of sedimentation was not commented upon. In view of the qualifications that can be made to Bird's results, the role mangroves play, and in particular pneumatophores, on the sedimentary processes is not clear. Also, it is not clear as to the effect mangroves have on seasonal and spatial accretionary trends in mangals.

Sedimentary Sequences in Mangals

Three types of swamps have been denoted according to their dominant mode of sedimentation (Scholl, 1969). These are the autochthonous, allochthonous and mixed swamps. The former class is largely formed from *in situ* sedimentation whilst allochthonous swamps are dominated by clastic sediment derived from outside sources. The mixed swamp is a combination of the two other classes. Mangals can grow on a variety of substrates such as coral reefs, mud, sand and peat (Chapman, 1944) and in a variety of coastal locations (Saenger *et al.*, 1977). However, the type of material that mangroves grow on is rarely commented upon in detail. For instance, the deposits beneath mangals of the Niger delta have been variously commented upon as silts and clays (Allen, 1964) and muds (Allen, 1965). The complexity of the development of swamps, involving point bars, barrier islands and the interdigitation of coarse and fine sediment, was commented upon elsewhere (Allen, 1970).

Changes in sedimentary patterns that result from the establishment of mangroves are seldom noted. Such features are quite dramatically illustrated on vegetated coral cays. Often the sediment suddenly changes from being coarse to fine. Sedimentary changes are important since they appear to influence the type of mangrove that grows on a site (Watson, 1928; Ding Hou, 1958;

Giglioli and Thornton, 1965; MacNae, 1968; Baltzer, 1972). The relationships which can exist between sediment type, landform and associated vegetation have been clearly identified within extensive mangals (Gledhill, 1963; Thom, 1967; Tucker, 1973; Thom *et al.*, 1975; Cook and Mayo, 1977). As well as influencing where mangroves grow, sediment type can influence the establishment of mangroves (McMillan, 1971), and the distribution of mangrove fauna (Tucker, 1973; Boyé *et al.*, 1975; Day, 1975; Plaziat, 1975).

Experimental Design and Analysis

Experiments were devised to measure two aspects of the sedimentary environment. These were the amount of material being transported through the mangals and the accretion rates at particular points through these mangals. Associated with the latter problem the influence of plants on the accretion rate was also investigated.

During the last few decades various methods have been utilized to measure the rate of accretion within vegetation zones. To date most techniques have been applied only to salt marshes, which because of their location on the intertidal flat are influenced only by the upper tidal range. Within mangals the technique chosen had to withstand repeated diurnal inundations and direct wave action. Steers (1938) successfully utilized the burial of a layer of coal dust on the surface of a salt marsh to detect changes in the surface level. However, because of the salt marsh location, the dust layer experiences only relatively low energy conditions. It was thought that the higher energy conditions experienced towards the seaward front of the mangroves would rapidly scatter rather than bury the dust.

Ranwell (1964) working on the salt marshes of Poole Harbour, Dorset and Bridgewater Bay, Somerset, U.K., found that bamboo sticks inserted into the sediment provided the most reliable results for accretion rates. Again, however, he was dealing with conditions existing in the upper tidal ranges. Consequently low frequencies and durations of tidal water cover would be expected. In a mangrove situation where frequency and duration of inundation may be quite considerable, it was felt that bamboo sticks would attract marine organisms in search of both food and a growth habitat. False accretion readings could possibly result from this.

In the present study, galvanized metal rods were also used since animals could neither feed off them nor live within them. Stations were chosen within each vegetation zone along a transect through the mangals in order to study the influence of vegetation on the variable rates of deposition across the intertidal flat. Generally, the depth of each zone was sufficiently narrow that only one station was located within the zone. The exceptions to this were the *Rhizophora* zone on Magnetic Island and the swamp on Orpheus Island which comprised primarily *Rhizophora* sp. Initially only one station was chosen, station 9, in the *Rhizophora* zone on Magnetic Island. During 1975, however, two more stations, 7 and 8, were set up.

On Orpheus Island four sets of rods were located in the *Rhizophora* swamp and for comparative purposes one on the adjacent sand flat. The peripheral location of the stations had a logical explanation. The primary visit was made when the tides were decreasing in height on the falling spring to neap tides of the tidal range. At low tide the front of the mangroves was still inundated by a temporary rise in water level caused by the presence of Cyclone Una. Consequently stations in such a situation could not be set up either without disturbing the substratum or with any degree of accuracy. Because of the nature of the substratum and its high mobility, accretion readings were taken after two tidal cycles on each visit.

Rods were inserted so that only ten centimetres remained exposed above the swamp surface. Where possible disturbances to the flow of water could take place, for example around the prop roots of a *Rhizophora* sp. or the buttress roots of *Ceriops* sp., rods were located both in the "open" away from the influence of the trees and close to the obstruction so that the effect of the obstruction could be recorded. Because of the nature of the substratum at Saunders Beach, rods were placed either side of the trunk of a *Ceriops tagal* tree in the creekward *Ceriops* zone as well as in the open. Records were made of the amount of rod that was exposed, at each visit, using a micrometer gauge. Variations in height were noted to the nearest millimetre.

An attempt was also made to simulate the effect of pneumatophores on the rates of accretion. Initially rods were set up in a 10cm grid of 5 rows and 10 columns which was located seaward of the mangrove fringe on the lower tidal flat. Further examination of pneumatophores of *Avicennia eucalyptifolia* and *Sonneratia alba* revealed that the spacing varied according to the distance from the trunk (Table 1.2). Therefore similar grids to the first one were set up on the bare intertidal muds in front of the mangroves with spacings of the rods of 10, 5, 2.5 and 1cms (B, A, C, D respectively in Figure 2.5). The grids were formed from 6mm metal rods which were welded onto a metal frame. Legs were attached to each corner so that when the frames were sunk into the mud, the legs settled on to the buried reef flat preventing any subsidence of the frames. The extra frames were set up in March 1975. Variations in surface levels were observed on a monthly basis. To compare the effect of the grids in the mangroves and in the open the 2.5cm grid was taken out in January 1976 and placed in the *Avicennia/Sonneratia* fringe. The grid was located close to the pneumatophores. Another grid made up of individual rods was placed on the lower tidal flat. Variations in ground level were recorded at various time intervals until August 1976.

Estimates of the amount of material transported through the vegetation zones of the various swamps were made. It may be expected that the tidal and wave energy decreases in a landward direction since the depth and velocity of water diminishes in that direction. Vegetation is also thought to play a role in reducing the velocity of water moving through a swamp. At Bimini Atoll, Bahamas, Scoffin (1970) found there was no current movement one metre inside a stand of *Rhizophora mangle*. Nevertheless, since there are a variety of vegetation types at the stations considered in this project it is of interest to observe their effect, if any, on the transported load.

Three different methods of studying sediment movement have been used. Postma (1961) found sampling offshore areas and tidal channels to be a relatively simple task. Sample bottles were lowered over the side of a boat at regular time intervals during the tidal cycle. Samples were taken at set depths. Anderson (1973) working on the New Hampshire marshes was able to "plumb" the intertidal flat. He buried a series of pipes, into the mud, and connected the landward end to a vacuum pump. At the required location the pipes came to the surface. Foot valves were attached to the ends of the pipes at heights of 15 and 30cm above the surface. At regular time intervals Anderson was able to operate the vacuum pump and collect samples. To duplicate such an experiment was beyond the means of this research programme. Pestrong (1972) used a series of uni-directional bottom samplers to collect bed load samples. These samplers allowed water to enter only on either the flood or the ebb tide, trapping sediment in a fine mesh at the distal end. Although simple in construction and application it was thought to be inappropriate in this project for three reasons. First the sediment at the study sites are bimodal with a high proportion of silts and clays. Second, there is a large amount of organic debris on the swamp floor and rootlets in the sediment which may be transported. Therefore there would be a high risk of one of two responses to the placing of uni-directional samplers on the swamp floor. If the gauge mesh was too large (>63 microns) large amounts of bed load could be lost. If the mesh size was considerably smaller than 63 microns the mesh could become blocked. The flow of water would then be directed around rather than through the sampler. Third, since the traps could not be retrieved until after they had been uncovered by the tide, it would be impossible to clean out all of the sediment from the traps.

Similar problems were encountered by Fisher and Likens (1973) in an investigation of fluvially suspended particulate matter. Fisher and Likens overcame their problems by varying the length of time their nets were in the water according to the rate of river discharge and sediment concentration in the river. It was not possible to incorporate such flexible procedures because of the range of locations from which samples were obtained.

A compromise sampling scheme was thus devised for this programme which was similar to but less sophisticated than that used by Carter *et al.* (1973). Plastic bottles were supported in an upright position by a metal frame 15 and 30cm above the ground. Another bottle was inserted into the swamp surface so that the lip was flush with the ground. When the tide came in, water could enter the plastic bottles. The bottles were left out for two tidal cycles. Some bottles were lost, in spite of being attached to a rod sunk into the ground, due to hydrostatic pressure of water welling up through the soil on an incoming tide.

Control experiments were made on the banks of Ross River, Townsville, to determine whether the sample that was collected reflected the conditions of the initial inflow of water rather than the overall tidal conditions. Due to the theft of the apparatus during the experiments it was not possible to comment on the values for the 15 and 30cm samples. However, the bed load samples were gauged. Bottles were successfully inserted into the ground on two occasions.

Additionally at each station a soil sample was taken from the surface, and at 10cm and 30cm depth. These samples were analyzed mechanically. The data were then analyzed using moment statistics to find the mean, sorting, skewness and kurtosis for each sample.

Mangrove Communities as an Expression of Past and Present Land Surface Processes

Mangals are a response to the sum of all past and present processes operating on the intertidal slope and high tidal flat. The study of contemporary phenomena should thus take into account the evolutionary trends within the swamp. What has happened in the long term development of mangals is just as important as the short term changes and contemporary plant/process interaction, if an understanding of the disposition of mangroves is to be achieved.

The presence of mangroves in the sedimentary sequence, at any locality, is indicated by a combination of two features. These are root material and organic litter. Litter is preserved to the greatest extent in areas which have a negligible tidal current or in depressions. Thus only small amounts of organic matter would be transported out of the mangal. Most of the litter produced would be used to build up the land surface. Unfortunately the possibility of occurrence for such sites in the study area is relatively small. The most common organic matter in the sedimentary profile is root material. The amount preserved depends on a number of factors, such as the species present, since different species produce different amounts of root material; length of time a species has colonized a site; the depositional and erosional history of the locality; and the degree of chemical alteration, especially oxidation and humification, that has taken place since the production of the root material.

Organic matter may survive for long periods at depth below the sediment surface. Such evidence can be dated using radiometric techniques. Consequently, in conjunction with the sedimentary evidence, organic matter can play an important role in reconstructing the evolution of an area. This has been demonstrated particularly well on the Gulf of Mexico coast of Louisiana and Florida (e.g. Frazier and Osanik, 1969; Spackman, Riegel and Dolsen, 1969), Tabasco, Mexico (Thom, 1967), Burdekin River, Queensland (Hopley, 1971), Ord River, W.A. (Thom *et al.*, 1975), and West Malaysia (Coleman *et al.*, 1970).

Plant residues have been used to identify particular types of plants as well as changes in environmental conditions which may result from climatic changes or a change in the quality of stream discharge (Jennings, 1975). Perhaps the most widespread use of the range, type and extinction of organic deposits is to give an indication of changes in sea level and sediment input into an area. This is particularly true for deposits related to the Holocene rise in sea level (Scholl, 1969). Nevertheless, the presence of organic matter does not necessarily guarantee a solution to the problem of sea level changes. Jennings (1975) argued that mangrove deposits on King Sound, W.A., indicated a Holocene sea level higher than today's. In a neighbouring area Thom *et al.* (1975) suggested that the disposition of the deposits at the Ord River-Cambridge Gulf area could be adequately explained in terms of the changing geometry of the estuary with the Holocene rise in sea level and the associated localized variations in water level on the periphery of the area.

Evidence for such studies is often collected using a corer and examining the deposits brought to the surface. If organic remains are found in sufficient quantities it is possible to derive an age for the deposits using radio carbon dating techniques. Interpretation of the results is subject to difficulties related to the quality of the sample analyzed as well as post-depositional conditions in the sampling locality. It is generally assumed that the samples are collected without contamination from their surroundings. However, in some situations it is recognized that a degree of contamination may have occurred due to the introduction of younger C14 isotope into the sample from water moving through the soil and sediment profile. Using mangrove derived organic matter it is also difficult to determine the relative location of that sample on the intertidal slope and high tidal flat. Different areas have different tidal ranges. The tidal range experienced today is probably different from that in the past. Different species also have different altitudinal ranges. The peats and organic debris are assumed to be developed *in situ* and have not been redeposited from elsewhere. Because of the nature of the deposits they may be subjected to compression and/or subsidence if overlain by a thick mass of sediment. The actual position of emplacement may also be difficult to determine, especially if the locality has been subjected to differential warping associated with water loading and unloading of the continental shelf during the glacial and interglacial stages (Bloom, 1967; Walcott, 1972; Chappell, 1974; Clark *et al.*, 1978), or regional tectonic activity. Lastly, it may be difficult to confirm or corroborate the results from associated evidence (Bloom, 1967; Gill and Hopley, 1972) such as other datable evidence from associated deposits and stratigraphic evidence from neighbouring areas.

The swamps chosen for this study are typical of many along the Queensland coastline. Although the stratigraphy is readily compiled it is only by good fortune that material suitable for dating is found. The material was collected using a piston peat and clay corer. It comprised a 2.5cm diameter stainless steel tube, 30cm long. A piston was made to closely fit the internal bore of the tube. One end of the piston was attached to graduated rods 1m long. On recovery of the corer from depth the sample was able to be extruded using the piston. Apart from the upper 0.5m, little compression of the sample took place. This was a function of the moisture content of the samples, the amount of compression increasing as the samples decreased in water content. By logging the cores that were recovered it is possible to reach an understanding of the mangal's evolution. A corollary of this is to gain a greater appreciation of the effect of contemporary processes operating in the mangals.

CHAPTER TWO

REGIONAL SETTING AND SITE CHARACTERISTICS

This study is primarily concerned with mangals and their development in the Townsville area, North Queensland. For this purpose three sites with contrasting environmental conditions were chosen, Figure 2.1. The two principal sites were located on the west coast of Magnetic Island and on the right bank of Althaus Creek at Saunders Beach (Jalloonda). A third site was considered on the west coast of Orpheus Island. The sites, Figures 2.2 and 2.3, had the following characteristics:

(i) Magnetic Island: west coast, relatively fine sediment on an adamellite basement with an adjacent fringing reef. Magnetic Island is located 8km offshore from Townsville.

(ii) Saunders Beach: right bank of a tidal creek, Althaus Creek, subject to a varying degree of freshwater and saltwater influence. Saunders Beach is located 25km north of Townsville.

(iii) Orpheus Island: west coast, coarse grained substratum on an adamellite basement leading to an offshore fringing reef. The island, which is one of the Palm Island Group, is approximately 75km north of Townsville.

Three criteria were used to choose the sites investigated in this study. These were:

(i) Representativeness

(ii) Security of equipment

(iii) Accessibility.

(i) Representativeness: The sites chosen are typical of conditions found along the North Queensland coastline. Offshore high islands frequently have a fringing reef with mangal development on the more landward parts of the reef flat, for example the Palm Island Group and the islands in the Whitsunday Passage. Where hard rock outcrops on the mainland coastline, fringing reefs may develop if conditions are suitable. These may in turn be colonized in part by mangals, for example Yule Point, Cairns (Bird, 1971b). On the west coast of Magnetic Island the mangal overlies both the adamellite basement and part of a fringing reef which has been covered to a large extent by coral rubble and fine sediment (Foster, 1974). Much of the Queensland coast is developed on a Pleistocene and Holocene infilled coastal plain dissected by rivers and creeks which are tidal at their mouths. Mangroves frequently border these channels. Thus mangroves grow on both an open accreting coastline and an estuarine coastline.

On a broad scale there is a basic similarity between the zonation present at the various coastal swamps. Nevertheless minor variations in the precise details would occur, especially towards the upper limits of tidal influence along tidal creeks. Within an area, it can be assumed that the mangals will experience a similar climatic regime and tidal regime.

(ii) Security of equipment: In many ways this is an important consideration. Equipment needs to be left both overnight and for many months with little or no change of it being removed by members of the public. This could not be assured for the mangals south of the Ross River, which enters the sea just south of Townsville's harbour. Trial experimental equipment for this project was stolen on several occasions. Having a remote site still does not guarantee a lack of interference. On one occasion during a series of unsuccessful experiments, cables linking velocity sensing equipment were cut and the control panel confiscated by the police during one of their "routine" beach patrols. They detained it until they were convinced the equipment was not to be used for dynamiting fish!

(iii) Accessibility: Given that the preceding two conditions can be met, then difficulty of access can be a limiting factor in deciding where to locate the study sites. Of primary concern was the fact that an individual had to be able to reach the sites alone. The mangals at Alligator and Crocodile Creeks met the first two criteria but their access was too difficult for an individual to negotiate. Possible alternative sites were around Cape Bowling Green

Bay and the Bohle River. The former area has even greater problems of accessibility for an individual than Alligator and Crocodile Creeks. These difficulties are reduced to a certain extent with the establishment of the Australian Institute of Marine Sciences at Turtle Bay. The access tracks to the Bohle River are often flooded during the wet season. Alternative routes across the salt pans are also cut on the high spring tides as well as being almost impassable during the wet season. Consequently since access could not be guaranteed for the whole year, this area was rejected.

The three sites that were investigated in this project are representative of conditions in which mangals occur in North Queensland. As far as could be ascertained at the start of the study, the sites were secure and they could be reached quite easily both in the wet and dry seasons.

Climate

The most recent and comprehensive review of Townsville's climate is given by Oliver (1978). The salient features are given in Figure 2.4. Temperatures in Townsville are relatively high throughout the year with a mean annual temperature of 24.4°C. The mean maximum temperature is 28.2°C, whilst the mean minimum temperature is 20.6°C, an average yearly range of 7.6°C. Highest temperatures develop on average in January and the lowest in July. Notwithstanding the temperature trends, the mean receipt of solar radiation is greatest between September and December, when there are least clouds in the sky and relatively longer days.

Rainfall at Townsville is highly seasonal with an average of 1163mm (1871-1970). Most rain falls between January and April (76% average annual total) and 89% of the total falls on average between November and April. Coupled with a high evaporation rate, January, February and March are on average the only months to have a moisture surplus. The basic features of the rainfall pattern in Townsville are (a) low reliability and high variability, and (b) the incidence of much of the rainfall as falls of high intensity and short duration (Murtha and Reid, 1976). Data show that 48% of the annual totals will be 25% greater or smaller than the average (Oliver, 1978).

Intensities of up to 93.3mm in one hour and 126.6mm in a six hour period are expected once in 10 years (Commonwealth of Australia, 1970). Such falls are generally associated with cyclones or rain depressions associated with tropical cyclone decay. On average 3-4 cyclones per year may affect the Queensland coast (Oliver, 1973). Locally, twelve cyclones passed within 55km of Townsville between 1940 and 1969.

On Magnetic Island the rainfall records are less complete and are variable in their duration. Smith (1978) quotes average yearly figures for Horseshoe Bay and Townsville (8/69-9/74) as 1829mm and 1202mm respectively. That is a 52% difference in values. For Geoffrey Bay, Picnic Bay and Townsville (7/70-9/74) the average yearly values are 2096mm, 1825mm and 1394mm respectively. These represent differences of 50% and 30% respectively from the Townsville figure. During the main period of investigation of this study in 1974 and 1975, values for Townsville were 1706mm and 1447mm respectively. For the same period figures for Nelly Bay, Magnetic Island, were 2535mm and 1707mm or 49% and 18% respectively greater than their corresponding Townsville readings. For Townsville 86% and 40% of the rainfall fell between January and March in 1974 and 1975 respectively. Magnetic Island, however, experienced 86% and 24% of its rainfall over the same period. The 1974 figure included a storm of 364.7mm during the night of 22/23 January 1974 which accounted for 24% of the precipitation for that month. Because rainfall records for Magnetic Island are available for only a short period, Townsville's figures were used as a guide to the regional climate.

1975, the year in which soil sampling and chemical analysis were undertaken, the data contained two of the wettest months for many years. September (81.4mm) was the fifth wettest since records commenced in 1871 and the wettest September since 1926. October (252.8mm) was the second wettest on record and the wettest October since 1930.

Winds displayed a consistent pattern through the year. 61.2% of the total winds at 9 a.m. come from between north-east and south-east. A more persistent north-east trend is observed for the 3 p.m.

data. Townsville does not experience very strong winds except during tropical cyclones or thunderstorm squalls. At Townsville airport 77.4% of all winds including calms are less than 5.1m/s at 9 a.m. decreasing to 30.6% of all winds at 3 p.m. The foreshore conditions would be different from those at the airport since the winds here would have been affected by friction and topographic influences. On the foreshore land and sea breezes may also play an important role (Oliver, 1978). Local wind fields may also play an important role around coastal islands.

Vegetation

The distribution of mangroves along the Queensland coast was, until quite recently, known only in a superficial manner. The first extensive report of mangals and mangroves was MacNae (1966). He essentially concentrated on the region between Cairns and Townsville. Later work has widened our knowledge of community and plant distributions (Jones, 1971; Pedley and Isbell, 1971; Saenger and Hopkins, 1975; Saenger *et al.*, 1977). A more comprehensive study of mangal characteristics and plant distributions is currently being undertaken by the Australian Institute of Marine Science (Bunt, 1978).

The mangal vegetation in the Townsville area and on Magnetic Island has been described in some detail by MacNae (1966, 1967, 1968). He recognized five zones in these mangals:

(i) a landward fringe that may either be forested or colonized by *Avicennia* and by halophytes;
(ii) *Ceriops* thicket;
(iii) *Bruguiera* forests;
(iv) *Rhizophora* forests;
(v) seaward fringe of *Avicennia* and *Sonneratia*.

Not all these vegetation zones were recognized along the chosen transects. The zones recognized in this study have been identified on the basis of the speciation. Generally the zones were dominated by one species. Other species may be present in the zone but in very much reduced numbers. On Magnetic Island the zones that were found along the transect through the mangal were (Figure 2.5):

(i) *Ceriops* zone;
(ii) *Rhizophora* zone;
(iii) Seaward fringe of *Avicennia* sp. and *Sonneratia* sp.

(i) The *Ceriops* zone is dominated by *Ceriops tagal* var. *australis* ranging in height from 1m to 5m. Towards its inner edge there are dead specimens of *Xylocarpus australasicum*. Station 1 is located 47m from the landward edge of the zone. Station 6 is located just landward of the *Ceriops/Rhizophora* boundary. This boundary, like many found in the mangal, is quite precise, one being able to step across from one zone into the next. The *Ceriops* zone, however, is not a continuous zone. It is interrupted on the upper intertidal slope by a salt flat, on which Station 3 is situated. Around the salt flat halophytes and some *Avicennia eucalyptifolia* are found. On the landward edge of the salt flat is a zone of *Arthrocnemum leiostachyum* and the occasional *A. eucalyptifolia*. Some seedlings of *Osbornia octodonta* have become established in this zone since 1976. Station 2 is located in this zone. Station 4 is situated in a zone of *A. leiostachyum* with the occasional seedlings of *A. eucalyptifolia* and *Suaeda maritima*, and Station 5 in a zone dominated by the latter two species.

(ii) Stations 7, 8 and 9 are spaced approximately equidistantly through the widest zone, the *Rhizophora* zone. This consists of *R. stylosa*, not *R. mucronata* as initially reported (Spenceley, 1976). Saplings of *R. lamarkii* (pers.comm. N. Duke, AIMS, 1976) have been found in addition to the occasional sapling of *Bruguiera gymnorrhiza*. The size, location and distribution of both species of trees suggest that they have established themselves since Cyclone Althea in December 1971. One effect of this cyclone was widespread destruction of the mangroves, especially *Rhizophora* species. Although some windthrow took place immediately, trees have progressively died, with over 50% of the *Rhizophora* trees having been killed since 1971 (Plate 2). Gill and Tomlinson (1969) found that *Rhizophora* spp. lose their ability to regenerate by shoot development on reaching maturity, although they gave no reason for this. So once badly damaged, they cannot recover. Station 7 is located in one of these devastated areas whilst the other two stations are under a closed canopy cover. Trees range in height from 3m to 8m.

(iii) The narrow seaward fringe comprises *A. eucalyptifolia* and *Sonneratia alba,* Station 10, approximately 3m to 4m in height. Seaward of this fringe is the bare lower intertidal slope which is uncovered on the low spring tides. Station 11 is located on this area.

The vegetation at Saunders Beach differs from that on Magnetic Island, Figure 2.6. Two transects were laid out. Along the first transect, Saunders Beach 1, the zonation starts on the creek bank with a narrow mixed zone containing *R. stylosa*, as the most abundant species, with occasional *Lumnitzera racemosa, A. eucalyptifolia, C. tagal, Aegialitis annulata, Bruguiera exaristata* and *Xylocarpus australasicum.* Station 12 is located in this zone. At a higher level on the bank is a band of *C. tagal*. Two stations, 13 and 15, are located in it. A narrow *Sporobolus virginicus* community with occasional *C. tagal*, is present on top of the bank which occurs in the *Ceriops* zone. Station 14 is situated on the bank top. Inland, but at a slightly lower elevation, is a salt pan with a narrow zone of *Arthrocnemum leiostachyum* and the occasional *A. eucalyptifolia* located on its periphery. Station 16 is located in this peripheral zone whilst Station 17 is sited on the salt pan.

Three vegetation zones are recognized along the second transect, Saunders Beach 2. Station 18 is located in a narrow mixed vegetation zone of *R. stylosa, B. exaristata, C. tagal* and *A. eucalyptifolia.* This zone is present on the creek bank at the edge of a sand ridge. Landward of this ridge is a mixed zone of *R. stylosa* and *B. exaristata,* Station 19. Further landward is a zone of *C. tagal*. *Osbornia octodonta* is occasionally found in this zone but is more commonly located on the landward periphery along with *Xylocarpus granatum.* Two stations, 20 and 21, are located in this *Ceriops* zone.

The last locality that has been considered is a small mangal on the west coast of Orpheus Island in Hazard Bay, Figure 2.3. The mangal is simple, consisting predominantly of *R. stylosa.* On the landward edge there are a few *A. eucalyptifolia, O. octodonta* and

B. gymnorrhiza. Four stations, R1-R4, are present in the swamp, with a fifth, R5, which was set up for comparative purposes, on the sandy intertidal slope. The peripheral location of the stations in the mangal is related to the prevailing conditions when the stations were set up. At that time Cyclone Una was in the vicinity. This had the effect of raising the water level by many centimetres. This precluded a wider distribution of stations since the sites would have been grossly disturbed whilst being set up. Heights for these stations have been estimated using the time that they were uncovered by the tide against the standard tidal curve.

Using the actual water levels recorded by the Harbour Board at Townsville for the period October 1973 to December 1975, the frequency of inundation for any particular level can be readily obtained. Figures have been grouped for three monthly periods for the duration of the project starting in October 1973. The percentage frequency of inundation for specific stations and vegetation zones within the mangals are given in Table 2.1 and Figure 2.7. The data relate solely to the extent of the mangroves observed along the transects. Over the distance of several kilometres, as on Magnetic Island, the height of the different zones may vary to a considerable degree depending on local influences. What is quite clear is that similar mangrove zones cover a different altitudinal extent and hence have a different frequency of inundation. Variations in the landward extent of the *Ceriops* zone can be attributed to geomorphic influences. The same limitation is partly true for the *Rhizophora* zone on Orpheus Island. This cannot be said for the *Rhizophora* zone on Magnetic Island and the mixed vegetation zones at Saunders Beach. It is quite clear that the salt flats, Stations 3 and 17, both have a greater frequency of inundation than large portions of the *Ceriops* zones. The only zone to be inundated on every high tide is the seaward *Avicennia/Sonneratia* fringe on Magnetic Island.

Geology and Soils

The geology of the area in which the sites are situated is simple, comprising volcanic rocks, dyke swarms and acid plutonic rocks of late Palaeozoic age which are overlain by Quaternary deposits to form the coastal plain (Stephenson, 1970; Paine, 1972).

Within the Quaternary infill deposits, which dominate Queensland's coastal plain, chemical alteration, migration and redeposition of materials may take place. Dolomite of Holocene origin has been found on the supratidal flat at Broad Sound (Cook and Polach, 1973) and carbonate nodules of Pleistocene age have been found at the mouth of the Bohle River (Hopley and Murtha, 1975). In the Townsville region the coastal plain comprises a sequence of piedmont fans and fluvial deposits at the base of the Paluma Range, which have undergone a series of mobilization, weathering and cementation phases. With a variable sea-level position during the Pleistocene and Holocene, the coastal sediments comprise an interdigitating series of marine and fluvial deposits (Hopley and Murtha, 1975). This is apparent at Saunders Beach. At the other two study sites Quaternary deposits are present in the form of piedmont slope deposits and intertidal slope sediments which are related to the Holocene transgression.

The textural differences between sediments from the various sites and stations can be quite marked. Samples were collected from each station and the results of their sedimentological analysis are given in Tables 2.2, 2.3 and 2.4 and Figures 2.8 and 2.9. To avoid confusion only the surface data have been plotted.

Plots of the Magnetic Island data, Figure 2.8, indicate that there is a general decrease in average particle size from the land to the sea. The exceptions to this are sediments from the two *Ceriops* zones, Stations 1 and 6, and the landward *Rhizophora* (7) station. Their average values are coarser than 1.0 phi unit. The sorting of all the samples is remarkably similar with less than 0.7 phi units difference between the extreme values. The plot of mean phi against skewness shows a similar relationship. Again with the exception of sediments from Stations 1, 6 and 7, the mean grain size decreases and the particle size distribution becomes more symmetrical in a seaward direction. Thus the distribution changes from one with a predominantly fine tail to one with a coarse tail.

Plotting skewness against kurtosis reveals that both decrease in a seaward direction. Thus the particle size distribution becomes less concentrated in any one class and more uniformly distributed throughout the classes. The data suggest that there are three sedimentological areas. These comprise Stations 1, 6 and 7; Stations 2, 3, 4, 5 and 8, and Stations 9, 10, and 11. The sediments in these areas are probably combinations of two types of sediment input. The landward zones are subjected to surface drainage from the upland area which comes close to the mangroves. In the wet season torrential rain floods creeks which carry coarse grains into the landward *Ceriops* zone and possibly the neighbouring *Arthrocnemum* zone. Combined with the terrigenous sediments are sediments that have undergone marine influences. These are predominantly fine material, less than 63 microns in size. On the southern end of Cockle Bay, coarse material is at present being reworked and transported northward to form a spit in front of the mangroves. The mixture of this material with the fines, which have been transported in suspension by surface forces and marine organisms plays an important role in explaining variations in the sedimentary characteristics through the mangrove swamp. Similar arrays of sediment types have been found in other swamps and marshes such as those on the south-eastern shores of the Ria de Arosa (north-west Spain) (De Jong and Poortman, 1970).

A different relationship is present at Saunders Beach. From the plots, Figure 2.8, it is evident that there are two distinct sedimentary provinces at Saunders Beach 1. Creekward of Station 15 the mean grain size is 2.0 to 2.5 phi units ± 1.0 to 1.3 phi units. Landward of Station 14 the mean grain size decreases to be more than 3.2 phi units ± 1.4 to 1.5 phi units. Likewise the sediment samples are differentiated with respect to skewness. Samples landward of Station 14 are negatively skewed whilst those creekward are positively skewed. The kurtosis of the samples is more variable. Samples finer than 2.8 phi units are found at Stations 14, 15 and 17. The remaining samples are between 2.0 and 2.5.

For Saunders Beach 2 the sediments have a greater uniformity than those from the first transect. The mean grain sizes are between 1.9 and 2.2 phi units ± 0.9 to 1.3 phi units. The upper values are relatively large because of the increase in the amount of fines at Station 19. Samples from Stations 18 and 20 are negatively skewed with kurtosis values of 3.2 and 3.9 respectively.

In contrast, samples from Stations 19 and 21 are positively skewed with kurtosis values of 2.3 and 3.2 respectively. Thus although there is an increase in fines at Station 19, the grain size distribution is more normally distributed than that of the samples from the other sites. Throughout the two areas the amount of calcium carbonate in the samples is low, the greatest amount being 7.0% by weight.

Analysis of the sediments from Orpheus Island reveals a highly variable substratum, Figure 2.9. Sample means range from 0.0 phi to 1.8 phi and sorting from 0.75 phi to 1.73 phi. Skewness and kurtosis are just as variable. Skewness varies from -0.4 to 0.7 and kurtosis from 1.86 to 4.83. The percentage carbonate content is also highly variable, ranging from 31.8% to 68.8%. Thus the plots indicate a number of sedimentary provinces. However, since this is a relatively dynamic environment in terms of the amount of sediment that is moved the results can be interpreted meaningfully only in terms of the high heterogeneity of the sediment characteristics of that mangal. A similar situation has been found in Nelly Bay on Magnetic Island (Smith, 1978). In this instance the results were interpreted as representing a mixture of beach and reef flat material.

Because of the recent nature of the sediments within the mangals, the amount of soil development must necessarily be minimal. The gradation of particle size need not be regular either across the intertidal slope or with depth. Consequently it is difficult to assign meaningfully a particular Northcote classification to them. On the Townsville coastal Plain, Murtha (1975, 1978) grades the soils under the saltwater couch as Dd 2.43 and those beneath the mangal as Uf 6.31. However, this does not take into account all the textural variations that may be present. For example the coarse sediment beneath the mangals on Orpheus Island is quite different from that which is present in the inner portions of the mangal on Magnetic Island. Sediment on the high tidal flat on Magnetic Island is coarser than that on the upper part of the intertidal slope. In a more general statement Murtha (1978) classifies soils beneath mangals as solonchaks and those beneath saltwater couch as solodic soils.

Soils that are developing beneath a closed vegetation canopy, especially *Rhizophora* spp., tend to be organically rich due to the presence of a dense root network. Beneath a *Ceriops* sp. cover there is not so much organic material. Neither soil types have much pedological organization because either the soils are inundated relatively frequently or the material is too coarse. Where fine material prevails under the *Ceriops*, mottling is present as an indication of a fluctuating water table and hence an alternation of oxidizing and reducing conditions.

Greatest pedological organization is seen beneath the salt flats. Typically the profile has a thin oxidized surface layer, which represents recently deposited material; a narrow band of black reduced sediment; and a zone of light grey sediment with orange iron mottling, representing a periodically oxidized area. Below this a zone of organic mucks is often found.

This arrangement is similar to that described on marine deposits in the Netherlands (van Straaten, 1954). He recognized three basic sections in the soil profile. From the surface downwards they are: (1) Hydroxide zone, (2) Monosulphuric zone, and (3) Bisulphuric zone. The former zone corresponds to a zone of oxidation or aeration. The brownish or yellowish grey colour is due to ferri-hydroxides or limonitic iron. The thickness of the zone is dependent on factors such as porosity of sediment, activity of burrowing animals and the rate of sedimentation. Faunal activity helps to distribute oxygen throughout the sediment. If the rate of deposition is slow or near zero the zone will be only very thin. However, a thick zone will result if sedimentation is rapid. Below this is a black, anaerobic zone. This is probably due to an *in situ* chemical reaction without any transportation of ions through the profile. Some pyrites may also be present in the zone. Below the monosulphuric zone is a bisulphuric or pyrite zone. The colour is characterized by a grey colour or the "natural" pigmentation of the sediment. A hydroxide deposit may occur where old roots have been growing.

In order to compare the chemical composition of the soils with that of the bedrock (Stephenson, 1970) a number of total analyses were conducted on samples collected from the bare salt flat and the lower intertidal slope. The results of the analyses are given in Table 2.5. Elemental composition of the soil samples reveals a relative deficit in the amount of silica present with respect to the parent material. This is probably due to the fact that the quartz in the igneous rock is relatively resistant to weathering and remains for a longer period as coarse material. Thus a decrease in coarse material in the sediment would be reflected in a relative drop in the amount of silica present. Therefore if the other elements were in the same proportion in the soil as they are in the rock then it would be expected that a relative increase in proportions would occur for these elements. However, this is not so. An increase in percentage is found for TiO_2, ΣFe_2O_3 and particularly MgO. A greater concentration of CaO is found in the lower intertidal slope which probably reflects the presence of a buried reef flat. The increase in NaO in the 10cm and 20cm samples in the bare flat possibly reflects concentration of NaO due to evaporation of water brought towards the surface by capillary action. Significant decreases are observed in Al_2O_3, MnO and K_2O which may be due to leaching.

The soil results indicate a general leaching or reduction in the levels of the major elements through the profile. The exceptions to this are silica and potassium which show a marginal increase. A similar leaching trend is observed in the trace elements, although nickel, cobalt and lead were not detected in any sample. The striking feature of the data is the high strontium level in the sample taken from the lower tidal flat. This is attributed to the presence of a buried coral reef flat which is situated at a variable depth, 20-30cm, beneath the sediment surface. Cuff and O'Donnell (1975) have shown that aragonitic coral, *Acropora hyacynthus*, from Little Broadhurst reef, North Queensland, have strontium levels between 15,700 and 18,000 p.p.m. On average this is a 2152 concentration factor compared with average seawater. The relatively high values of CaO(%) and Sr(p.p.m.) are therefore seen as a reflection of the slow release, and adsorption by the clay particles of the major and minor elements, from the buried coral flat together with remnants of present day decaying organic shell debris.

Tides and Water Characteristics

The most recent definitive work on tides of Australia is by Easton (1970). This work has been summarized with respect to the Great Barrier Reef section of the Queensland coast by Pickard *et al.* (1977). For the North Queensland zone, Cairns was taken as the standard port. Much that is written about that port is applicable to Townsville. Compared with ports in the southern portion of the State, the semi-diurnal tides have a greater solar influence and an increased neap-spring tide fluctuation. Small variations occur in heights of higher low water and low high water near the solstices while adjacent high tides may differ by up to 1.1m. Maximum values occur on the spring tide. Diurnal inequalities are more pronounced at high tides than at low water. In March and September the difference is less than 0.6m, varying slightly throughout each month. The succession of tides usually follows the pattern higher high water—high low water—low high water—lower low water. Highest tides in March occur during the morning; in June during the night; in September during the afternoon; and in December during the day. Tides are uniform with respect to diurnal and semi-diurnal influences. At Townsville mean spring and neap tide ranges are 2.5m and 0.8m respectively. Spring tides generally occur 1 or 2 days prior to the full moon. Data for the port of Townsville are:

	m
Mean High Water Springs	2.9
Mean High Water Neaps	2.0
Mean Low Water Neaps	1.2
Mean Low Water Springs	0.4
Mean High Water	2.4
Mean Level	1.59

(Dept of Harbours and Marine, 1976)

Tropical cyclones frequently cross the coastline. Because of the wide shallow shelf offshore from Townsville, storm surges associated with cyclones are potentially destructive (Hopley and Harvey, 1976). When Cyclone Althea crossed the coast on 24 December 1971, 48km north of Townsville, the Townsville Harbour gauge recorded water levels of 2.8m above predicted with a maximum surge of 3.66m estimated at Toolakea (Hopley, 1974).

Variations in sea water temperatures parallel the trend in mean yearly air temperature fluctuations (Kenny, 1974). The maximum water temperatures, of less than 35^{o}C, are recorded in January. Temperatures decrease during the year to a minimum in June/July of approximately 20^{o}C. Offshore tidal salinities probably do not vary much throughout the year, having a value of between 30ppt and 35ppt. Pronounced seasonal variations, however, do occur at the mouths of creeks and rivers. For instance salinity fluctuations in Cleveland Bay are closely related to rainfall and the discharge over Aplin's Weir, Ross River. During winter months salinities slowly rise as far upstream as the weir. Salinities in mid-winter show a maximum at the mouth of the estuary of 37ppt and decline upstream to 33ppt at the weir. As summer approaches and evaporation increases the shallow upper area of the estuary where circulation is restricted, particularly on the neap tides, develops hyper-saline conditions with salinities of over 40ppt, declining to 37ppt in the lower estuary. Wet season flushing, however, reverses the gradient with fresh water occupying the upper estuary and even close to the mouth. Salinity may be as low as 1.5ppt on the surface and 12.2ppt on the bottom. Salinities quickly increase on cessation of flow of the Ross River and with the first subsequent spring tide (Grigg, 1972). It is anticipated that similar seasonal variations would be experienced at Althaus Creek adjacent to Saunders Beach (Jalloonda).

The sites are therefore located in a region which is characterized by a seasonally dry climate. Most rainfall occurs between November and April. This may be accompanied by periodic high energy episodes associated with tropical cyclones. These bring not only rains of high intensity but strong winds and an artificial rise in water level. This is superimposed on the yearly and semi-diurnal differences in tidal level, and can have important consequences on the viability and extent of the mangals. Seasonal variations in salinity are more noticeable in tidal reaches of creeks and rivers than in the open sea. Seasonal sea temperature variations are more marked than salinity changes. Geologically, the substrata are young but of variable age, quality and probable alteration.

CHAPTER THREE

FACTORS RELATED TO MANGROVE ZONATION

The relationships between the soil and the overlying vegetation were investigated for two contrasting sites in the Townsville region. The Magnetic Island site is an example of an open accreting coastal situation whilst the Saunders Beach sites represent an estuarine situation. Stations located within the delineated vegetation zones were sampled on a regular basis between November 1973 and December 1975, Magnetic Island being more intensely sampled than Saunders Beach.

Soil Chemical Results

Data were obtained for both macro nutrients in the soil and for the ground water salinity. From these, spatial and temporal trends could be determined for each chemical variable.

Magnetic Island

The raw data of the elemental analyses are given in Tables 3.1 to 3.11 and 3.22. These have been graphed to illustrate spatial trends and temporal trends, Figures 3.1 to 3.32. A more detailed analysis of each chemical variable is given below.

(i) pH (KCl) and pH (H_2O)

Two measurements were taken for pH since it is thought that each represents a different facet of the environment. pH measured in a KCl solution is thought to indicate the background pH value whilst a measurement taken in distilled water reflects the seasonal pH variation (Navalkar and Bharucha, 1949). Spatially the general trend is a curve with two peaks and troughs. pH values rise from about pH6.0 in the landward zone to about pH9 on the salt flat/seaward *Arthrocnemum* zone. A rapid decline follows towards Stations 7 and 8 in the *Rhizophora* zone to pH3 to 4. Values then rise again to a new peak in the mangrove fringe and lower intertidal slope. The trends observed in the pH KCl figures are essentially duplicated by those measured in a pH H_2O solution. The main difference, however, is that the range in values is larger in the latter solution. As a general rule, pH decreases with depth. Although the same general trend is observed in all three layers, the surface layer displays the least variation. This is seen when pH trends are considered in a time dimension. Low values are recorded in February/March for all stations except Station 8. Again, there is a decrease in pH with depth, the lower levels having a greater variation than the surface. Because of the constancy of many of the surface measurements, the trend of pH maxima in the salt flat/seaward *Arthrocnemum* zone and the two seaward zones is quite pronounced.

(ii) Water Soluble Carbonate and Bicarbonate

No traces were detected.

(iii) Water Soluble Chloride (WSCl)

The general trend of the data is an increase from the landward *Ceriops* zone from an average of about 39.4m.e.% to 88.8m.e.% in the bare salt flat. A decline in values occurs seaward. There is a secondary peak value at Station 6. This may reflect balances obtained between tidal wetting and flushing of salts out of the system and concentration due to increased evaporation with a sparse canopy layer. Variations are most readily apparent in the 10cm and the 30cm layers. The surface layer displays a more erratic pattern. Here moisture conditions vary greatly due to fluctuating water table levels and the activities of burrowing animals. At stations without a dense vegetation cover, concentration of salts by evaporation and the ensuing capillarity of saline solutions from below towards the surface is highly important. As a rule the 30cm layer has higher values than the 10cm layer. Seasonal trends can be seen in the data, especially in the landward sites. Chloride concentrations tend to decrease at the beginning of the year (February and March), rising to a secondary peak and trough in May/June and July-August respectively. Maxima are recorded in October/November before the values sharply decline in December with the onset of higher tides and the wet season. The trends and deviations in the data disappear in a seaward direction as the frequency and duration of tidal cover increases.

(iv) Water Soluble Sulphate ($WSSO_4$)

Two trends are visible in the data. First, there is a marked increase in water soluble sulphate with depth, and second, most sulphate is observed beneath *Rhizophora* vegetation, apart from a minor peak in the salt flat area. Highest sulphate values are generally associated with areas containing large quantities of fibrous organic matter, particularly beneath *Rhizophora* spp. When waterlogged, similar soils are generally found to contain high sulphide concentrations. On drying biological oxidation takes place due to bacteria such as *Thiobacillus thio-oxidans* oxidizing the sulphides and decomposing organic matter (Tomlinson, 1957; Hart, 1959; Hesse, 1961a). However it has also been suggested that the sea is the primary source of sulphate in the sediment (Watts, 1960).

(v) Soluble Sodium (SolNa)

Trends in the data are similar at both the 10cm and 30cm levels. Concentrations increase from the land (about 300m.e.%) towards the salt flat (about 700m.e.%). Seaward of this station (3), concentrations decline to about 200m.e.%. In both these levels sodium concentration is similar. However, the surface layer concentration is more variable, often being much higher than values in the other layers. For instance the levels in surface layers attain values of more than 1000m.e.% in the dry season. Like the variations in the chloride concentration, this is probably due to seasonal tidal fluctuations and evaporation of surface waters concentrating sodium in the surface layers. Ground water variations, in depth and salinity, may also play a significant role in the layers' concentration. On a time scale a general build-up in sodium concentration is observed through the year from a low in January to a high in October/November, in spite of the fact that September and October 1975 were two of the wettest months on record in Townsville.

(vi) Soluble Potassium (SolK)

Variations in the concentration of soluble potassium are quite different from those of soluble sodium. A general build-up in concentrations occur throughout the year to October/November, from 4 to 24m.e.%. The stations on the upper part of the intertidal slope and high tidal flat have a greater variability than other stations to seaward. This is especially noticeable in the surface layers. On average, the concentration in the 10cm layer is generally less than the other two layers. An anomalously high value is present at all stations in February 1975. The reasons for this are uncertain.

(vii) Soluble Calcium (SolCa)

In all layers there is an increase in concentration from the land to the sea, especially seaward of the central *Rhizophora* Station 8. Little variation is observed between layers for any one month, generally being less than 1m.e.%. Most stations appear to have two high readings—one in February and another in October/November, with a subsidiary peak in June/July. The former two high values could be related to an influx of fresh water (Russell, 1970) due to heavy rainfall. Such an explanation is not tenable in the latter case which may be related to variations in the sea water concentrations.

(viii) Soluble Magnesium (SolMg)

Trends in soluble magnesium concentrations are far more difficult to discern. For instance, the landward *Arthrocnemum* zone, with a concentration of about 40m.e.%, shows little if any variation for the 10cm and 30cm layers. However the surface layer shows marked monthly variations (152 ± 86m.e.%). No seasonal variation in concentration could be identified. As a broad generalization, highest values occur in the salt flat or the landward *Arthrocnemum* zones declining towards both the sea and the land.

(ix) Exchangeable Sodium (ExNa)

Exchangeable sodium levels are much lower than those for soluble sodium. The trend in the data is also different. In all layers there are increases in concentrations seawards from the land, approximately 4m.e.%, to Station 8, 12m.e.% in the *Rhizophora* zone, after which the levels decline. No seasonal trend is apparent in the data. In the landward six zones the surface exchangeable sodium record was generally lower than that for the 10cm and 30cm layers. In the *Rhizophora*, mangrove fringe, and lower tidal flat stations, the position is reversed with the surface layer generally having higher values, up to 13.92m.e.%.

(x) Exchangeable Potassium (ExK)

It is difficult to determine trends when dealing with concentrations of less than 3m.e.%. However there appears to be a spatial variation similar to that of exchangeable sodium. Exchangeable K levels generally rise from the land to Station 5, declining in concentration at Stations 6 and 7. A second peak in the data is found at Station 8, after which a decrease in concentrations is observed. Temporally there is no seasonal trend of the cation although there is a persistent low value in the February figure. This may represent the influence of fresh water due to rainfall.

(xi) Exchangeable Calcium (ExCa)

This cation displays a marked spatial variation. In all levels there is little difference between the first seven stations seaward from the land, (3-10m.e.%). Station 8 displays a slight increase in value. However, Station 9 at the front of the *Rhizophora* zone has a large increase in concentration from 14 to 49m.e.%. This concentration is maintained in the mangrove fringe and the lower intertidal slope stations. The influence of the buried reef flat is clearly illustrated. Seasonal trends are not clear although Stations 4-11 inclusive display a marked fall in concentrations from May to August in the dry season.

(xii) Exchangeable Magnesium (ExMg)

The data are fairly consistent in a spatial context with a decrease in concentration with depth. Two peaks in the data are persistently found across the intertidal flat at the salt flat and either Station 8 or 9 in the *Rhizophora* zone, the latter stations having the larger value. Temporally, an anomaly appears in the data. Most of the concentrations are between 5 and 15m.e.%. However, in January, February and July extremely low values were found at all stations. Whilst an influx in fresh water could be invoked to explain this in January and February, no such explanation could satisfy the July figures. A calibration error of a x 10 factor (which is most logical in terms of making up the standards and conversion of ppm to m.e.%) would only induce a peak in all the graphs. Consideration of the ExCa/ExMg ratio is thought to be a satisfactory built-in check. As can be seen from Figure 3.31, no discrepancies can be seen since a slight down turn in ExCa values had also been observed.

(xiii) ExNa/ExK; ExCa/ExMg

The ratios of the cations are included in the analysis since it has been shown that for two *Atriplex* spp. it was the Na/K ratio which was the important controlling factor for healthy growth rather than absolute concentrations (Ashby and Beadle, 1957). Also, cationic ratios have been used in the description of saline soils, e.g. Vieillefon (1969) and Hervieu (1968). Similar trends are found in both ratios. The basic fluctuation in ExNa/ExK is a decrease seaward to the salt flat/*Arthrocnemum* zones, rising to Station 7 or 8, followed by a decline seaward. ExNa varies between 2 to 10 times more abundant than ExK. Likewise for ExCa/ExMg there is a fall in value to the salt flat followed by a rapid rise seaward. On the landward zones, ExMg is 2 to 3 times more abundant than ExCa. This situation is reversed on the seaward edge of the swamp due to the influence of the buried coral reef flat.

(xiv) Groundwater Salinity

Data were collected on a monthly basis from November 1973 to December 1975 inclusive. Initially samples were taken from all stations. However, because of the activity of burrowing molluscs and the shallowness of the sediment in the mangrove fringe and on the lower inter tidal slope, it was not readily apparent whether the water table or the residual surface water was being sampled. Consequently sampling at these two stations was discontinued. The results are given in Table 3.22. In an attempt to discern the broad trends and to smooth out some of the irregularities in the data, a four monthly running mean was calculated (Figure 3.32).

Some distinct trends are clearly visible in the data. Salinity values increase from the land to the bare salt flat, values ranging from 13.2ppt to 141.28ppt. Seaward, salinity progressively decreases to 25.1ppt—38ppt in the *Rhizophora* zone. This is probably due to two factors. The strong seasonality in rainfall is clearly seen by the influence of the heavy rainfall in the wet season on the ground-water salinities. This is evident particularly at Station 1, the landward *Ceriops* zone, where salinities as low as 13.2ppt have been recorded. The other contributing factor is the tidal range and the degree of vegetation cover. During the dry season the spring tides are significantly lower than during the wet season. Hence the degree of exposure of the upper intertidal slope increases through the year. Evaporation of surface water, the rate of which increases with the reduction in canopy cover, leaves behind a salt deposit which, when no longer influenced by fresh water flushing or tidal water, may develop into a saline surface skin. This is evident when the bed load sample salinities are considered. Readings from the upper intertidal slope, especially those taken in July, August and September, have values considerably higher than normal seawater. Thus part of the surface salt deposit has been taken into solution by the incoming tidal waters.

The seasonal variability in salinity also increases from both the land and the sea towards the bare salt flat. The latter station has a range of 50.9ppt (90.4ppt to 141.3ppt). This contrasts with a 13ppt range (25ppt to 38ppt) beneath the *Rhizophora* forest and a

39.6ppt range (13.2ppt to 52.8ppt) beneath Station 1, the *Ceriops* thicket.

The trends in the soil chemical data for Magnetic Island are given below:

pHKCl	Spatial trend, highest values on the salt flat and lowest in the *Rhizophora* zone. Lack of seasonal trend.
pHH_2O	Similar to pHKCl but with a slightly larger range in values.
WSCl	Highest values on the salt flat decreasing to land and sea. Seasonal trend more developed in landward than seaward zones.
$WSSO_4$	Values increase with depth with greatest values in the *Rhizophora* zone.
SolNa	Highest values on salt flat decreasing to land and sea. Greater variation in surface layers than at depth. Concentration least in wet season and greatest at end of dry season.
SolK	Lack of spatial trend but landward and seaward two zones have lower concentrations than other zones. Higher values at end of dry season, lower in wet season, with highest values on upper portion of intertidal slope.
SolCa	Concentrations increase from the land to the sea. Lack of reliable seasonal trends.
SolMg	Landward *Arthrocnemum* zone and salt flat have highest concentrations, decreasing to land and sea. Surface values show greatest variation.
ExNa	Increase from land to the *Rhizophora* zone. Lack of a seasonal trend.
ExK	Highest values in the *Suaeda/Avicennia* zone and Station 8 in the *Rhizophora* zone. Lack of a seasonal trend.
ExCa	Increase from land to the sea, sharply within *Rhizophora* zone. No clear seasonal pattern.
ExMg	Highest concentration on salt flat and in *Rhizophora* zone. Lower values tend to occur in the wet season.
ExNa/ExK	Lowest values on salt flat and highest in *Rhizophora* zone.
ExCa/ExMg	Similar to ExNa/ExK.

Salinity Highest values on salt flat decreasing to sea and land. Marked seasonal variations, lowest in the wet season. Variation greatest on salt flat, least in *Rhizophora* zone.

Saunders Beach

A similar range of analyses was conducted on data collected along two transects at Saunders Beach. The Saunders Beach stations were sampled every three months, in January, April, July and October 1975, and in January 1976, and their results are given in Figures 3.33-3.63 and Tables 3.12 to 3.21, and 3.23.

(i) pH KCL and pH H_2O

A number of features are discernible in the data. For both types of readings, pH at the first transect falls to a low in the *Sporobolus* zone, and rises again inland while at the second transect the lowest pH values are observed at the mixed *Rhizophora/Bruguiera* zone. Little variation is seen between the different levels, there being generally less than 0.5 units difference between the three readings. However the pH H_2O readings often differ by more than 1.0 unit from the pH KCl readings. This is probably due to ionic interference at the electrode.

(ii) Water Soluble Chloride (WSCl)

At Saunders Beach there is a build-up in concentration from the creek inland with the highest value on the salt flat, even though it is lower than the landward *Ceriops* zone. The exception to this is the *Sporobolus* zone, Station 14, which contains virtually no Cl during the whole year. At Saunders Beach 2 the greatest concentration is in the mixed *Rhizophora/Bruguiera* zone (Station 19). It is interesting to note that in this zone the Cl status is similar to the lower two layers of the *Arthrocnemum* and salt flat zones at Saunders Beach 1. The only difference between the zones is that the surface concentrations of the *Arthrocnemum* and salt flat zones are considerably higher than the former zone. Station 19 is also located under a vegetation canopy and is located at a lower elevation. Little seasonal variation is observed at the Saunders Beach 2 stations. However, marked seasonal variations are observed at Saunders Beach 1, although this is mainly confined to the surface layers, with highest values being found during the dry season. Differences in the January figures are probably a function of the variation in the onset of the seasonal rains with respect to the sampling time.

(iii) Water Soluble Sulphate ($WSSO_4$)

The trend of the sulphate data is similar to that of the chlorides with little difference between the layers at each station, apart from the surface layer at Saunders Beach 1 which may be up to five times that of the deeper layers. Greater concentrations are found on the samphire and salt falt zone, Saunders Beach 1, and the *Rhizophora/Bruguiera* zone at Saunders Beach 2. The *Sporobolus* station has virtually no sulphates present. A seasonal trend is apparent with the lowest values in the wet season and highest in the dry.

(iv) Water Soluble Carbonates and Bicarbonates

Neither is detected.

(v) Soluble Sodium (SolNa)

Again a marked seasonal trend is apparent for SolNa. Lowest values are found in the wet season and the highest values in the dry with the inland stations having the biggest values of almost 900m.e.%. At Saunders Beach 1 most variation occurs in the surface layers. The discrepancy between this and the other two layers increases and decreases in the dry and wet seasons. The exception to this trend is at the *Sporobolus* station where the 30cm layer displays most variability. At Saunders Beach 2 little difference occurs between the layers although the 30cm layer normally has a higher concentration than the surface layer. Greatest concentrations occur in Station 19, the *Rhizophora/Bruguiera* zone.

(vi) Soluble Potassium (SolK)

Variations displayed by SolK are similar to those found in SolNa. Concentrations increase inland, on the first transect, from about 1m.e.% in all levels on the creek bank to about 6m.e.% in the 10cm and 30cm layers of the salt flat area. Surface concentrations at this station range between 12m.e.% and 16m.e.%. There are marked seasonal variations in the data with lower values being present in the wet season and higher ones in the dry. These trends are more noticeable in the surface than the sub-surface levels. On the second transect Station 19 displays the highest concentrations. Unlike transect 1, the sub-surface levels, in all groups, have slightly higher values than the surface. A seasonal trend is apparent in the data although values are significantly less than those of transect 1.

(vii) Soluble Calcium (SolCa)

Similar trends to the above are also seen in SolCa on transect 1. Concentrations decline from the creek bank to the *Sporobolus* zone before increasing again inland. Once again Station 19 has the greatest concentration in the second transect. Distinct seasonal trends can be identified in all the data. The wet season produces low values, less than 4m.e.%, whilst this is increased up to 200m.e.% at some stations during the dry season. In spite of differences in canopy cover and height of the surface, the mixed *Rhizophora/Bruguiera* zone, Station 19, has similar concentrations to those of the *Arthrocnemum* and salt flat zones, Stations 16 and 17 respectively. Variations between layers in the former station, 19, are generally less than those which exist in the other two zones. A similarity also exists at the various stations beneath a *Ceriops* cover.

(viii) Soluble Magnesium (SolMg)

Values across transect 1 for soluble magnesium display less variation than the SolCa readings. Generally Stations 12 to 15 inclusive, as far inland as the landward *Ceriops* zone, have a concentration of less than 25m.e.% in all layers throughout the year. For the 10cm and 30cm layers of the *Arthrocnemum* and salt flat zones, Stations 16 and 18, the values progressively increase to about 80m.e.% in the latter zone during the sampling programme. The surface figures for these two zones show a rapid increase to almost 300m.e.%. However, in January 1976 the surface values are considerably lower, less than 80m.e.%. The large difference between the two January figures may be a reflection of the sampling times with respect to the onset of the wet season. Data from the second transect are generally higher than their counterparts at Saunders Beach 1 but are, as a rule, still below 70m.e.%. Once again Station 19 has the highest concentrations although this is in the 30cm layer rather than the surface.

(ix) Exchangeable Sodium (ExNa)

Following a decline inland to the *Sporobolus* zone at Saunders Beach 1, values increase to about 8m.e.% on the salt flat. Variations at a station are generally less than 4m.e.% and often less than 2m.e.%. On the second transect Stations 18, 20 and 21 on the creek bank and in the *Ceriops* zone have values of less than 6m.e.% whilst at Station 19 the maximum value was 17.05m.e.%. No seasonal trend is apparent in the data for either transect.

(x) Exchangeable Potassium (ExK)

The trends on both transects are virtually identical to ExNa. The sole difference is the elemental concentration. On transect 1, the maximum value found is 2.27m.e.% at Station 17 whilst on transect 2 it is 3.96m.e.% in the mixed *Rhizophora/Bruguiera* zone, Station 19.

(xi) Exchangeable Calcium (ExCa)

Exchangeable calcium shows a similar pattern across the intertidal zone to that of exchangeable sodium. Surface figures are higher than those for the other two layers with a greater interlayer similarity being found at Saunders Beach 2 stations than at Saunders Beach 1. A marked seasonal pattern is found in the data. At Saunders Beach 1, although variations occur in all layers, the greatest fluctuations are found in the surface layer, e.g. 20-650m.e.% for the *Arthrocnemum* zone. At Saunders Beach 2 all layers display a seasonal variation ranging from 2m.e.% to 130m.e.% in Station 20 to 6m.e.% to 310m.e.% at Station 19.

Highest seasonal values are generally found in April and July. The unseasonal wetness of September and October 1975 presumably contributed towards the declining concentrations in the October figures.

(xii) Exchangeable Magnesium (ExMg)

Once again the pattern is similar to that for most other ions. However, the concentrations of ExMg in all three layers in Station 19 are more than those of any other station. Seasonal variations are difficult to ascribe to the data although the surface information suggests that trends may be present. Low values are found for January 1975 but they remain fairly constant for the succeeding four sample periods apart from in the samphire and salt flat zones, transect 1, which have a July maxima of 13.95m.e.% and 11.71m.e.% respectively. The low values would ordinarily be attributed to the influx of fresh water but evidence of the chloride and soluble magnesium data appear to contradict this.

(xiii) ExNa/ExK; ExCa/ExMg

No clear patterns are present for either of these cationic ratios at Saunders Beach 1, although at Saunders Beach 2 the situation is simpler. For ExNa/ExK the concentration factor is constant throughout the year for Station 19 whilst Stations 18, 20 and 21 display a greater variation. No seasonal fluctuation could be identified. Marked variations are found across the intertidal zone at Saunders Beach 1 but a slight seasonal trend could be distinguished. Distinct seasonal trends are seen for the ExCa/ExMg ratios. Although the raw data display a maxima in Station 19, their ratios produce a minimum value. In 1975 least variation is found in Station 12 and Station 17, adjacent to the creek and on the salt flat respectively. In all cases the concentration factor is severely reduced in January 1976.

(xiv) Ground Water Salinity

A seasonal trend, similar to that on Magnetic Island, is present with high values in the dry season and low values in the wet. However, the distribution of values along transects is of interest. The creek bank stations on both transects do not display marked seasonal variations although their concentrations range from 20ppt to 40ppt. More definite seasonal trends are present in the data for Station 17, ranging from about 46ppt in the wet season to over 100ppt in the dry season. Station 16 is uniformly high, ranging from 41ppt to about 53ppt. Stations 19, 20 and 21 on the second transect have a tendency for lower values during the wet season and higher values during the dry season.

However, values on the salt flat and *Arthrocnemum* zone are larger than those under a *Ceriops* cover, even though the latter is situated higher on the intertidal slope and not influenced by fresh water seepage. The variation in values therefore may be intimately related to the extent of the vegetation cover and the amount of radiation incident on the ground.

The trends in the soil chemical data for Saunders Beach are given below:

pHKCl — SB1—lowest under the *Sporobolus* zone, increasing creekward and landward.
SB2—lowest in the *Rhizophora/Bruguiera* zone, increasing creekward and landward.
Lack of a seasonal trend.

pHH_2O — Similar trend to above but with lower values.

WSCl — SB1—Decrease from the creek to the *Sporobolus* zone, then increasing to the salt flat. Marked seasonal trend especially in the surface layers.
SB2—greatest concentration in the *Rhizophora/Bruguiera* zone decreasing to land and the creek. Lack of a seasonal trend.

$WSSO_4$	SB1—similar to WSCl. SB2—similar to WSCl but with a seasonal trend.
SolNa	SB1—lowest value in the *Sporobolus* zone and highest on the salt flat. Marked seasonal trends with the surface concentrations varying the most. SB2—highest values in the *Rhizophora/Bruguiera* zone but with 30cm layer having the greatest concentration. Unclear seasonal pattern.
SolK	SB1—increase in concentrations to the salt flat with marked seasonal variations especially in the surface layer. SB2—greatest concentrations in the *Rhizophora/Bruguiera* zone especially in the sub-surface layers. Seasonal variation present.
SolCa	SB1—lowest concentrations on the *Sporobolus* zone and highest on the salt flat. Seasonal variation present. SB2—highest concentration in the *Rhizophora/Bruguiera* zone. Seasonal variation present.
SolMg	SB1—increase in concentration to the salt flat. Seasonal variation greatest in the surface layer. SB2—highest values in the *Rhizophora/Bruguiera* zone especially in the sub-surface layers. A seasonal trend is present.
ExNa	SB1—lowest values in the *Sporobolus* zone and highest in the salt flat. No seasonal trend apparent. SB2—highest values in the *Rhizophora/Bruguiera* zone with no seasonal trend apparent.
ExK	SB1—similar trend to ExNa. SB2—similar trend to ExNa.
ExCa	SB1—lowest value in the *Sporobolus* zone, increasing to land and the creek. Seasonal variation greatest in the surface layer. SB2—highest values in the *Rhizophora/Bruguiera* zone, with marked seasonal variations.
ExMg	SB1—lowest values in the *Sporobolus* zone, highest on the salt falt. No appreciable seasonal variation. SB2—highest value in the *Rhizophora/Bruguiera* zone. No appreciable seasonal variation.

ExNa/ExK SB1—marked variation along the transect. Possible seasonal variation.

SB2—lack of a seasonal trend with great variation in the ratio, except in the *Rhizophora/Bruguiera* zone.

SB2—lack of a seasonal trend with great variation in the ratio, except in the *Rhizophora/Bruguiera* zone.

ExCa/ExMg SB1—general decrease landward. Seasonal trend present.

SB2—lowest ratio in the *Rhizophora/Bruguiera* zone. Seasonal trend present.

Salinity SB1—general increase landward, seasonal pattern greatest on the salt flat.

SB2—increase in a landward direction, with a seasonal pattern present.

Statistical Analysis of the Data

The data from the two mangal areas were analyzed using a number of statistical techniques. Factor analysis was used to explain the relationship between the variables being studied. A cut-off point of eigenvalue 1.0 was utilized in determining the number of factors for consideration. This meant that only factors that account for at least the amount of total variance of an individual variable were treated as significant. Because of the complex nature of the data, being collected by station, through time and with a depth component, the analysis has been conducted by considering each individual sediment layer in turn.

In this way the covariance in the data is accounted for or explained only in terms of variations in space. The time element in this instance can be considered to be equivalent to analyzing a series of replicates for each station. Because of the possibility of a variable source of calcium in the various mangals the analyses were run both with and without that element. These runs are identified as 12v (variables) and 10v respectively.

The data arranged by stations were then processed using discriminant analysis. The technique was used in a classificatory role. By this means stations with a similar multivariate profile could be identified. Lastly, multiple regression analysis was used to identify any significant relationship that may exist between the dependent variable of ground water salinity and rainfall, exposure, height of land surface and distance from the landward margins of the mangal. The results are given in detail in Volume II.

(i) Factor Analysis

Magnetic Island

The results of the analysis, Tables 3.24 to 3.31, are similar for each layer and for each of the separate runs. As a rule the percentage of the covariance that is explained by the first factor is greater in the 10v than in the 12v analysis. Values range from 36%-38% compared with 31%-33% for the 10v and 12v analyses respectively. For each layer the factors are dominated by water soluble chloride, water soluble sodium and soluble magnesium. Occasionally water soluble sulphate is identified as an important variable. The sole exception to this trend is in the result for the 30cm layer, when exchangeable sodium, exchangeable potassium and exchangeable magnesium are highly loaded on the first factor.

Four out of the six possible second factors are dominated by pH, pHKCl and pHH_2O. The factor accounts for between 19% and 22% of the covariance. The two exceptions to the above are the second factors of the 12v analysis for the 10cm and the 30cm layers. Exchangeable calcium, soluble calcium and exchangeable magnesium dominate these factors, with water soluble sulphate also being important in the latter analysis. The percentage explanation of the covariance is 21.4% and 19.07% respectively.

The third and fourth significant factors, which are present in all of the analyses, provide a less uniform picture. Consequently it is more difficult to give a general interpretation to the results. For both the 12v and the 10v analyses of the surface data exchangeable sodium, potassium and magnesium are highly loaded on the third factors. They have a 16.7% and 17.3% explanation of the covariance respectively. The third factor is similar for both the 10cm and the 30cm layers in each of the 12v and the 10v analyses.

In the 12v analyses pHKCl and pHH_2O are highly loaded on that factor, explaining 17.9% and 15.5% of the covariance respectively. In the 10v analyses water soluble sulphate and soluble potassium are loaded highly on the third factor and explain 12.3% and 15.98% of the covariance related to the 10cm and 30cm layers respectively.

Little similarity is seen between the variables that have a high loading on the fourth factor either between the 12v and the 10v analysis or between layers. For the 12v and the 10v analyses respectively the important variables with regard to the percentage explanation of the covariance for that factor are:

(a) Surface : Soluble calcium, exchangeable calcium 14.4%
: Water soluble sulphate, soluble potassium 8.1%

(b) 10cm : Water soluble sulphate, soluble potassium, soluble calcium 9.14%
: Exchangeable sodium, potassium and magnesium 9.6%

(c) 30cm : Exchangeable sodium, potassium and magnesium 13.46%
: Water soluble chloride, soluble sodium, soluble magnesium 11.44%

Distinct trends are present in the data when the two most important factors, with respect to the amount of common variance, are considered. The first factor can be designated a salt factor, with high loadings for water soluble chloride, soluble sodium and soluble magnesium. The sole exception to this is the first factor of the 30cm layer (10v) which can be given an exchangeable cation label. Likewise the second factor is predominantly a pH factor. The two exceptions to this, the 10cm and 30cm layers (12v), are dominated by calcium and exchangeable magnesium, with water soluble sulphate playing a minor role. Although labels can be attached to the third and fourth factors for individual layers, there appears to be a lack of similarity both between layers as well as between the 12v and 10v analyses. Labels such as exchangeable cations; water soluble sulphate and soluble potassium; pH; calcium; and salt trends can be given to the factors. The combined percentage explanation of the covariance for the third and fourth factors generally lies between 20% and 30%. The total amount of the covariance which is accounted for by the four factors ranges between 80% and 85% with each of the 10v analyses having a slightly higher value than the 12v analyses.

Saunders Beach

A separate analysis was conducted on each transect at Saunders Beach because of their different zonal characteristics, Tables 3.32 to 3.45. The first factor for each analysis, on the Saunders Beach 1 data based on twelve and ten variables accounts for over 50% of the covariance in the data. Values range from 55%-62% (12v) and 61%-72% (10v) with the latter being greater than the former at each depth. A similarity exists in the solutions to each analysis since the majority of variables are highly loaded on the first factor. These are water soluble chloride; water soluble sulphate; soluble sodium, potassium, and magnesium; and exchangeable sodium and potassium. The exceptions to this are 10cm (12v) which also includes exchangeable magnesium in the list and the surface analysis (10v) which does not include water soluble sulphate and exchangeable potassium.

The percentage explanation of the covariance is always greater in the 12v than the 10v analyses on the second factor. Amounts explained range from 13%-18% (12v) to 12%-15% (10v). Soluble calcium and exchangeable calcium are highly important in all three analyses (12v). However, for the surface data water soluble sulphate and exchangeable magnesium also are highly loaded onto the second factor. For the 10v analyses pHH_2O is the most important parameter with pHKCl being of secondary importance in the surface analyses.

Only some of the analyses produce a third factor which has an eigenvalue of more than 1.0. In the 12v analyses pHH_2O is the most important variable with pHKCl being of secondary importance in the surface analysis. Between 8%-10% of the covariance is explained by this factor. In the 10v analyses a third significant factor is produced only in the 30cm data analysis. pHKCl and exchangeable magnesium are highly loaded on this factor which explains 9.66% of the covariance.

Tentative qualitative labels can be given to each of the factors. These can apply in a general sense because of the similarity of the results. However, there may be subtle differences between the results of individual layers. The first factor in most cases can be considered a size factor since a majority of the variables are highly loaded on this factor. The exception (surface, 10v) can be considered a salt factor. The second factor (12v) is basically a calcium factor whilst the third factor is predominantly a pH factor. The second factor (10v) can be designated a pH factor. Because the 10v analysis tends to produce only two significant factors a slight reduction in the total amount of covariance that is explained by the analyses is found with respect to the 12v analyses. This is not so when three factors are identified (30cm, 10v). The values for the 12v and 10v analyses are surface 84.3%, 79.6%; 10cm 86.4%, 83.9%; and 30cm 87.5%, 94.5%.

Results from Saunders Beach 2 produce a similar result for the 12v and 10v analyses and for the 10cm and 30cm layers. The surface analyses produce a first factor dominated by water soluble chloride and sulphate, and soluble sodium, potassium and magnesium, accounting for 52.3% and 56.9% of the covariance in the 12v and 10v analyses respectively. For the 10cm and 30cm data all variables other than pHKCl and pHH_2O have high loadings on the first factor. This factor accounts for 64.7% (12v), 71.0% (10v), and 65.6% (12v), 73.1% (10v), for the 10cm and 30cm data respectively.

In most instances the second factor is dominated by pHKCl and pHH_2O. The two exceptions to this are the surface (12v) which also has soluble and exchangeable calcium with high loadings on the factor and 10cm (10v) which also has soluble magnesium associated with it. Analysis of the surface data is the only result to produce a third significant factor which comprises exchangeable sodium, potassium and magnesium for both the 12v and 10v analyses.

Qualitative labels can be readily assigned to each factor. In the surface layer the first factor is a salt factor, the second a pH factor (pH/calcium, 12v) and an exchangeable cation factor for the third factor. For the 10cm and 30cm analyses, the first factor is a general size factor whilst the second is a pH factor. In each pair of analyses, 12v and 10v, it is found that the latter accounts for a greater amount of the total covariance in the data.

(ii) Discriminant Analysis

Whilst the underlying structure of the data has been derived using factor analysis, the similarity between the stations in multivariate space has not been assessed. This can be achieved using discriminant analysis as a classification procedure. The data items are located about discriminant vectors which are projected into multivariate space such that there is a minimum ratio of the difference between a pair of station multivariate means to the multivariate variance within the two stations' data (Davis, 1973). The significance of the Mahalanobis distance measure between each pair of stations is tested using F values. The null hypothesis that is tested is that there is no significant difference between the stations. The rejection level for this hypothesis is P = 0.05. Those stations that conform to the hypothesis, that is those not having a statistically significant difference between them, are listed in Tables 3.46 to 3.54.

Magnetic Island

Because a similar underlying structure is identified in the data using both twelve and 10 variables, the discriminant analysis is computed using all twelve variables. The results, Tables 3.46 to 3.48, illustrate an overall dissimilarity between the stations, at each depth, with respect to their multivariate chemical profile. At the surface, only Stations 4/6, 10/11 are considered to be similar. At the other two depths a slightly different relationship emerges. At 10cm Stations 1/2, 5; 2/4, 5; 4/5; 10/11 are similar, whilst at Stations 4/5, 6; 5/6 are thought to be similar to each other. A series of other analyses were conducted in connection with the surface data, including other variables such as the duration each station had been exposed by tidal water prior to sampling, the ground water salinity, the ratios of exchangeable sodium : exchangeable potassium and exchangeable calcium; exchangeable magnesium, since they may indicate a limiting relationship with the uptake of the associated ions (Ashby and Beadle, 1957). The results obtained are essentially the same as the results produced by the analysis of the chemical data. The only major difference to occur is found when only the ratios are used. in the analysis the results indicate that Stations 1/6, 7, 8; 2/3, 4, 5, 6; 3/4, 5; 4/5, 6; 7/8 are similar to each other.

Overall the results suggest that there is a lack of unity and coherence between the stations. Stations 10 and 11 are consistently separated out as being similar. Likewise similarity is indicated for Stations 2, 4, 5 and 6 on the upper part of the intertidal slope. It is only when the ratio data for the surface are considered in isolation that a greater number of affinities are recorded. Consequently there appears to be an association between some of the stations on the upper intertidal slope and between the most seaward two stations. The remaining stations have dissimilar characteristics when compared to each other.

Saunders Beach

As in the factor analysis, the two transects have been considered as separate units. At the P = 0.05 level for Saunders Beach 1 a distinct correspondence in the results occurs between the layers, Tables 3.49 to 3.51. A similarity is present between Stations 12, 13 and 15. On the surface there is a degree of association between Station 14 on top of the levee bank with Station 15 in the inner *Ceriops* zone. The 30cm data for Station 14 is also similar in multivariate space to Stations 12 and 13. It is also found that at each depth, Stations 16 and 17 are different from each other and from all other stations on the transect.

For Saunders Beach 2, Tables 3.52 to 3.54, there is an affinity at all levels between Stations 18 and 21, at either end of the transect and between Stations 20 and 21 in the *Ceriops* zone. Station 19 is considered to be different from each of the other stations on the transect. Consideration of other variables such as ratio of the exchangeable cations and exposure time prior to sampling produces a similar result.

(iii) Multiple Regression Analysis

The ground water salinity data for Magnetic Island was analysed using multiple regression analysis. Variables included in the analysis were:

(a) the height of the land surface
(b) distance from the landward edge of the mangal
(c) rainfall for the 4 days prior to sampling
(d) rainfall between sampling dates
(e) total rainfall for the previous two months
(f) total rainfall for the previous three months
(g) exposure for the 24 hours prior to sampling
(h) exposure for the previous four days
(i) exposure between sampling periods
(j) exposure for the previous two months.

The variables had been chosed for a number of reasons. Parameters (a) and (b) and by inference (g)-(j) are central to the ideas developed by MacNae (1966, 1967, 1968). Rainfall for the previous 4 days has been found to have a significant influence on ionic concentrations (Davison, 1950). The increasing length of time associated with variables (c) to (j) inclusive, is to identify any lag effect that the variables may exert on the ground water salinity.

Although ground water salinity data for Stations 10 and 11 were not collected for the whole period, values for the salinity of water caught in the sediment traps are known. Because of the location of the two stations these data were included as being representative of the conditions likely to prevail at the stations.

The results of a series of stepwise regression analyses are quite conclusive. When all the stations are considered the analysis producing the largest multiple R comprises height of the station, distance seaward and total exposure between sampling periods, Table 3.55. The multiple R is 0.59676 which when squared indicates that only 35.612% of the variance in the data is accounted for by the three variables. All other analyses produced an inferior result. If, however, Stations 1 and 2 are omitted, because their ground water salinity values may be influenced by freshwater seepage, a different result is derived. Again the same three variables are considered to be statistically important. Multiple R is 0.95063 with an R squared value of 0.9037. Even though the exposure between sampling periods is a statistically significant variable, it provides only an increase of 0.0047 in the R squared value compared with the result obtained using the height and distance variables.

The analyses showed that precipitation, as considered above, has no statistically significant effect on the ground water salinity on Magnetic Island. This is in direct contrast to results of Davison (1950). However, he was working on an area adjacent to creeks. Under these conditions it is possible that data from Saunders Beach may have produced a similar result. However, it was not possible to assess this hypothesis.

Discussion

The trends and variations in several soil chemical variables have been described above. It is apparent that there are fundamental differences in the behaviour of the variables on an open accreting coastline compared with an estuarine coastline. On an open accreting coastline there appears to be a highly variable spatial trend in the data, which may be due to a number of reasons. A peak concentration for calcium in the seaward *Rhizophora* station, *Avicennia/Sonneratia* fringe and the bare lower intertidal slope appears to be related to the underlying substratum.

Where the greatest elemental concentration occurs on the upper intertidal slope it is invariably located on the salt flat. This is particularly so for the soluble ionic data. The most likely cause of this peak is the lack of a dense vegetation. In the absence of a vegetation cover, there is an increase in the amount of direct insolation incident on the ground. This enables a significant increase in the evaporation rate to take place with respect to that experienced under a closed canopy. This is further augmented by the low frequency and duration of tidal cover in this part of the intertidal zone and the highly seasonal nature of the precipitation. Consequently there is a lack of flushing of the elements and an increase in elemental concentration is allowed to develop.

A third area within the *Rhizophora* zone experiences a peak or secondary peak for elements such as soluble sulphate and exchangeable sodium. This would be associated with the presence of a dense root network which is characteristic of *Rhizophora* trees (Hart, 1959; Hesse, 1961b; Giglioli and Thornton, 1965).

Coupled with a highly variable spatial trend is a lack of a seasonal trend in most elemental concentrations. A temporal pattern is displayed in water soluble chloride, soluble sodium and soluble potassium. The trend is particularly apparent in the surface layers and on the upper portion of the intertidal slope.

The data from an estuarine situation contrast quite markedly with those of an open accreting coastline. In this situation there are both strong spatial and temporal fluctuations in the ions that were measured. The pattern for most variables along the first transect at Saunders Beach is for a decline in concentration up the creek bank to the *Sporobolus* zone. Concentrations then increase towards the salt flat even though the zones are located at progressively lower elevations. The main difference is the absence of a dense vegetation cover on the salt flat and the *Arthrocnemum* zone.

Along the second transect at Saunders Beach concentrations increase landward from the creek to the *Rhizophora/Bruguiera* zone before declining further inland. Of interest is the fact that the level of concentration of several of the variables is higher under the closed *Rhizophora/Bruguiera* canopy than at any other zone or station that was sampled. This could be related to the complex interactions that take place between the soil organic matter and the clay particles. However, the effect of sub-surface characteristics, for instance water flow, should not be discounted.

The exceptionally high values for exchangeable calcium that were found in a number of zones at Saunders Beach are probably also affected by sub-surface conditions. Carbonate nodules have been found within the coastal plain deposits (Hopley and Murtha, 1975) and dolomitic nodules have been found in a similar situation at Broad Sound (Cook, 1973). The presence of any dolomitic concretions could also influence the magnesium concentrations at Saunders Beach.

Data from both transects also display marked seasonal variations. Lowest concentrations are found during the wet season and the highest values during the dry season. The combined effect of mixing fresh and sea water, properties of clay minerals, pH and sulphate may be important (Russell, 1970).

The differences which exist between the two types of coastal location in the Townsville area augment the differences cited by Diemont and Wijngaarden (1975). If the trends displayed in the data sets from the Townsville region can be taken as a guide then not only are there large scale differences in soil and water characteristics between the two types of coast but there would also be variations in the spatial and temporal expression of those differences.

In spite of the differences which exist in the elemental concentrations between the stations, and the spatial and temporal variations between the sites, an underlying similarity is expressed in the statistical analyses. The tendency within the factor analyses for each site is for the first derived factor to represent a salt factor and for the second to be designated a pH factor. Between 50% and 60% of the covariance is explained by these two factors. Up to another 30% of the covariance may be explained by the third and fourth factors.

The results from the classification of the zones provide a number of apparently conflicting conclusions. Zones on the upper intertidal zone on Magnetic Island are thought to be similar to each other based on the soil chemical data. This is in spite of the fact that there is little floristic similarity between the zones. Likewise the soil characteristics of the mangrove fringe and the bare lower intertidal slope are similar to each other. However, the stations within the *Rhizophora* zone are not classified as being similar to each other, nor are the two *Ceriops* stations.

The fact that Station 7 within the *Rhizophora* zone is not similar to stations either side of it may be a reflection of its location on the intertidal slope and the decimation of the overlying vegetation. Since it is located at about mean high water neaps, the effect of the recent destruction of the vegetation canopy on the insolation/evaporation characteristics may be important. The soil chemical concentrations may have retained some of the qualities that were developed under a closed canopy; a time lag operating between the disturbance and the development of a new equilibrium condition. With new seedlings establishing themselves it may be some time before the system re-establishes a dynamic equilibrium state.

The data from Saunders Beach produce a contrasting interpretation to that from Magnetic Island. Along the first transect all zones under a closed canopy irrespective of elevation are associated with each other. The *Arthrocnemum* and salt flat zones are dissimilar to both each other and all other zones. Likewise along the second transect a similarity exists between the mixed creek bank zone and the landward *Ceriops* zone. The intervening *Rhizophora/Bruguiera* zone is considered different from any of the other zones on the transect.

The problem of zonation is further complicated if the ground water salinity results from Magnetic Island have a wider application. The spatial trend is for an increase in salinity from the seaward margins of the mangal, about 35ppt, inland to about 110ppt on the salt flat. Further landward the values decrease to about

35ppt. Higher values are found during the dry season than the wet season with greatest variation occurring at those zones with minimal vegetation cover. The apparent controls of the landward increase in salinity is reflected in the multiple regression analysis. The ground water salinity results are best explained in terms of the height of the land surface and the distance seaward from the landward margin of the mangal. Exposure between sampling periods was significantly correlated to the salinity variable but accounted for only a small amount of the variance.

Overall the results indicate that the soil/plant relationships highlighted by Navalkar and Bharucha (1950) are not as simple as they suggested. Rather than investigating only a few variables the results suggest that the whole soil condition has to be considered. The role of salinity, especially ground water salinity, is a complicating problem. What is clear, however, is that the salinity values found towards the limits of tidal inundation under a closed vegetation canopy, are well within those tolerated by the majority of mangrove species (MacNae, 1968). The highest values are found on bare or partially covered areas which are located at lower elevations. Consequently the subsuming importance of salinity in controlling the zonation of mangroves (MacNae, 1966, 1967, 1968) has to be tested in relation to the development of salt flats. The question has to be asked whether or not the bare salt flats are part of the "normal" zonational sequence in seasonally dry climates. If they are not, and in fact represent an aberration to the usual sequence, how then are they formed?

The Development of Bare Salt Flats

Bare salt flats have been recognised in many parts of the world in association with mangals. They are found at various sites on the intertidal slope and high tidal flat. They cover a wider distribution than associated features located in mid- and high-latitude salt marshes and have a different mode of origin.

Within mangals they have been reported from such diverse areas as Senegal (Tricart, 1956), Malagasy (Berthois and Guilcher, 1956; Battistini, 1959), near Gladstone (Fosberg, 1961), the Burdekin delta south of Townsville (Coleman *et al.*, 1966), Broad Sound area, Queensland (Cook, 1973); the Ord River delta (Thom *et al.*, 1975), and the Fitzroy estuary in Western Australia (Jennings, 1975). Fosberg also lists a widespread presence in Ecuador, Malaysia, Sumatra, the Philippines, Thailand, the Ryukyu Islands, Micronesia, Fiji, New Zealand, Hawaii, New Guinea, S.W. coast of West Africa, Florida, and the Caribbean.

A number of common characteristics have been ascribed to the areas where bare salt flats are found.

(i) A very large tide range.

(ii) A dry, or at least a reasonably dry climate (Fosberg, 1961).

(iii) A location close to but above the mean high water spring tides, hence an infrequent submergence by spring or storm tides.

(iv) A hypersaline condition with salinity values being greater than 40ppt and often greater than 100ppt (Spenceley, 1976).

Their mode of origin is quite clearly stated by Fosberg (1961):

> It is suggested that the bare zone described above is the area inundated by high spring tides, occurring only during a short period each month, and dried out, with resulting concentration of salt, between inundations. This oscillation between inundation and extreme dryness, and especially the concentration of salt during dry seasons in periods between spring tides, very probably exceeds the tolerance of even such halophytes as mangroves and various salt marsh plants. Some of those plants can tolerate pure salt water with no inconvenience, though their striking zonation indicates sensitivity to differences in salinity. It is probable that no available plant species have been able to develop adaptations to the augmented salt concentration brought about by evaporation over much longer periods than daily or half-daily fluctuations. (p.D-217)

This idea is reiterated by MacNae (1968) adding that once die-back is initiate the bare flat areas will expand outwards.

Alternative ideas have also been suggested. Battistini (1959) commenting on bare areas in the Sambirano delta, Malagasy, thought that apart from hypersalinity, they might also be initiated by an influx of fresh water from the delta, resulting in widespread mortality of plants. This is unlikely since mangroves are faculative halophytes not obligative (Barbour, 1970). Greatest growth is found in brackish waters and is common found on banks of tidal creeks and rivers that may contain fresh water, for instance many rivers entering the Gulf of Papua. Hervieu (1968) reports of a hypothesis advanced by Durand. He suggests that the bare areas may be created in response to the acidification of the terrain by hydrolysis of sulphates formed by the oxidation of sulphide present in the reduction zone.

More recently Thom *et al.* (1975) have elaborated the ideas put forward by Fosberg and MacNae, developing them into a short-term model of the development and distribution of mangroves in the Ord River delta. In this model they incorporate a sedimentation component in explaining the bare areas. Since the distribution of mangroves is thought to be more a response to an environmental gradient (Clarke and Hannon, 1970; Thom *et al.*, 1975) than a successional sequence in time (Richards, 1952), the mangrove zones move outwards as the height of the land increases above the MHWST mark. The land above MHWST becomes hypersaline as the frequency and duration of inundation by tidal water decreases. Hypersalinity eventually initiates die-back of the vegetation and inhibits the regeneration of the halophytes, thus creating the bare areas.

Even though these hypotheses appear to be quite sound and plausible, some doubts can be raised about their applications in reality. With a notable exception (Giglioli and King, 1966), there is a lack of published evidence on the salinity found beneath the salt flat. Although it is thought that no plants can survive hypersaline conditions, it is fairly well known that species such as *Avicennia marina* and *Lumnitzera racemosa* grow in soils with a salinity greater than 90% (MacNae, 1968). Although the salt flats are considered to be restricted to areas with a seasonally dry climate, they are also found in North Queensland near Cardwell (mean annual rainfall 2113mm) and Innisfail (3596mm). It is therefore apparent that bare salt flats have a wider distribution than originally believed and that causes other than hypersalinity as developed in the manner described by Fosberg and MacNae have to be examined. Evidence from a series of sites on Magnetic Island and at Saunders Beach was collected in order to resolve the difficulties outlined above.

Data collected at the Magnetic Island sites on 8 July 1974 (Figure 3.64) seem to agree with the accepted theory that salinity would increase in a landward direction. Increasing height above tidal datum means that the frequency of inundation decreases and the duration of emersion increases. Hence hypersaline conditions are able to develop. The lower salinity values in the landward *Ceriops* and *Arthrocnemum* zones could be attributed to the influence of fresh water seepage. This argument is less convincing when data at Saunders Beach and another site on Magnetic Island are considered. At Saunders Beach on 19 July 1974, a pit dug on the bare salt flat (height 2.9m) contained water with a salinity of 90.6ppt against 42.12ppt for a sample taken beneath a *Ceriops* zone (height approximately 3.2m) that surrounds the "island" on the bare flat (Figure 2.6). Similarly another bare patch located in the seaward *Ceriops* zone about 2km north of the transect on Magnetic Island produced contrary results. The bare flat is found about 50m seaward of the upper *Ceriops* limit at a height of approximately 2.0m relative to tidal datum. The area has a maximum width of 15m and a maximum length of 30m. Five holes, 10m apart, were dug across the feature. Hole 1 was located in a stand of *Ceriops tagal*, with the occasional *Rhizophora stylosa* and *Avicennia eucalyptifolia*; hole 2 on the edge of the bare patch/vegetated area; hole 3 in the bare area which contains stumps of dead *Ceriops tagal*; hole 4 located in an area of mixed dead and living *Ceriops tagal*; and hole 5 in an area of living *C. tagal*. Little variation was seen in the depths of watertable which was 30, 27, 33, 26 and 23cm deep respectively. However, there is a significant variation in the salinity of the watertable (Figure 3.64). Thus the salinity value in the bare area is almost twice that of samples taken 10m either side of hole 3. It was also noticed that in holes 1, 2, 4 and 5 fibrous roots occurred in the top ten centimetres. They were absent from hole 3. This indicates a rapid breakdqwn of organic matter once the covering vegetation has died. The loss of the vegetation cover allows a greater penetration of sunlight onto the bare ground surface, enhancing the evaporation of ground water causing salt to be precipitated at or near the surface. Hypersaline conditions would therefore develop locally in this area.

Thus the evidence that has been collected in this study suggests that hypersalinity may result from, rather than be the cause of, breaks in the vegetation canopy. Once a break has occurred, more insolation is able to reach the surface, evaporation of surface and sub-surface moisture takes place at an increased rate and hypersaline conditions develop. Causes of breaks in the canopy could be drought conditions or catastrophic events such as cyclones. More recently it has been suggested that lightning strikes could play a significant role in initiating small clearings in the mangal (Paijmans and Rollet, 1977).

Although it has been demonstrated that hypersalinity *per se* is not the cause of the development of salt flats, perusal of the literature suggests that these features have a wider altitudinal range within the mangal than is generally acknowledged. Therefore they could have a number of different origins. Two broad types may be recognised which, with Australian examples, are:

(i) Relict Flats—Barrattas Creek, Cape Bowling Green Bay

(ii) Contemporary Flats

- (a) Long-term devleopment—Broad Sound, Queensland and the Ord River, Western Australia
- (b) Short-term development—Magnetic Island.

Relict flats are typical of the high tidal flats on the Burdekin delta (Coleman *et al.*, 1966; and more comprehensively, Hopley, 1970). The flats lie below 6m above State datum but occur

2-5m above the range of contemporary features. In early Holocene times the Burdekin River discharged into Bowling Green Bay, incising the older Pleistocene surface. However, continued sedimentation allowed the early Holocene Burdekin River to infill its channel until such time as it was able to break through, in times of flood, between The Rocks and Stokes Range. Eventually this became the preferred route to the sea, abandoning its outlet to Bowling Green Bay. The diversion of the Burdekin took place prior to the maximum level attained by the mid-Holocene transgression. Consequently with the continued rise of the sea, tidal creeks developed in the abandoned deltaic deposits. Sedimentation patterns typical of a low energy environment were created. It is probable that the creeks were lined by mangroves. However, with the late Holocene fall in sea level, the creeks and tidal flats would have been abandoned, yet remaining related to the present-day drainage system. Consequently wide areas of salt flats have been abandoned by all but the exceptional tidal influences. The high salt content has precluded the development of non-halophytic vegetation.

Contemporary flats can be divided into two categories: related to long-term and short-term development. Long-term development sites are caused by the progressive seaward extension and increase in height due to deposition, of the intertidal zone. The tidal flats at Broad Sound, Queensland, and the Ord River, W.A., are typical of this subset. At Broad Sound the coastline has shifted seaward by depositional progradation for the last 5,000 years (Cook and Polach, 1973), accompanied by minor tectonic activity (Cook and Mayo, 1978). Thom *et al.* (1975) and Cook (1973) indicate that the flats are covered only by higher spring tides, although at the Ord River there are also bare areas a metre or so below mean high water spring tides. The low gradient and shallow microtopography allows tidal water to remain in discrete areas for longer periods than normally expected. Thus fine particles, which would ordinarily be taken out of the area, settle out of suspension, thereby building up the surface. Evaporation of the standing water precipitates salts. Therefore a salt crust augmented by salt brought up from beneath the surface by capillary action helps to create hypersaline conditions. Die-back is inferred to occur in consequence of the hypersaline conditions.

Although *Avicennia* spp. can grow in salinities greater than 90ppt (MacNae, 1968), they would be close to their upper tolerance limit in such conditions. Cook (1973) found a mean value of 110.7ppt in the supra-tidal zone at Broad Sound, which is probably too saline for mangroves, However hypersalinity need not be the initial cause of die-back. With the progressive build-up of the sediment and extension seaward of the mangroves, the landward edges become more remote from tidal waters. Pits have been dug several metres deep into the salt flats at the Fitzroy estuary without encountering the watertable (Dr J.N. Jennings, pers.comm., 1976). In a seasonally dry climate mangroves would therefore die simply from lack of water. Having died, a break in the canopy would then occur allowing hypersaline conditions to develop because of increased evaporation caused by increased insolation reaching the ground surface.

Short-term flats are generally found at about mean high water spring tides. It has been demonstrated above that the hypersalinity within the bare area is a consequence of a break in the vegetation canopy. Such a break may be initiated via a number of processes such as cyclonic activity, in areas prone to tropical cyclones, or possibly lightning strikes. The persistence of such features will depend very much on the presence of seedlings and their viability with respect to the new conditions prevailing at the bare area once recolonization is attempted. The idea that the bare areas are due to differences in the sulphate concentrations is not thought to be tenable in the local context. Evidence from both Magnetic Island and Saunders Beach suggests that there is little difference in the water soluble sulphate in the bare areas compared with adjacent vegetation zones.

In summary, the development of salt flats has been described. It is quite evident that they occur at varying levels within the mangals. They also have a variety of different origins. Once initiated however, the hypersaline conditions that develop preclude re-establishment of mangrove species over the area.

Synthesis

Data pertaining to the physical and chemical environment within two mangals in the Townsville area have been collected and analysed. It is clearly indicated that the chemical parameters that have been measured behave in different ways in the two localities. The parameters on Magnetic Island tend on the whole to have a spatial variation along the transect but show only a minimal seasonal trend. Values obtained from the two transects at Saunders Beach have a pattern which contrasts with that at Magnetic Island. Both of the creek side transects display marked seasonal variations in the ion concentrations. A differential spatial trend is also present. In spite of these differences there is a certain similarity between results obtained from the factor analyses. Both the first and second factors, a salt factor and a pH factor, are common to most analyses although the actual variables concerned and the magnitude of their loadings may vary between analyses. The two factors account for just over 50% of the covariance in the data, leaving almost the same amount unexplained. The remaining factors tend to be quite different from each other in terms of their variable composition and their loadings. Nevertheless after taking into account all factors with eigenvalues greater than 1.0 as much as 20% of the covariance is still unexplained.

Discriminant analysis has been used to classify the data. The results from Magnetic Island suggest that there is a degree of association between several zones on the upper portion of the intertidal slope (salt flat, samphire and seaward *Ceriops* zones) as well as between the mangrove fringe and the bare lower intertidal slope. The remaining zones are classified as separate entities from each other. At Saunders Beach 1 there is a degree of affinity between the zones situated under a closed canopy, as indicated by Stations 12 to 15. The samphire and salt flat zones are classified separately. Likewise at Saunders Beach 2 the zones with a closed canopy are grouped together apart from the *Bruguiera/ Rhizophora* zone.

Trends in the ground water salinity have also been described.

The data are fullest for the stations on Magnetic Island. Distinct spatial and seasonal trends are present in the data. Concentrations are least in the wet season and greatest in the dry season. Concentrations also increase from the sea to the salt flat before declining under the influence of fresh ground water. In trying to explain the trends in the ground water salinity, multiple regression analysis was used. Statistically, distance landward, height of the ground and exposure between sampling are found to be significant variables. Even so when all zones are considered, a maximum of 35.6% of the variance is explained by these variables. Once the landward *Ceriops* and *Arthrocnemum/Avicennia* zones are omitted from the analysis the amount of the variance explained increases to 90.37%. Precipitation is not found to be statistically significant in explaining this relationship.

Much of the literature devoted to mangals consider bare salt flats to be part of the "normal" sequence in mangals developed under dry or seasonally dry climates. They are thought to be caused by hypersalinity. However, results in this study suggest that the hypersalinity is caused by a break in the vegetation canopy, and is not a cause of it. The reasons behind a break in the vegetation are varied and include cyclonic damage, lightning strikes or drought. Consequently salt falts need not be considered as part of the "normal" development of mangals.

Therefore in terms of contemporary factors which influence the zonation of mangroves the data collected in this project suggest that it is the multivariate soil chemical profile that is more important in explaining differences between the zones rather than salinity *per se* or individual ions.

CHAPTER FOUR

SEDIMENTATION IN MANGALS

Within the intertidal zone the sediments are subjected to a variety of marine processes. The intensity of the processes is related to factors such as position on the intertidal zone, micro relief, wave energy, sediment concentration and particle size distribution both on the intertidal zone and by the related bedload and suspended load. The presence of a vegetation cover on the intertidal zone may cause a further modification to the rate and intensity of sedimentary processes on the intertidal slope and high tidal flat. It is the intention of this chapter to consider the trends in sedimentation along a number of transects through mangals which have a variety of characteristics. Two parameters are considered. These are first, the rates of sedimentation recorded at pegs located along the transects in conjunction with an experiment to simulate the effect of pneumatophores on sedimentation processes; and second, the variations and trends in the amounts of material transported through a mangal.

Complementary to studies of contemporary processes is an investigation of the evolution of the swamps. In this way an attempt is made to relate variations and trends in the present-day phenomena to changes in the stratigraphic profile beneath the swamps.

Magnetic Island—Rates of Sedimentation

The data from this study are presented in Table 4.1. The data reveal no apparent seasonal pattern to the variations in erosion and deposition. However, there are significant features in the relative rates of deposition along the transect. Many accretionary events are quite minor in intensity. A clear break exists between those erosional and depositional events which were less than or greater than 3mm. Fewer than 25% of the total number of observations on Magnetic Island were greater than 3mm. Using this criterion the eleven stations along the transect can be grouped into four groups. These are Stations 1 and 6; Stations 2-5 inclusive; Stations 7, 8 and 9; Stations 10 and 11.

Station 1, the most landward station is situated in the inner *Ceriops* zone. A contrast exists between observations taken in the open and those taken within the buttress roots of the tree. Monthly rates of change which are greater than plus or minus 3mm are few in the open. All are negative, and the net result during the study period is an erosion of the surface of 17mm. A different effect is seen adjacent to the tree. Episodes of high erosion or deposition are more frequent with the latter predominating. Overall a net amount of 8mm is deposited between the buttress roots. Station 6, situated in the seaward *Ceriops* zone, displays a similar pattern. In the open, the amount of material deposited in major depositional events exceeds that eroded in major erosional events. However, considering all results a net erosion of 6mm is experienced at the station. Within the buttress roots the opposite occurs, deposition exceeding erosion. A net deposition of 23mm occurred during the study period.

Stations 2, 3, 4 and 5 are located on the upper portion of the intertidal slope within a 0.4m absolute height range of each other. They are grouped together because of the general lack of extreme episodic events. That is to say, there are only a few monthly periods when a net amount of more than 3mm has been eroded or deposited. Stations 2 and 5 experience none, whilst Station 3 on the bare area has only two such events, both towards the start of the project. Station 4 has an unusual pattern including the local raising of the surface, by crab activity, between April and May 1975 by 22mm. Since then erosion predominates at that station.

Stations 7, 8 and 9 are located within the *Rhizophora* (NB Stations 7 and 8 were operating only for 1975). The patterns of erosion and deposition differ between stations as well as within each station. In particular at Stations 7 and 8, episodes of erosion and deposition exceeding 3mm are more common than at any other station. However, in both instances the net effect close to the prop root is one of deposition whilst further away from the prop root erosion is experienced. Random variations are not seen at Station 9 during 1975, though large generally positive variations do occur, for the rod in the open, and negative for the rod close to the prop root. Again, however, there is no similarity in the trends behind the prop root and in the open.

The last group, that of Stations 10 and 11, are in the narrow seaward mangrove fringe and on the lower portion of the intertidal slope respectively. Both stations have a high number of events greater than ±3mm. However, although there is a degree of similarity between erosional and depositional events at Station 10, at Station 11 there does not appear to be a predictable relationship. Even though deposition exceeds erosion within the higher ordered events at Station 10, the remaining smaller events are dominated by erosion. This has led to a net erosion at this station. Station 11 is dominated overall by depositional forces although there are big erosional episodes during the study period. Nevertheless net accretion of 7mm occurs at this station.

Although the stations can be grouped together into four categories a number of trends can be observed in the complete data along the transect. For stations in the open, away from the influence of vegetation, net erosion is experienced for the duration of the study. Pegs which are located close to the prop and buttress roots at Stations 1, 6, 7 and 8 within the *Ceriops* and *Rhizophora* zones sustain a net deposition. Erosion rather than deposition takes place close to the roots and pneumatophores at Stations 9 and 10, which are located on the front of the *Rhizophora* zone and in the mangrove fringe. This localised effect may be due to the higher energy conditions experienced at the front of the mangroves which may be sufficient to cause local scouring around obstructions. On the whole it is found that a period of high deposition is followed by a sequence of erosion removing the previously deposited material. However, the converse is not true. That is to say, a period of intense erosion is not necessarily followed immediately by a period of deposition.

Using the data from the entire transect the results of surface accretion show no general trends in terms of deposition during any particular month along the transect. It is more usual to find erosion or nil variation through the mangal. Overall there is no reduction in the intensity of the erosional and depositional episodes in a landward direction, although there is a decrease in the frequency of months with significant amounts of erosion. The exception to this is Station 1 in the inner *Ceriops* zone, which especially around the roots displays marked variations. This may be due to the combined influence of one or more of the following factors; overland flow from landward sources; stem flow; or slightly coarser sediment in this area. If the erosional velocities required for the average particle size in the *Ceriops* zone and on the salt flat are compared (e.g., Morisawa, 1968), it can be seen that less force is required to erode individual grains in the former zone than the latter. This in turn would cause a greater variation in the surface level than at areas with finer material.

Although there is a lack of a pattern in the monthly variations, when the data is grouped into seasonal periods of 3 months, Table 4.2, to compare the rates with those at Saunders Beach, a distinct pattern emerges for the whole transect. The results for the periods January to March and July to September indicate that most of the stations experience erosion and net erosion occurs along the entire transect. During the periods April to June and October to December most stations along the transect experience deposition with a net positive accretion for the whole transect. This trend is apparent for both 1974 and 1975 with the exception of October to December 1975. At this time a majority of stations show a pattern of aggradation. However a high amount of erosion at Station 8, close to the prop roots, and in the open at Station 9 results in a net result of erosion for the whole transect.

Saunders Beach—Rates of Sedimentation

The results for this site are given in Table 4.3. Certain trends are immediately apparent in the data. Along both transects high positive and negative accretion values, i.e. deposition and erosion of more than 3mm, are quite common. In spite of this each transect line displays slightly differing characteristics. Along the first transect there is a trend for an increasing activity up the creek bank to Station 13 as well as on the lee side of the bank at Station 15. Both these stations are located within the *Ceriops* zone. At these two stations the measurements made at the pegs in the open display far greater variations than those at pegs adjacent to the roots. The exception to this is one episode of extreme erosion (>200mm) at the peg situated within the buttress roots of a *Ceriops* tree at Station 15. Contrary to the trend in the two *Ceriops* zones the activity in the mixed creekbank assemblage is far greater around the prop roots than in the open. The overall result for measurements against all rods on the creek bank is one of net deposition.

The contrary is found for the three stations in the overbank situation, Stations 15, 16 and 17. Net erosion is present in all three stations, the amount decreasing with a decrease in elevation as the stations become less associated with vegetational influences going from the *Ceriops* to the *Arthrocnemum* zone and lastly the salt flat. Not only does the amount of net erosion decrease but the frequency and magnitude of high accretionary activity decreases in the same direction, in spite of an increase in the frequency and duration of tidal cover.

Stations 12 and 13, the mixed creek bank and *Ceriops* zone, appear to display similar broad trends of deposition and erosion. Stations 16 and 17, in the *Arthrocnemum* zone and on the salt flat, also have similar trends whilst the results from Station 15 in the inner *Ceriops* zone are anomalous. Since the results are for the main at three monthly intervals, they may mask shorter term trends.

Highly variable deposition and erosion rates are present at pegs at each station along the second transect. The four stations can be divided into two groups, Station 18 on the creek bank and Station 19, in the *Rhizophora/Bruguiera* zone, and Stations 20 and 21 in the *Ceriops* zone. The former station shows no seasonal trend in the accretion rates with erosion dominating all but the last reading. Hence that station displays a net erosion. The other three stations each display a net deposition, the amount generally decreasing as the height of the land surface increases, with one minor exception. As a rule the rate of surface change behind the roots is greater than in the open. The rate of variation decreases, however, in a landward direction. During the first three sample periods there appears to be an accord between the groups with respect to erosion or deposition. However the trend is not so obvious in the last two sampling periods.

Orpheus Island—Rates of Sedimentation

The site at Orpheus Island is more remote than the previous two locations. Visits were made in December 1973, September 1974, and February 1975. The results are given in Table 4.4.

A number of features are immediately apparent from the table. Pegs are continuously being lost either by erosion and subsequent burial or directly due to burial. Because of this the table is incomplete and trends in sedimentation rates are difficult to decipher. Rates of erosion and deposition are quite variable both between and within a station. No trends of erosion or deposition can be identified since the rates are highly variable within a 24-hour period and the sites were visited only after long time intervals. What can be said is that this particular swamp is highly dynamic. Material is constantly being transported through the swamp. In spite of this, the mangroves still manage to survive in this locality.

A Simulation of Pneumatophores

From the results given above it is apparent that the prop roots, buttress roots and pneumatophores influence the rates of sedimentation in mangals. This idea has subsequently been pursued in a series of experiments. A series of grids, of different spacing between the metal rods was set up to simulate the effect of pneumatophores. This was achieved by the use of grids of metal rods of various spacings. After a brief reconnaissance of the *Avicennia eucalyptifolia* zone on the southern side of Ross River in 1973 a grid made up of lengths of 6mm diameter metal rod welded onto a framework was placed in the mud on the seaward front of the mangrove fringe of Magnetic Island on the bare lower intertidal slope. The legs on which the framework sat were of such a length that the 10cm long rods were approximately half covered by mud when the legs were firmly placed on to the submerged coral reef flat. The grid comprised four rows and ten columns of rods spaced 10cm apart. During 1974 the average readings of the grid differed from the lower intertidal slope readings only slightly by recording an extra 4.2mm of erosion (Table 4.1).

Further work in the mangrove fringe indicated that the pneumatophores increased in spacing, and hence decreased in density, with distance from the tree trunk (Table 1.2). Consequently four different grids were constructed in a similar fashion to the initial pattern but with spacings between the rods of 10cm, 5cm, 2.5cm and 1cm, B, A, C, D respectively (Figure 2.5). These grids comprised 5 rows and 10 columns except for the 5cm grid which had only 9 columns. Initially the grids were inserted into the mud in March 1975. The system was allowed one month to settle before readings were initiated (Table 4.5). Variation in levels was recorded until July 1975. During the period of observation light to variable winds were recorded at the official weather bureau in Townsville, with the occasional gust over 20 knots. However, because of th sheltered nature of the weather station, the wind records are atypical of the open coast. On exposed coasts there were many days with winds greater than 30 knots and rough seas were experienced. Their effect on the lee of the island can only be estimated because of its inaccessibility during high tides. The experiments were repeated in January 1976.

Because of the closer approximation of the 2.5cm grid to the average spacing of pneumatophores this grid was removed from its original setting on the lower tidal flat and inserted into the mangrove fringe. Another 2.5cm grid, comprising 30cm rods inserted into the ground such that 10cm remained exposed, was located at the new position on the lower tidal flat. Readings were taken intermittently ceasing in August 1976 (Table 4.6). The weather during this second experiment was variable. During the early part of the year, in the wet season, intermittent storms accompanied by strong winds were prevalent. During the rest of the year, in the dry season, the winds were less variable and more constant in their direction, coming from the south east.

During the period of observation for the first experiment in 1975, the reference pegs located on the bare mud and and *Avicennia/ Sonneratia* fringe showed only minor variations in the amounts deposited and eroded. The variations in the sediment level were greater at the reference stage on the lower tidal flat than in the mangrove fringe. In the first month both pegs recorded erosion, -1.2cm on the bare mud and -0.3cm on the mangrove fringe. However, in the course of the next two months the surfaces had essentially been built up to their previous levels.

The situation within the grids was different. From the start of this experiment the 1cm grid experienced scour. It took longer for a similar change to occur on the 2.5cm and 5cm grids. The 10cm grid displayed only minor variations during the course of the experiment. Thus in the immediate proximity of the three smaller grids severe scour was initiated. Scour was restricted to within 30cm around each grid. In the case of the 1cm grid sufficient scour was maintained for the whole frame to be toppled over prior to the depression being infilled. By July 1975 a new equilibrium condition existed. The hollows excavated by the sea were partially infilled. It is significant however that the framework of the 2.5cm and 5cm grids remained exposed above the mud. In the case of the 2.5cm grid the gap between the frame and the sediment surface on the seaward side of the grid was greater than that on the landward side, the amounts being 5cm and 4cm respectively.

Although no measurements were made during the wet season of 1976, relative erosion was again observed, followed by a period of deposition in the dry season. Thus by 21 August 1976, the average height of the rods in the 10cm and 5cm grids was 6.9cm and 10.4cm respectively. This compared with 5.8cm for the reference peg on the lower tidal flat and 9.5cm for the peg in the mangrove fringe. The latter reading indicated that 0.6cm had been eroded in the *Avicennia/Sonneratia* fringe since April 1975. The former reading (5.8cm) had probably been affected by burrowing molluscs and cannot therefore be used as a reliable guide. Data from the 10cm and 5cm grids indicated a net change of 1.0cm deposition and 2.6cm erosion respectively.

The results of the second experiment which utilized the two 2.5cm grids (Table 4.6), indicated that significant changes in the rates of deposition followed the seasonal weather patterns. During the wet season, when intermittent storms accompanied by strong winds were prevalent, erosion occurred. Likewise in the dry season, when the winds were less variable and more constant in their direction, deposition was the dominant process. Thus a cut and fill situation appears to prevail (Spenceley, 1977).

During the time of the experiment with the two 2.5cm grids measurements at the peg on the bare mud, Station 11, displayed a similar trend to those of the 2.5cm grid located in the mud. However, the measurements made at the peg at Station 10 within the mangrove fringe showed a net erosion during the same time periods. This is probably related to either the local density of the root network or to the fact that readings from an individual rod in such a system need not necessarily operate in the same way as the remaining rods or pneumatophores. That is to say edge or boundary effects may have influenced individual results.

Discussion

The results presented above illustrate a number of different facets of sedimentation within mangals. Even though different trends are observed in the various swamps there are sufficient similarities to allow generalised statements on sedimentation to be made. The mangal on Magnetic Island appears to be undergoing a period of erosion. The amount that is being lost varies along the transect, reducing to a large degree in a landward direction. A similar trend is observed in the episodic erosional and depositional events, the frequency and intensity of which decrease towards the land. The exceptions to this relate to the stations located in the two *Ceriops* zones. Here it is found that the episodic erosional and depositional events are much greater than those of the other stations on the upper intertidal slope and high tidal flat. This is true even for the highest and most landward station. This could be due to a number of reasons.

The coarser material at these two zones may be more readily moved than the finer cohesive sediment at other zones. When moved a greater response is seen in the surface level. The presence of the trees could be important. Buttress roots may allow the generation of local eddies which have a differential effect on the sediment movement. The roots probably have a different hydraulic function from the sparse low growing halophytes and algal mats. Any stem flow would also tend to be concentrated between the roots. The most landward station could also be affected by overland flow and sheetwash from the neighbouring hillslopes.

Algal mats have been noted to play an important role in the sedimentary sequence (Neumann *et al.*, 1970). Although there is a net loss from the salt flat on Magnetic Island and at Saunders Beach, losses are probably far less than would have been the case had the surface lacked an algal covering. The alga on Magnetic Island, *Microcoleus chthonoplastes* (Dr I. Price, pers. comm., 1974), is thought to immobilise sediment deposited by settling (Neumann *et al.*, 1970). The filaments of blue green algae together with their mucilaginous secretions combine to bind deposited sediment. Neumann *et al.* (1970) found three types of algal mats in the Bahamas divided according to composition and microstructure: a fibrous, rigid *Cladophoropsis* mat; a thin, gelatinous *Lyngbya* mat; and a cohesive, aggregated *Schizothrix* mat. Experimenting with an underwater flume on surfaces both with and without the algal mat, they found that the algal surface was able to withstand velocities 2-5 times greater than the surface lacking such a cover. The intact mat surface could also withstand direct current velocities 3-9 times higher than the recorded maximum velocity of 13cm/sec.

Gunatilaka (1975) likewise found three types of algal mats on Mannar Lagoon, Ceylon. Recognition was based on morphological grounds, forming a zonation from high water mark seawards; a smooth rounded mat zone with discrete structures; a crinkled and blistered zone; a smooth flat-mat zone without perceptible relief. Depending on the duration of flooding, maximum velocities recorded in each zone ranged from 1-10cm/sec, 6-12cm/sec and 10-15cm/sec from the landward to the seaward zone respectively. Algal mats generally were not present when velocities of 19cm/sec were exceeded. A desiccation gradient is also associated with the velocity gradient.

Thus areas less frequently immersed crack when dried for a sufficient period of time. Once the surface is broken, erosion of the substratum would take place long before critical erosional velocities, for the erosion of the intact surface, are reached. This may, in part, explain the results obtained in this study. By virtue of breaking the mat surface to insert the rod, sufficient local interference may be experienced for erosion to occur on a micro-scale. Therefore, the measured rates might not accurately reflect the natural situation on the salt flats.

Research completed on temperate salt marshes has shown that the rate of accretion is positively correlated with the age of the swamp, marsh height and the height or weight of vegetation. Negative correlations were found between distance seaward from the land and density of the vegetation (Ranwell, 1964). The presence of dense swards appears to have the same morphological function as prop roots and buttress roots in mangroves. Under specific conditions the effect of these roots is to act as a barrier, thereby reducing tidal velocities and creating an environment that is suitable for transported material to settle out of suspension. Having been deposited it is unable to be resuspended by the reduced velocities. However, because of the nature of the barrier, roots can also act as an interfering agent, as can be seen from the results obtained by placing rods immediately behind the roots. The overall results from Magnetic Island show that immediately behind roots there is relative deposition whilst at a greater distance away there is relative erosion of the surface. The exceptions to this are the stations located close to the front of the *Rhizophora* zone and in the *Avicennia/Sonneratia* fringe. Here there is erosion close to the prop roots and pneumatophores.

The dichotomous role of the peculiar mangrove adaptations is seen in the results of the pneumatophore experiments. The initial experiment resulted in little difference occurring between measurements at the 10cm grid and the reference peg. However, erosion started immediately after insertion of the 1cm grid. Initiation of erosion was not apparent at the 2.5cm and 5cm grids until the second monthly visit. Within three months erosion beneath the 1cm grid was sufficent to cause the grid to become unstable and fall over. Once the obstruction and source of destructive interference had been removed, the hollow was infilled with sediment. At the same time a depression remained beneath the 2.5cm and 5cm grids. For the duration of this experiment, erosion was observed only within 30cm of each grid.

The second experiment involved inserting a 2.5cm grid in the lower intertidal flat and the mangrove fringe in January 1976. Measurements were taken at intermittent intervals. Similar results to the previous experiments were recorded at each grid. However, significant differences in the magnitude of the readings exist. Less erosion and deposition took place in the *Avicennia/Sonneratia* fringe than on the lower intertidal slope. Infilling also took place in the 5cm grid although no intermediate readings were made. Two distinct phases were thus observed, related to the prevailing weather conditions. A phase of cut was initiated during the wet season with its short period of high energy conditions. Cut continued into the dry season. Eventually the more constant energy environment in the dry season prevailed and fill was initiated.

Reid (1977) working on a steep sandy beach at Turtle Bay, AIMS, has shown that the beach is made up of a number of interacting sub-cells within the beach system. Each cell displayed its own discrete seasonal pattern of erosion and deposition. Tidal height and wave height were recognised as the dominant controlling variables with rainfall, through its influence on the level of the water table, also being important. Similar relationships have been suggested by studies in Jahore (Hill, 1966), Hawaii (Moberley, 1968) and Hong Kong (Williams, 1974).

Therefore, it may be that the presence of the mangroves is a complicating factor to the overall general pattern of sub-cell development. Apart from sub-cells operating along the beach, these may be further sub-divided across the intertidal slope with the active seaward portion of the mangal behaving differently from the landward portions of the intertidal slope. Since only one transect was monitored through the mangal it is not possible to elaborate on this aspect. However, as is evident from other accretionary evidence, cut is at present more important than fill along this transect.

In view of the apparent lack of seasonal variation in the monthly readings, the cut and fill trend in the pneumatophore experiment is unexpected. A similar trend is observed for the duration of the pneumatophore experiment in 1975 in front of the mangal but not for the grid located on the mangal fringe. For the three three-monthly periods at the beginning of 1975, results from the transect on Magnetic Island reveal a sequence of erosion, deposition and erosion, which again is slightly out of phase with the experiment. The differences can be explained in part by the very nature of the experiment which was conducted to inquire into the role of pneumatophores on sedimentary processes. Consequently the rods were chosen for their similarity in dimensions to that of the pneumatophores and they had a set spacing.

In nature the spacings are not as regular and the results of the second experiment could possibly be related to edge effects. In these experiments the "pneumatophores" suddenly present themselves as obstructions to the flow of water. In reality there is often a progressive increase in density of the pneumatophores towards an individual tree. Consequently the motion of the water may be modified to a certain degree prior to its flowing through pneumatophores of a higher density. In the experiments any modifications to the water motion would not have taken place prior to the water flowing through the grids. In the second experiment, the grid placed in the *Avicennia/Sonneratia* fringe would in fact have a greater density locally due to the pneumatophores already present, than the grid on the bare mud. Nevertheless, the surface modifications were considerably less than those on the bare mud.

Rods located at other stations would have been influenced by different properties. The roots would have been thicker and more widely spaced. Hence they would have different hydraulic characteristics from the pneumatophores. Coupled with a decline in energy conditions through the swamp, as illustrated by the episodic cut and fill events, the response along the transect would not necessarily be the same even for adjacent stations.

Evidence from the Saunders Beach sites suggests a general similarity to Magnetic Island; the amount of accretion decreasing away from the creek. Two features are prominent in the data. The zone bordering the creek is subjected to two influences. First, the zone is influenced by the current on the ebb and flood tide as well as the increased creek currents due to heavy run off in the wet season. The second factor is the result of minor channelling down the creek bank on an ebbing tide. This latter influence is more important at Saunders Beach than on Magnetic Island because of the steeper gradient on the creek bank than across the intertidal slope. No doubt similar processes operate on the banks of creeks that drain through the Magnetic Island swamp. Although this may explain the extreme variations along the creek bank, it cannot account for the erosion of more than 200mm at a peg placed in the buttress roots of a *Ceriops* tree in the inner *Ceriops* zone, Saunders Beach 1.

Two possible causes are responsible for the localised erosion. The first involves intense precipitation and streaming of intercepted rainfall down the tree trunk. Flow may therefore be concentrated within the buttress roots and cause rapid scouring. Similar effects have been noticed at the base of large trees in tropical rainforests, removing leaf litter and duff, and soil scouring on the downslope side of the tree trunk (Birot, 1968:76; Ruxton, 1971).

The second possible cause is linked to the first and has been observed within Papuan mangals. Intercepted water streams down the branches to the main trunk. However, on its journey to the base of the trunk, the flow of water is arrested by a piece of bark or a lenticel sticking out from the tree trunk. From this point the water drips in a constant stream to the ground. The concentrated impact of the water droplets erodes the soil. The effect is accentuated if the tree is leaning slightly off the vertical.

Many *Ceriops tagal* trees both at Saunders Beach and on Magnetic Island have their buttress roots completely exposed, revealing the secondary root system beneath. The trees are generally situated on the upper part of the intertidal slope where tidal velocities are expected to be low and would not normally promote such erosion. Either of the two suggested causes provides a logical and workable solution to the problem.

Coupled with the pneumatophore experiment, the results from Orpheus Island are more important than is initially apparent. It is evident that even in slight seas there are rapid and highly variable changes in the surface level at Orpheus Island. Nevertheless two points must be emphasised. First, changes are not great on any one tide, the large variations occurring only on sand banks. Second, and more important, is the fact that the *Rhizophora* manages to survive in that siutation. Consequently there must be a limiting factor which governs the amount and depth of material that may be shifted in low to medium energy conditions. The limiting depth is probably where sediment is bound by rootlets. This is evident from the pneumatophore experiment where, although some erosion took place beneath the 2.5cm grid, the amount eroded in the mangrove fringe was much less than on the lower intertidal slope. Therefore, either the rootlets are binding the sediment or there are some electrostatic cohesive forces operating on the sediment. A combination of the two processes may be operating. Because of the nature of the substratum the former factor is probably more prevalent on Orpheus Island.

Scoffin (1970) working on similar material at Bimini Atoll, Bahamas, reports that in comparison with marine grasses and various algal mats, roots of *Rhizophora mangle* are the most efficient sediment binders. He reports that the roots are able to withstand erosion when current velocities are 40cm/sec. Therefore except in times of extreme energy conditions the fine rootlets bind the soil ensuring the establishment and maintenance of the mangroves. It is only the surface unbound and cohesionless soil that is being shifted within the mangal.

The situation on Magnetic Island is slightly different. Resistance to erosion is due to two factors; the effect of roots binding the sediment and of electrostatic forces which exist between clay particles. These forces are augmented by electrostatic forces related to the plant system. Plant root systems are known to possess a cation exchange capacity which varies between species (Metson, 1971). Thus since both the rootlet surface and the surfaces of the clay and colloidal particles hold exchangeable ions, a variable degree of cohesion exists between the surfaces (Comber, 1964; Metson, 1971). Higher electrolytic concentrations in waters surrounding the plants are due to osmotic absorption of water by the roots of *Spartina* grass might aid flocculation and thereby increase clay deposition (Pestrong, 1972).

The pattern of accretion in mangrove swamps appears to be different from that on salt marshes. It has been demonstrated (Ranwell, 1964, 1972) that for immature marshes the zone of maximum accretion is close to the upper limit of the marsh. However in older swamps this zone is located further seaward. Landward there is a negative correlation between height of the land surface and the accretion rate, whilst seaward of the zone of maximum accretion there is a positive correlation (Richards, 1934). Evidence produced in this study suggests a different pattern. Maximum rates of accretion are found close to the seaward extent of the mangroves, declining inland. However, above mean high water spring tides the rate increases as the swamps come under the influence of sub-aerial as well as marine processes.

The variable influence of sub-aerial processes is related to the different structural anatomy of mangal and salt marsh species and the effectiveness of incident precipitation. The effectiveness of rainfall depends on the frequency, duration and intensity of precipitation as well as the amount intercepted and stored within the vegetation canopy. In the tropics, rainfall tends to be highly variable in the first three factors. Rainfall is also quite localised in its distribution (Nieuwolt, 1977; Jackson 1977). This contrasts with conditions found in higher latitudes (Barry and Chorley, 1971).

The size of the water droplets also has an important role to play in modifying the ground surface microtopography. The size of the droplets dripping from a leaf is quite different from that which occurrs naturally (Williams, 1969). The bigger droplets also possess a higher terminal velocity. When dealing with tall trees, the terminal velocity of the water droplets would be attained before the droplet reaches the ground. Consequently, they are potentially able to cause greater splash erosion with the transfer of momentum which takes place on impact on to the surface.

Therefore the effect of rainfall would be quite different in mangals from salt marshes. Beneath the mangroves some erosion will take place due to water droplets falling off leaves several metres above the ground. Being less concentrated than water flowing down the trunk, any results are likely to be less dramatic. This depends on the type of vegetation, *Ceriops* spp. being structurally different from *Rhizophora* spp., and whether the surface is emerged or not from tidal water. In salt marshes a dense sward of samphires would restrict the effect of rain splash erosion. Greatest surface modification would occur only where the samphires are less densely spaced. The effect of drips falling from leaves would be minimal.

Consequently the role mangroves play is different from that of salt marshes. By implication the role of salt marshes is merely one of reducing the energy of the covering waters thereby allowing material to fall out of suspension. The samphire vegetation would also have the effect of reducing the number of times the critical erosional velocity is exceeded. Therefore once material is deposited it is infrequently resuspended and transported away. Such ideas influence much that has been written about mangroves (e.g. Steers, 1959; Craighead, 1964; Derijard, 1965; Bird, 1971a). Although mangroves reduce tidal currents they need not necessarily reduce velocities to such an extent that erosion is prevented (Zenkovich, 1967). The more important role that mangroves play is therefore one of binding the soil, creating a stable environment for the growth of mangroves.

Sediment Transportation

On each visit to the stations during the study plastic bottles were left out to collect water and sediment samples. Principally during 1974 samples were collected from 0cm, 15cm and 30cm above the ground surface. During 1975 samples were collected only from the surface. The collected material was wet sieved into particle sizes above and below 63 micron diameter, dried and weighed. The ratio between the two components was calculated as well as the total load per unit time covered for the basal sample. The purpose of this experiment was to assess the amount of material that was passing through the swamps; to see if the amounts differ between stations and hence vegetation types; and to observe the degree of attenuation of the sediment load in a landward direction.

Magnetic Island

The results from this site are given in Table 4.7. Even though the sampling was undertaken as close to the highest spring tide as was practicably possible, the seasonal fluctuation in tidal levels meant that not all stations were covered at each sampling time. Often some of the stations were only covered by one high tide due to the differences in tidal heights with adjacent high tides. An effort has been made to counteract that influence by considering the amount of material trapped per unit time the bottle was covered by tidal waters. Some bottles were also lost during the tidal cycle even though they were pegged down. The experiment on Magnetic Island had two phases. During the initial phase, from November 1973 to October 1974 inclusive, samples were taken from 0cm, 15cm and 30cm above the surface at Stations 1-6, and 9-11 inclusive. The second phase was from November 1974 to December 1975 inclusive when only the 0cm sample was collected from Stations 1-11 inclusive.

In spite of the limitations to the methodology used, the consistency of the pattern over most of the 26 collection periods appears to justify some general conclusions. Quite distinct trends are readily apparent in the data. Within any one set of three bottles at a station generally there is a decrease in sediment concentration with an increase in height above the surface in terms of absolute amounts trapped in the bottles. Within that general trend there is a general decrease in the coarser than 63 microns: finer than 63 microns ratio. That is to say, the sediment becomes finer with increasing height above the ground surface. There are occasions when the reverse trend is present. For most stations this is due to an increase in coarse organic matter, leaf and bark remains. For Stations 1 and 6, located in the *Ceriops* zones, the coarser quartz grains which are present in the surface are often lifted off the surface and moved by a saltation process. Being large particles relative to the silts and clays even the presence of one grain is sufficient to considerably affect the answer.

Spatially a persistent pattern or trend is present. It is found that when considering the concentration of material in the surface sample (0cm) the amount of material increases from Station 11 on the bare mud on the lower intertidal slope, to Station 10 in the mangrove fringe before declining in concentration inland to about Station 7 in the *Rhizophora* zone. Further inland there is an increase in concentration to Station 5, in the *Arthrocnemum*/*Avicennia* zone, but not as great as at Station 10. Further landward the concentration decreases to Station 3, on the salt flat, before rising slightly again to Station 1 in the inner *Ceriops* zone.

Consideration of the amount trapped per unit time covered reveals a slightly different trend. There is a rise in the value of mg/l/hour concentrations from Station 11 to Station 10. Landward there is a general decline to Stations 7 and 6 before the levels rise again to Station 1. Temporally, however, there appears to be no seasonal pattern in the data. Even though in the exposed part of Cleveland Bay there is a seasonal pattern to the marine energy environment, the apparent lack of one in the mangal attests to the limiting conditions for the establishment and successful germination of mangroves. They are only found to any great extent where energy conditions are normally low.

Saunders Beach

A similar set of experiences was carried out at Saunders Beach. During the course of this study six separate samples were taken, mainly in 1975. To fit around the Magnetic Island collection times, these stations were sampled on the second highest high tide in the month. Not all of the stations were covered at each sampling period due to the monthly and seasonal tidal cycle. Consequently there are many gaps in the data. The trends are therefore not as clear as at Magnetic Island, the results being given in Table 4.8.

The first transect, Saunders Beach 1, has the most incomplete record. However, it is apparent that there is a decrease in the concentration of trapped material from the creek edge up the bank. Even though Stations 15, 16 and 17 on the leeward side of the bank were only sampled twice, their results still exhibit a trend. As the height increases the concentration both in terms of the total amount as well as mg/l/hour increases from the salt flat to the *Arthrocnemum* zone before decreasing again to the *Ceriops* zone, Station 15. The concentration at Station 15 is still greater though than on the salt flat, which is located at a lower elevation.

The second transect, Saunders Beach 2, has a more complete record. The trend here is for a decrease in total amount trapped with an increase in height from the creek inland, Stations 18 to 21. The relationship is, however, not always clear. What is more clearly portrayed is the increase in mg/l/hour values with an increase in height of the land surface to Station 20 before dropping slightly to Station 21, in the *Ceriops* zone. The value at this latter station is generally greater than that at Stations 18 and 19 situated at much lower altitudes. Overall there is a marked fining of material that is trapped, from the surface to the 30cm sample.

Orpheus Island

The data for Orpheus Island is given in Table 4.9. The information is incomplete due to bottles being lost during the sampling exercise. An accident in the laboratory also destroyed several samples. The station was visited during two wet seasons and the intervening dry season. What is immediately apparent from the data is the highly variable nature of the results. Large differences exist between the amounts trapped at each station at any one sampling time as well as at duplicates placed at some stations during the July 1974 sampling period.

Often the bottles are completely full thus giving a minimal figure regarding the amount of material being transported through the swamp. In terms of size and amount of material trapped in the bottles there is a decrease in amounts trapped and an increase in fines with height above the surface. Apart from that the principal result from this mangal is again the clear indication of the highly mobile nature of the surface environment in which the mangroves are growing.

Discussion

Because of the nature of the experiments and the fact that the bottles are left out for two tidal cycles, it is initially uncertain whether or not each tidal cycle has an equal contribution to the total amount that is finally collected. Attempts were made on the banks of Ross River to monitor the differences on each tidal cycle. Initial attempts using the stands were unsuccessful, each time the equipment being removed by persons unknown. Results were eventually obtained only for two experiments using plastic bottles inserted into the ground so that the lip of the bottle was flush with the ground surface. The first experiment consisted of a bottle, A, left in the ground for two tidal cycles. Bottle B was inserted for the first tidal cycle, after which it was extracted and Bottle C was inserted. The results are:

	>63 microns mg	<63 microns mg	Σmg
B	5,461.3	3,234.7	8,696.0
C	6,407.9	2,298.7	8,706.6
	11,869.2	5,533.4	17,402.6
A	18,844.0	5,674.6	24,519.0
100(B+C)/A	62.99%	97.51%	70.98%

The second experiment comprised two bottles, D and E, placed 0.5cm apart, for two tidal cycles.

	>63 microns mg	<63 microns mg	Σmg
D	1,390.9	1,016.7	2,407.6
E	449.6	728.7	1,178.3
100E/D	32,32%	71.67%	48.94%

The two experiments produced unexpected results. In the first experiment it is found that the amount of fine material that is trapped by bottles B and C is almost identical to that trapped in Bottle A. A much reduced component is found in the coarser material for bottles B and C, compared with A. Summing the information together it is found that 70.98% of the load trapped in the bottle left out for two tidal cycles is trapped in the bottles each left out for one cycle. It could be argued that the results are influenced by a different tidal height on each cycle, hence a different energy regime for a varying period of time.

This cannot be said about the second experiment when both bottles were left out for both tidal cycles. In this experiment, even though the bottles were located 0.5m apart, the results are quite different. 48.94% of the total amount trapped in bottle D, 2,407.6mg, is found in bottle E, 1,178.3mg. The variation between the amounts trapped are much greater for the coarse component than the fine. The results seem to indicate that there is a highly variable concentration of sediment in the tidal wedge as it floods and ebbs across the intertidal zone. This feature could possibly affect the interpretation of the results from the mangals on Magnetic Island, at Saunders Beach and on Orpheus Island. However, the prominent feature of the data from the former two sites is that the patterns along the transects are persistent through time. Consequently it is possible to look at the data regarding them not so much in an absolute but in relative terms.

Generally there is a decrease in the amount of material that is trapped, with increasing height above the ground surface as well as an increase in material finer than 63 microns. Consideration of the total amount trapped at stations along the three transects at

Saunders Beach and on Magnetic Island suggests a slightly different trend for each transect. However, when the amount trapped per unit time covered is calculated for the surface trap a common picture emerges. There is a distinct decline in the amounts trapped with an increase in height from the seaward or creekward edge of the mangrove to about 2.7m or 2.8m above tidal datum. Above this level there is an increase in the amounts trapped. Thus, in the part of the mangal where one would expect the least energy conditions to occur there is paradoxically an increase in the amount of material trapped per unit time covered. This could be explained in terms of a variation in grain size characteristics since relatively less force is required to move the larger, cohesionless particles than the finer particles subjected to cohesion forces. Since large variations in this parameter however are not present along all of the transects the effect of other causes is probably more important.

It has previously been noted (Pestrong, 1972; Anderson, 1972) that most material on the intertidal slope is resuspended by wave action rather than by tidal currents. Anderson (1973) and Pestrong also note that it is the initial rippling waves that cross the intertidal slope that cause the most change. The effect is particularly so on the flood tide but is also important on the ebb tide because the initial rippling wavelet possesses sufficient shear stress to break the physico-chemical bonding between flocs and bring them into suspension. With an increase in the depth of water there would be a progressive dilution of the matter in suspension. Hence there would be a decrease in the amount of material that is available to be trapped at 15cms and 30cms above the surface. Variations in the amount of material that is entrained by the wavelets and trapped in the bottles would reflect a number or combination of factors. These are:

(i) Differences in energy along the wavelet which may be due to the microtopography.

(ii) Different abilities to pick up material because of (i) or because of the variation in the physico-chemical factors.

(iii) Different stages of the wavelet reaching the trap at varying times.

The increase in amounts trapped per unit time covered across the upper part of the intertidal slope, therefore, is probably related to the fact that these stations experience a high concentration of material even though it is only for a short period of time. The total amounts of material trapped on Magnetic Island and on Saunders Beach 1 indicate that there is not a uniform decrease in amounts trapped with an increase in height. The data therefore suggests that in particular the mangrove adaptations may play a significant role in creating local eddy currents which enhance any scouring action caused by the initial wavelet. This is also very well demonstrated at the seaward mangrove fringe on Magnetic Island. Readings here are consistently higher than on the bare lower intertidal slope, yet both are at almost the same level. The only outward difference between them is the presence of pneumatophores in the mangrove fringe.

None of the results from stations on Magnetic Island and at Saunders Beach can compare with the results from Orpheus Island. The stations in the small mangal studied on that island show marked constrasts in the amounts of material transported both between stations and between sampling periods. The material is much coarser than at the other sites and potentially is moved more readily.

Past Processes in Mangals

Contemporary rates of deposition provide an indication of the short-term development of mangals. However the mangals as seen today are a result of a long evolutionary sequence. Today's activity is merely modifying the results of hundreds of years of dynamic interaction between marine and terrestrial forces acting on the coastline. Consequently an understanding of the evolution of the swamps provides a useful adjunct to a dicsussion of contemporary processes.

Two of the three swamps considered in this study were cored using a piston peat and clay corer. Data were obtained from Magnetic Island and the banks of Althaus Creek, Caunders Beach. The type and colour (Munsell soil wet) of the sediment were noted.

Material suitable for radiometric dating was collected and processed by Professor Kigoshi, Gakushuin University. The swamp on Orpheus Island was not cored because of the coarseness of the deposits. A peat and clay piston corer is not a suitable tool to use in such a situation. The age of the deposits was consequently derived from ancillary information such as the development of beachrock situated slightly landward of the swamp. In addition work was carried out in association with Professor A.L. Bloom (Cornell University), on a mangal situated on the southern side of Hinchinbrook Island. These results will also be presented.

Stratigraphic Evidence

Magnetic Island

The swamp on Magnetic Island was the most suitable swamp for coring of all the sites considered. The locations of the cores are given in Figure 4.1 and the core logs are given in Figure 4.2. A variable sub-surface basement is found on Magnetic Island. At the southern end, the granite basement is reached at a fairly constant level of between 1.0m and 1.5m beneath the surface near the landward edge of the swamp. The depth of sediment gradually reduces seaward to about 80cm in the middle of the *Rhizophora* zone, hole 8. Since the submerged coral reef is found 40cm below the surface, at hole 9, the reef and the granite probably meet at an intermediate position. The surface maintains its relatively constant level except at the extreme southern edge, hole 1, where it increases in depth to 2.8m, below the mangal. This relates to approximately modern tidal datum (T.D.). This probably indicates the unevenness of the granite surface, a feature common to that rock type (e.g. Thomas, 1974) although alternatively it may be a crevice between boulders. The rock surface continues at the same level northward for about 2 to 3km before it rapidly increases in depth. The basement is reached at 1.15m below the surface at hole 13. However, core 14, taken close to a granite exposure, is 3.5m long before reaching basement. This represents a depth of about -0.5m with respect to tidal datum. The core length increases to cover 4.6m, 100m seaward. About 2km further northward the last core, hole 16, recorded basement at 4.2m or approximately -1.2m (T.D.).

The varying depths to basement and variable stratigraphy in different cores suggest a complex evolution of the swamp. The most complete evidence is found in the northern section where basement is at greatest depth with respect to the present-day surface. An organic rich layer is found above a predominantly sandy beach or grus deposit, which contains some clays. The depth of the organic layer varies from 2.9 to 3.3m below the surface which probably is a reflection of variation in the surface microtopography. A mangrove peat sample taken from hole 15, at 3.1-3.2m, produced a C14 date of 7,230 ± 550 years B.P. (Gak-6265). The increase in fines in this layer suggests that coarse sediments have been excluded from this area. This could have been achieved by a change in wave patterns whereby coarse material was no longer brought on shore; by development of a spit or bar offshore or by a reduced supply of coarse material from fluvial and slope wash action. Above this layer is a thin coarse deposit which grades upwards into a stiff clay which is over 1m thick. Some coarse material, oyster shells and organic matter are found throughout the clay layer. The persistence of fine material throughout the profile from a depth of about 2.8m suggests that there has been an alteration in the source of sediment supply from material that is transported by saltation/traction and possibly locally derived, to material falling out of suspension and possibly of a more distant origin. From about 1.6m the amount of organic matter rapidly increases towards the surface.

A sample of root material taken from 1.3m-1.6m below the surface from hole 2 gave a C14 date of 1620 ± 100 years B.P. (Gak-6264). Sedimentation subsequently appears to have progressed without any changes in the depositional environmental conditions. A wood sample, thought to be part of a *Ceriops* tree, was dated at 690 ± 90 C14 years B.P. (Gak-6263). This was found at a depth of 25cm, 40m seaward of hole 6, beneath the present-day *Suaeda/ Avicennia* zone.

The landward extent of much of the swamp is bounded by granitic outcrops which act as cliffs. In the past, buried granitic areas would have acted as a shore platform. With a relatively stable sea level in recent times sub-aerial processes operating on the granitic material have influenced the type and character of surface sediment and hence nature of the vegetation at the inner edge of the mangal. This is amply demonstrated by holes 2, 3, 4 and 5. Surface deposits comprise grus material brought downslope by periodic episodes of surface run off following heavy rain in the wet season.

The long sandy ridge about 1m high which extends across the salt flats near West Point is probably a superficial deposit. Hole 16 was cored 10m from it and did not encounter any material similar to the ridge sediments. Consequently it is suggested that this and recurved deposits at the seaward end may be typical of a chenier ridge that has undergone modification by marine processes.

Saunders Beach

Core recovery at Saunders Beach was limited. Because of the nature of the sediments, both surface and sub-surface, only four cores of any length were obtained. The core logs are described in Figure 4.3. As can be seen, varying depths were penetrated before obstructions were met, generally in the form of a dense sand lens. Although organic matter was encountered, no material for C14 dating was seen in sufficient quantities, even from numerous subsidiary holes that were put down in the vicinity of the described profiles. Since the profiles at any one coring area were sufficiently similar only one type profile will be described for each locality.

The evidence suggests that the mangrove swamps have developed on a series of interdigitating sand and clay deposits which reflect the influence of marine processes as well as fluvial sediments in the form of sandy levee deposits and fine overbank deposits. For example, Station 12 and Station 18 have mean surface sediment values of 2.2 phi and 2.1 phi units respectively whilst Station 18 has a mean surface sediment value of 3.62 phi units. The core profile beneath the *Rhizophora/Bruguiera* zone (Saunders Beach 2) suggests that, if the Magnetic Island rates of sedimentation can be used in this situation, quiet lagoonal type conditions have been present for over 1500 years. Shell fragments found at the base of the core belong to the families *Naticidae*, *Telescopiidae* and *Terebridae*. All are shallow water types living on sandy beaches and are probably all existing forms (pers. comm. W. Dowd, Curator, Biological Sciences Museum, J.C.U.N.Q., 1975).

Orpheus Island

No cores are available for Orpheus Island. Many mangroves are established directly on to a rocky basement, their roots searching out the crevices and joints in the rocks. In these situations there are very little and highly variable amounts of sediment distributed through the swamps. Where mangroves are growing on a depth of sediment it is invariably a coarse sandy deposit which could not be penetrated by a peat corer.

Landward of the study swamp is an outcrop of beach rock, the upper surface of which is at approximately mean high water neaps. Similar deposits have been dated at less than 2,500 C14 years B.P. (Hopley, 1970). Because of the situation of the swamp and the lack of fine material that has gathered in the swamp it is highly likely that the mangroves are recent colonizers on this part of the coast, probably establishing themselves less than 2,500 years ago.

Hinchinbrook Island

Although not part of the detailed programme profiles of cores obtained in a project undertaken with Professor A.L. Bloom on the south side of Hinchinbrook Island, Figure 2.1, are of relevance. The swamp is situated at the mouth of a tidal creek which receives water from part of the mountainous interior. Spurs from the steep upland massif form an embayment that has been gradually infilled by marine and fluvial deposits during the Holocene rise in sea level. The vegetation is situated on a surface which gently shelves upwards to the hillslopes from about the mean high water mark. *Rhizophora* and *Bruguiera* spp. dominate the swamp although on the landward edges of the swamp other genera such as *Ceriops* and *Osbornia* are encountered.

The location of the core holes is given in Figure 4.4 and the logs are described in Figure 4.5. As is seen from the diagrams each core hole encounters basal material at a progressively greater depth, with increasing distance from the hillslope. All cores comprise a dark grey sticky mud with organic material, both fibrous root and bark chips, intermingling with the sediment. The amount of organic matter present varies between cores as well as vertically within individual cores. All cores end on a grus deposit which rests on a solid basement which presumably is the bedrock. Organic matter is often found just above the basement and a number of composite samples were collected and sent for C14 dating at Gakushuin University, Japan. The results are:

(i) Hole 6-1 (1.52 to 1.68m) GaK-4895 4680 ± 135 C14 years B.P.
(ii) Hole 6-2 (2.44 to 2.6m) GaK-4896 2180 ± 90 C14 years B.P.
(iii) Hole 6-3 (3.66 to 3.81m) GaK-4897 1350 ± 80 C14 years B.P.
(iv) Hole 7-1 (5.94 to 6.1m) GaK-4898 7130 ± 150 C14 years B.P.

The dates indicate an anomalous situation. They show that the further the site is from the hillslope on the left bank of the creek the younger the basal section of the core. On the right bank of the creek (7-1) the basal layers increase in age but are significantly older than the sample taken from relatively close to the hillslope. Only one solution seems to adequately explain the situation. As most samples that were dated were taken from just above the basement deposit and since the sediment surface of the swamp is devoid of organic material, especially when compared to Magnetic Island, there is a strong suggestion that the samples come from organic matter that had fallen into the creek and has subsequently become embedded into the creek wall. Thus at 7130 C14 years B.P. the creek was located in the vicinity of hole 7-1. With the continued rise of the level of the sea, infilling was maintained and the creek migrated across the intertidal flat incising its left bank. Sediment would have been reworked by lateral erosion and infilling probably would have occurred on the right bank incorporating organic debris (see van Straaten, 1954). Migration and infilling continued. Whether or not the creek maintained its lateral erosion as far as the hillslope is not known. About 4680 C14 years B.P. the creek had started to migrate again but in the opposite direction, incising into the right bank, reworking the recently redeposited sediment. This movement has progressed up to the present course, thereby destroying much of the evidence of its meandering path during the late Holocene.

Discussion

Any interpretation of the stratigraphy for the evolution of each mangrove swamp has to take due cognizance of sea level changes. Evidence from Australian shorelines suggests that at the maximum of the last glacial period, about 17000 years B.P., the sea level was located at between -130m and -160m (Chappell, 1974). From at least 15000 years B.P. there has been a progressive rise in the level of the sea as the amount of land locked water, in the form of ice, diminished. The problems associated with the Holocene transgression revolve around questions whether or not there has been a higher sea level subsequent to the post-glacial recovery of the sea and the time at which modern sea level was first achieved. Persuasive arguments have been made both against a post-glacial higher sea level (e.g. Thom *et al.*, 1969, Thom *et al.*, 1972) and for a post-glacial higher sea level (e.g. Gill and Hopley, 1972). The argument hinges around the preservation of datable evidence with which the hypothesis may be tested.

It has been suggested that along the central portion of the Queensland coastline there are distinct fault lines that have been active, albeit marginally, during the Holocene (Hopley, 1975; Cook and Mayo, 1978). Thus in areas of greatest displacement the evidence is preserved at the highest elevation. Since part of the coast has been subjected to upward movements it is equally probable that other portions of the coastline have subsided. The problem may be partially explained by ideas of Bloom (1967), Walcott (1972), Chappell(1974) and Clark *et al.* (1978) who suggest that the water loading on the continental shelf will produce an altitudinal deformation of shoreline evidence, the amount of deformation being largely dependent on the shelf's characteristics at that point.

Since the continental shelf in North Queensland varies in width between 120km and 170km and changes its alignment (Hopley, 1975), it is perhaps not surprising that the response across the continental shelf has been highly variable. Nevertheless, after extracting the tectonic/isostatic response it has been suggested that in the Townsville region sea level reached its present position by at least 6-5000 C14 years B.P. The transgression continued, reaching its maximum 4000-4500 C14 years B.P. A regression then took place until present-day sea level was reached about 2500 C14 years B.P. (Hopley, 1974b). It could be argued that the allowance for the tectonic displacement is not enough and that there has not been a higher sea level. However, evidence accumulated during the 1973 Great Barrier Reef Expedition north of Cairns suggests that there has been an emergence of at least 1 metre (Hopley, 1978).

Nonetheless, neither argument is of central concern to the interpretation of the mangrove data. What is important is the fact that material which has been used to reconstruct past sea levels from other localities in the Townsville area has been displaced relative to the sea level of its formation. Consequently the pattern of this displacement is important since the evidence from Magnetic Island should also reflect these changes.

There is a lack of evidence at many locations for a post-glacial high sea level. Therefore it can be assumed that if there was a higher sea level in the area evidence has been destroyed or on the hard rock coastlines, the bedrock is too durable for any impression to be made during the 2-3000 years of postulated higher sea level. No evidence of a higher sea level has been found in the Palm Island group north of Curacoa Island (Hopley, 1971). Since evidence has been produced only for a maximum +1.2m at Yule Point near Cairns (Bird, 1971b) it is possible that Hinchinbrook Island did not experience a significantly higher sea level. Thus on Hinchinbrook Island the evidence suggests a continuous sedimentary sequence of fine material deposited as the tidal creek system meanders across the intertidal slope, lateral erosional and depositional processes playing an important role (van Straaten, 1954). Unfortunately it is not possible to relate the dates to any sea level. The present depth of the creek is greater than 2m, even on the low tide. However, there is no guarantee that the depth has remained constant with time.

The Magnetic Island data indicates a similar picture to Hinchinbrook Island. Differences occur because fluvial/tidal creek influences play only a minor role in the sedimentary processes on Magnetic Island. The relationship between the estimated mean high water springs (MHWS) and the sediment surface is indicated in Figure 4.6. The two graphs illustrate: (A) the suggested sea level curve for the Townsville area including the tectonic component and the average sediment surface level of mangrove deposits on Magnetic Island, below present day MHWS, and (B) the hypothetical relationship between the submerged surface and the height of MHWS for Magnetic Island. In Graph A the vertical lines represent the altitudinal range in which a mangrove peat sample may occur with respect to the MHWS at the time of deposition. This is based on the assumptions that:

(i) any peaty sample is derived from a *Rhizophora* root fibre mat;

(ii) the altitudinal range of the *Rhizophora* forest on Magnetic Island has had a similar range in the past to today's range, which is about 1.6m;

(iii) the relative tidal range and height of MHWS was the same at the time of deposition as it is today, i.e. 2.9m;

(iv) little or no compaction has taken place.

Apart from the direct physical evidence of the location of the samples and the problems associated with it, uncertainties are also present regarding the "true" age of the samples. The horizontal lines on the graph represent one standard deviation of the beta rays counting statistical errors (Professor Kigoshi, pers. comm., 1976). Notwithstanding that, it has been found that there have been both long and short-term variations in the production of C14 (Rafter, 1971; Stuiver, 1967) and that carbon isotopes may be taken up in varying amounts by the different types of plants (Troughton, 1971). Consequently, the age determinations are possibly not absolute. The errors are compounded by possible contamination of the samples (Grant-Taylor, 1971).

Bearing this in mind a smoothed curve has been drawn on the graph. This is generally fixed by the evidence taken from beach rock samples, and gives an approximation of the sea level position during the last 7,500 years. The height of the data that present-day MHWS was reached at about 6000 C14 years B.P. rising to about +4.3m, 4000 to 3750 C14 years B.P. The sample taken from Herald Island, GaK-2014m has not been used to estimate the curve since it is thought that the sample has been raised disproportionately from the position of cementation (D. Hopley, pers. comm., 1977).

At about 7230 C14 years B.P. conditions were suitable for the development of a mangrove peat on Magnetic Island. On top of the thin organic layer is a narrow band of coarse material. This may represent remnants of a barrier which has passed through the swamp killing off the vegetation (Jennings and Coventry, 1973). A similar situation can be seen today on the southern end of Cockle Bay. Sea level continued to rise with an infilling of fine grained sediments. In some areas of the coast sedimentation was able to keep pace with the rise in the level of the sea. With the rise in sea level a fringing reef was able to develop on the western side of Magnetic Island. Today little living coral is found close to the shore. This may be attributed to the fall in sea level and/or to the deposition of fine grained material on the surface of the reef flat similar to Yule Point. The presence of this fringing reef may be responsible for the seaward extension of the mangrove swamp: considerably more infilling would have been necessary to produce a surface at a suitable depth for the establishment of mangroves had the reef been absent.

A mangrove peat deposit 5m below ground level, at approximately present tidal datum, beneath a Holocene beach sand ridge at Pallarenda has been dated at 5960 ± 230 C14 years B.P. (GaK-6018, A. Belperio, pers. comm.). On Magnetic Island no deposits of such an age were dated. This may be due to a number of related factors.

(i) The rate of increase in sea level recovery could have increased making the depth of water covering the inter-tidal slope too deep to allow mangrove colonisation.

(ii) The rate of sediment supply may have been reduced after the sand barrier (?) had passed through the mangroves. Consequently sedimentation would not have kept pace with the rise in sea level.

(iii) Mangrove mortality, due to the sand barrier (?), would have reduced the stability of the intertidal flat sediments. Therefore greater surface sediment reworking would have occurred. Thus the lack of a mangrove cover would have reduced the effective sedimentation rate. This feature is particularly noticeable when the average sedimentation rates are considered for Magnetic Island.

Average sedimentation rates can be calculated from the three C14 dates from Magnetic Island. Between 7230 and 1620 C14 years B.P. the average sedimentation rate was 30.3mm/100 years. The rate increased almost fourfold between 1620 and 690 C14 years B.P. to 129mm/100 years. Since then there has been a decrease to 36mm/100 years. These rates must be interpreted with care. The degree of contamination of the samples and their relative displacement is not known. It has also been assumed that there has been a continuous positive accretion throughout the time periods. Contemporary evidence suggests that this need not be the case.

A number of different reasons may explain the differences in the average sedimentation rates.

(i) The amount of material brought into the area might have changed with time.

(ii) The rate of fixation of the sediment would vary according to the presence and absence of mangroves.

(iii) The rate of sedimentation may vary quite considerably depending on the location of the bore hole and the position of growth of the original organic material in the mangal.

If the sample (GaK-6263) was part of a *Ceriops* tree then it would depict a sample taken from the back of the mangal (MacNae, 1966, 1967). Because of this situation, the supply of material from offshore would be reduced due to a reduction in transporting power of the tidal stream across the intertidal slope and the binding effect of vegetation on the sediment. Hence the rate of accretion on the upper part of the intertidal slope would be curtailed, the zone of maximum sedimentation having moved seaward. Therefore a reduction in the supply of sediment need not be required.

A similar situation has been observed in salt marshes in Britain. Comparing rates of sedimentation on the Dovey estuary, Wales (Richards, 1934) with that on Bridgewater Bay, Somerset and Poole Harbour, Dorset, Ranwell (1964) concludes that the area of maximum sedimentation is greatly influenced by the age of the swamp. The zone of maximum accretion moves seaward as the marsh matures.

Terrestrial influences also have influenced the landward margins of the swamp. Hole 5, cored inland from the mangrove swamp edge, reveals mangrove mud below a layer of sand. This suggests that sheet wash, in times of flood during the wet season may be influencing the inner margin of the mangrove by introducing coarse sand into the swamp.

The evidence at Saunders Beach does not contradict this interpretation. The evolution of the swamps here is intimately linked with the development across the coastal plain of the river systems which date from the Pleistocene. Using evidence from the Burdekin River delta to the south (Hopley, 1970), together with the disposition of landforms and their associated soils, an evolution of the coastal plain has been described (Hopley and Murtha, 1975). The deposition of sediments reflects the interplay of fluvial and marine influences under a variable climatic regime. The last time sea level was above present prior to the Holocene transgression was during the last interglacial (c.125,000 years B.P.) when sea level was at approximately +6m (Bloom *et al.*, 1974). Thus remnants of an old shoreline observed today on the coastal plain probably date from this period. Other Pleistocene deposits have been shown to post date this shoreline.

During the Holocene sandy material was brought onshore in a series of transgressive and regressive cycles (Driscoll and Hopley, 1968). Although there is no clear evidence of a higher sea level, a greater than 30cm salting cliff is observed cut into the Pleistocene clay plain on the right bank of Althaus Creek. Since the salting cliff is only reached on the extrene high tides it could have been cut at a time of higher sea level. Alternatively it could also be related to the intermittent peak flood situation and be a recent phenomenon. Occasional islands of terrestrial vegetation (e.g. *Heteropogon contortus, Chloris barbarta, Acacia florvescens* and *Mimusopus elengii*) are found on the salt flat. The islands' surfaces are severely incised to depths of more than 30cm. The highest points of the islands are above all but the exceptional tidal level. Whether or not the surface represents a remnant of an old flood plain that has now been incised is open to conjecture. Therefore from the interdigitation of the deposits at Althaus Creek and their evolutionary sequence, the establishment of mangroves at Saunders Beach is probably related to the attainment of a stable coastline and sea level during the last 2,500 years.

A similar conclusion is reached for the time of development of the mangals on Orpheus Island. Beach rock which is found landward of the mangal that was studies is at approximately high water neaps. Similar deposits on the mainland (Shelly Beach and Balgal Beach) have been dated at less than 2500 C14 years B.P. A younger date for mangroves established is therefore highly likely.

Evidence collected at Hinchinbrook Island extended back as far as 7,130 years. Little could be concluded about the height of the sediment surface with respect to the prevailing sea level. The dated samples are interpreted as materials which have been incorporated into a laterally eroding and accreting tidal creek system. Therefore the evidence could have come from more than 2m below the prevailing sea level.

Synthesis

Three aspects of the sedimentary environment present in mangals in the Townsville region have been studied in this project. They relate to the pattern of accretion and the amount of material being transported through the swamps. The evidence from the three mangals that have been investigated tends to complement one another.

Distinct trends are apparent in the data, which are common to most of the transects. Sufficient variations have been noted during 1974 and 1975 to account for features observed in the swamps.

The evidence collected in this study greatly amplifies ideas promulgated by Bird (1971a) and Scoffin (1970). Prop roots are thought to play a significant role in reducing tidal current velocities (Scoffin, 1970) whilst pneumatophores are thought to create a quiet environment which allows the deposition of material out of suspension (Bird, 1971a). Evidence from both the pneumatophores and sedimentation transportation experiments attests to the influence of mangroves along transects through the mangals. It has been shown that the density of pneumatophores directly influences the rates of accretion, but not necessarily in the manner previously suggested. A close network of pneumatophores encourages erosion to take place whilst an open network has little or no effect on the processes. However the effect within the fringe of *Avicennia* and *Sonneratia* is less marked than on the adjacent bare mud. It is also found on Orpheus Island that under particular conditions the top five centimetres of sediment can be readily transported about the swamp with no apparent effect on the viability of the mangal. Therefore rather than necessarily producing a quiet environment for accretion in the swamp, the role mangroves play is that of binding the sediment thereby creating a stable environment for the maintenance of the mangal.

Since mangroves owe their existence to the presence of a relatively low to medium energy environment, the periodic occurrence of high energy conditions allows for the testing of the stabilizing influence of mangroves. Cyclone Althea crossed the North Queensland coast on 24 December 1971, 48km north of Townsville. On coastlines unprotected by mangroves erosion of up to 16m took place. The effect on mangrove protected coastlines was negligible (Hopley, 1974a). It has to be acknowledged, however, that wholesale mortality of mangroves has subsequently occurred, especially in *Rhizophora* spp. Cause(s) of death is unknown, although it has been found that while mature *Rhizophora* trees are unable to regenerate after damage, young saplings do have this facility (Gill and Tomlinson, 1969). Nevertheless the mangroves fulfilled their function and prevented massive coastal erosion at the time of high energy. Recolonization is at present under way. Thus if another major cyclone does not pass close to Townsville for a decade, the new trees will be well established and again able to fulfil their role.

Although both the erosional or depositional events of greater than 3mm and the amount of load transported appears to decrease in a landward direction through the mangals, there is an unexpected increase in both trends on the upper intertidal slope and high tidal flat. This is particularly apparent in the inner *Ceriops* zone on Magnetic Island. Similar trends are also apparent on other transects. The effect is clearly seen by the large numbers of *Ceriops* whose buttress roots have been excavated, exposing the secondary root system beneath, on both Magnetic Island and at Saunders Beach. In some instances the trees have subsequently collapsed. The erosion of more than 20cm from between a *Ceriops* buttress root at Saunders Beach suggests that stem or trunk flow or water dripping from the tree trunk during a storm may be responsible for the erosion. On Magnetic Island sheetwash and overland flow during the wet season from the adjacent hillslopes could also augment that effect.

Associated with this is the fact that the total amount trapped and amount trapped per unit time covered shows an increase in the inner zones with respect to stations immediately seaward. Unlike salt marshes the ground surface is relatively bare and thus the power of the initial wavelets is not further reduced. Material is therefore entrained and transported by the wavelet relatively easily. Since the inner reaches of the mangal are only covered for a short period of time by a thin layer of water there is little opportunity for losses to be replenished by material being deposited out of suspension. It is also noticeable that on all transects the inner, higher zones have relatively coarse sediments which are more easily moved than the finer material found on other zones.

Although there are basic similarities between the zones which allow some general statements to be made, differences also exist. The lack of a seasonal pattern for the monthly accretion rates on Magnetic Island is to a large extent overcome by considering differences based on a three monthly interval. With one minor exception alternations of erosion and deposition occur for the transect as a whole, for each period, during 1974 and 1975. Over all, a net erosion is found on the island. Such a trend cannot be identified for either transect at Saunders Beach even though they were sampled every three months in 1975. Instead of erosion the two transects are experiencing an active building up of the surfaces, with the exception of the overbank areas on Saunders Beach 1.

Trends are difficult to distinguish on Orpheus Island. The dominant feature of the mangal is the dynamic nature of its environment. Large changes can occur over one tidal cycle. However in the long term the *status quo* appears to be preserved and the mangal is being maintained as a viable unit.

The trends observed in the contemporary processes reinforce the interpretation of the stratigraphic evidence from Magnetic Island. Between 1620 C14 years B.P. and 690 C14 years B.P. the average sedimentation rate was 3.6 times greater than from 690 C14 years B.P. to the present. The actual rate may be slightly different due to a continuing modification of the surface features by processes operating today. Nevertheless the rate of sedimentation would have been reduced quite considerably since 690 C14 years B.P. Therefore if the woody sample was from a *Ceriops* tree it suggests that an upward and outward building of the swamp surface has taken place. Maximum variations in the surface sediments appear to be present in the seaward portions of the mangal with progressively reduced activity to landward. Less material is therefore available to allow the surface to be built up beneath the *Ceriops* zone. Consequently the rate of deposition would appear to decrease whether or not there has been a regional decline in the amount of material entering the system.

Overall, the results indicate that the sedimentary environments within the mangals can be divided vertically into two sections. First there is that portion of the sediment lying under the surface that is bound together by a combination of rootlets, electrostatic forces and/or interparticle cohesion forces, and second, the overlying material not bound together by roots. The depth of the latter section varies both within a zone and between zones as well as between mangals. However it is within this section of the sediment that most of the surface variations occur. Material is added and removed. The largest variations occur where there is least living root material, a trend which is augmented by the presence of prop and buttress roots and pneumatophores. In the presence of an organic root mat or a surface algal mat, the intensity of surface variations decreases quite markedly. The annual increment of root material will bind more sediment but in an area of positive accretion the roots will still remain below the surface.

As demonstrated by the Orpheus Island results considerable amounts of sediment may move about a swamp with no apparent effect on the mangroves. Deleterious effects primarily occur when there is either a progressive erosion of an area or when there is rapid deposition, especially of relatively coarse material. In the former instance, the roots come closer to the surface. Because of this the rate of erosion would probably be reduced. However if the trend persists the trees may be undermined and collapse in a similar fashion to many *Ceriops* specimens at Saunders Beach and on Magnetic Island. Short intense periods of erosion, e.g. during cyclonic conditions, may also severely undermine the trees and their root systems and may cause their death.

With a strong depositional trend of material, such as on the southern portion of the mangal on Magnetic Island, the root systems are overwhelmed. Death results either from the burial of the above ground portions of the roots by sediment or the blocking of the lenticels by fine particles. In either case death by suffocation may ensue. In the situation where neither deposition nor erosion is excessive there is a progressive upward and outward building of the mangal sediment surface with a moderately dynamic surface veneer of sediment and a more stable less variable sediment layer beneath.

The difficulties of relating mangrove deposits to a prevailing sea level are exemplified in this study. On an open accreting coastline the evidence can be interpreted in a meaningful manner, with certain qualifications about the data. Far greater difficulties are experienced on an estuarine coastline. Problems exist from the interdigitation of marine and fluvial sediment of different textural characteristics as well as the organic material itself. It is quite evident that the Hinchinbrook Island data cannot be related to any particular sea level. In spite of this, an evolutionary sequence can be resolved for the part of the swamp that was investigated. Plentiful sediment appears to have been present in the mangal for several millenia. The sediment seems to be undergoing continuous reworking by tidal creeks that meander across the intertidal slope. Thus new material is deposited and older mangal deposits are destroyed or reworked.

CHAPTER FIVE

THE DEVELOPMENT OF MANGALS IN THE TOWNSVILLE REGION

In establishment and growth the mangroves in the Townsville region have overcome initial limitations imposed on them by the intensity of marine processes and the effect of the regional climate. However, once the mangroves establish themselves, an intimate set of interrelationships develop between the mangroves and their environment. Geomorphic processes operating across the intertidal slope may be modified by the presence of mangroves whilst aspects of the sedimentary environment may play a significant role in affecting the distribution of species on the intertidal slope.

It is against such a background that various hypotheses concerning the development of the zonation of mangroves within mangals have been proposed. The sites that were chosen for study in the Townsville area were selected for their representativeness, security, and accessibility. In addition, the mangal on Magnetic Island has been described already in various degrees of detail and a set of factors has been proposed to account for the zonation of these mangroves (MacNae, 1966, 1967, 1968). The present study has, in part, set out to test those factors and to see whether or not they have a wider application. If not it is pertinent to ask whether or not there are suitable alternative hypotheses that may be considered.

Apart from the problems of mangrove zonation, the presence of a vegetated intertidal slope is likely to have a modifying influence on the intensity of near shore marine processes. It is also suggested that the changing intensity of geomorphic and sedimentary processes may affect the distribution of mangroves within the mangals.

Relationship to past ideas—Mechanical Effect

This study has quantified some of the sedimentary processes which are operating within the mangals in the Townsville region. As such they provide a basis on which previous essentially qualitative ideas can be assessed.

A progressive decline in the energy conditions is found, moving through the mangals towards the high water mark. This is clearly indicated by the variations in the sediment levels and the amounts of material that are transported. Going from a creek inland the general trend in the accretionary rate is for greatest activity to occur in the mangals closest to tidal datum with a decline in the frequency and extent of major erosional and depositional episodes, plus or minus 3mm, occurring as the height of the land surface increases. Along a transect from the sea inland, on Magnetic Island, the area of greatest accretionary activity is located in from the mangrove fringe within the *Rhizophora* zone. The rates decrease further inland. This is a similar result to that of Bird (1971a), but by implication contrary to the velocity conditions suggested by Scoffin (1970).

A similar trend is displayed in the transported sediment data with peak values close to the front of the mangals, declining inland. This is related to the stabilizing influence of mangroves and the desiccation gradient which occurs across the intertidal slope (Thompson, 1968; Anderson, 1973). Consequently, higher critical erosional velocities are required for similar particle sizes on the upper portion of the intertidal slope than on the lower intertidal slope.

Although a general trend is present in both sets of data, important variations do occur on the high tidal flat and on salt flats. On salt flats, which in the sites studied are located at or just below mean high water spring tides, accretionary activity is minimal and only small quantities of sediment are trapped here. Apart from desiccation effects this is probably related to the binding ability of algal mats (Neumann *et al.*, 1970) and low velocities in such a situation (Gunatilaka, 1975). Further landward from the salt flats and above mean high water spring tides, where the frequency of tidal inundation is markedly reduced and a decrease in tidal current velocities is expected, there is an increase both in the amount of material eroded and deposited and in the quantity of sediment trapped.

The increased sedimentary activity on Magnetic Island could be explained in terms of overland flow initiated in the terrestrial environment or the slight movement of coarser material in that part of the intertidal zone. This would have the effect of producing a proportionally greater variation in the sediment surface than is possible with fine material. However, this is not a suitable explanation for the increased activity at Saunders Beach. Two possible processes can explain such a phenomenon when the high tidal flat is not covered by tidal waters. First, intercepted water streams down the tree trunk and the flow is concentrated between the buttress roots of the *Ceriops* trees. The alternative but related idea suggests that prior to the water reaching the ground, the water drips from an object projecting out from the tree trunk. The impact of the water is concentrated on a particular spot, causing erosion of the sediment.

When the area is covered by tidal waters results from the sediment transport experiment suggest another possible cause of the increased activity. Similar to the accretionary data, there is an increase in the amount of material trapped on the high tidal flat both in terms of absolute amounts and amount per unit time covered. Since wave activity is minimal in this situation, the importance of the initial rippling wavelet that precedes the flood tide and follows the ebb tide is emphasised. The effect of local wavelets resuspending material is a well known feature (Pestrong, 1972; Anderson, 1973). Data from the bed load experiment suggest that this wavelet does considerable work in breaking the bonds between adjacent sediment particles and incorporating them into the suspended and saltation load. However, the argument can be taken a stage further by considering what is happening at the limits of each flood tide. Here the wavelet resuspends material. However, since there is only a short period of time before the ebb tide starts receding, there is little opportunity for material to drop back out of suspension *in situ*. Consequently much of the material may be removed seaward. Elsewhere on the intertidal slope sufficient material may be deposited to mask this trend. Thus if the tidal levels do not exceed a particular level for several days, as often happens on spring tides, then a narrow band may exist on the upper intertidal slope where there may be net erosion taking place, even though net deposition is experienced to seaward. This is in contrast to locations on the lower section of the intertidal slope where sufficient time is available for material to be deposited either from resuspended material derived locally or from imported sediment.

The stabilising influence of mangroves has been illustrated by experiments that were conducted in detail on Magnetic Island. Pneumatophores have been demonstrated to restrict erosional processes at the seaward fringe of the mangals on Magnetic Island. This is not due to the dampening effect of the passage of tidal waters (Bird, 1971a), but rather to the binding capacity of rootlets attached to pneumatophores. The spacing of the pneumatophores, simulated by a series of metal rods, has been shown to play an important role in affecting the sediment response to a particular set of imposed energy conditions. A narrow spacing between adjacent rods allows the initiation of immediate scouring and erosion. A wider mesh produces only a minor modification of the surface level. In the presence of rootlets, the erosional effects are dampened considerably. Nevertheless the seaward fringe of the mangal on Magnetic Island appears to be subjected to a seasonal cut and fill in the wet and dry season respectively.

The stabilising effect of pneumatophores on the upper intertidal slope is not so readily apparent. Trends are masked in such a situation by the attendant desiccation gradient and hence the higher critical erosional velocities that are required to erode material. This does not necessarily mean that pneumatophores in this locality do not create an environment which is more conducive to the deposition of material. However, only minor variations in the surface level were observed under an *Avicennia* cover on the upper intertidal slope on Magnetic Island.

Consequently the results from this study suggest a non-linear distribution of energy through a mangal. This is seen from the modifications that are made to the sediment surface. The greatest variations in amounts of material eroded or deposited are round at the seaward edge of the mangals. The presence of prop roots and pneumatophores with their underground parts seem to have a number of functions other than physiological ones. Depending on the density of the pneumatophores and the size and frequency of the prop roots, they may locally increase scouring and the rate of erosion. Under relative high energy conditions these protrusions create local eddies thereby initiating excessive erosion in their immediate vicinity. This is clearly displayed at all three sites. However, the presence of rootlets binding the soil physically and/or electrochemically provides a natural limiting factor which restricts the vertical incision into the sediment. This allows the viability of the mangroves to be maintained, for instance, after cyclones (Hopley, 1974a), or where there is highly mobile unbound surface material that circulates about the swamps, as on Orpheus Island. Under calmer conditions, either climatically induced or due to the position on the intertidal slope, the obstructions which cause scouring appear to have a different function. They subdue the energy conditions even more and allow material to be dropped out of suspension, as has been suggested by Bird (1971a).

Therefore by considering the interplay between terrestrial and marine forces it can be seen why the inner portions of the mangals may be more dynamic than initially thought. If the effects were mainly depositional rather than erosional, factors such as crab activity would have to be taken into account. However, in the mangals studied the effect of crabs bringing material to the surface appears to be minor. Certainly the mounds built up pale into insignificance when compared with those created at the rear of many Papuan mangals (Paijmans and Rollet, 1977).

Overall the data suggests that Magnetic Island is undergoing a period of net erosion. Saunders Beach appears to be subject to a net deposition of material. The condition of the Orpheus Island mangal is difficult to comment on in a meaningful manner. This swamp is the most dynamic of the three mangals that were studied. A lot of surface material is being circulated about the swamp. Whether the mangal is suffering a net erosion or a net deposition cannot be determined.

Relationship to past ideas—Ecological

A salt factor appears to be of central concern to the majority of ideas associated with factors that influence the zonation of mangroves within mangals. This has developed from the observed increase in ground salinity from the seaward to the landward margins of the mangal. The evidence found in this study seems to support this suggestion, particularly if the latter two zones on Magnetic Island are ignored because of the influence of fresh water seepage. The zonation therefore appears to conform with various models that have been put forward (MacNae, 1960, 1967, 1968; Chapman, 1970; Baltzer, 1969). Furthermore the sequence of zonation and associated salt flat appears to conform with the "expected" situation in mangals developing under seasonally dry climates (e.g., MacNae, 1966; Valentin, 1975; Saenger and Hopkins, 1975; Derijard, 1965; Walter, 1971). However consideration of the evolution and development of salt flats (Spenceley, 1976) suggests that they may be created in more than one way and that they are not necessarily confined in their distribution to seasonally dry climatic areas. If the salinity data collected from locations which have been affected by the development of salt flats are ignored, it is apparent both on Magnetic Island and at Saunders Beach that all mangroves are growing well within the tolerance ranges which have been suggested for the species (MacNae, 1968), albeit outwith the optimum conditions for growth (McMillan, 1974; Barbour, 1970). Therefore salinity need not have a subsuming control in these swamps.

Even though salinity *per se* may not be of direct importance in controlling the distribution of species it may be a competitor eliminator for particular species (Chapman, 1974; Walter, 1971; Clarke and Hannon, 1970). Walter (1971) also points out that in different situations factors other than salinity might be of greater importance. It has also been suggested that the range of salinity may be a controlling influence (MacNae, 1963), although little or no supporting evidence was produced. In this study, under a closed canopy only minor salinity variations were observed, except under the influence of fresh water seepage.

The distribution of mangroves has also been related to the frequency of tidal inundation and the height of the land surface. The precise connection between them has not been clearly identified although the two factors usually have been used to reinforce the salinity parameter. A comparison of the levels at which different mangroves grow in the Townsville district, Table 2.1, implies that other factors, at least locally, are of greater importance. A more promising field of inquiry is to associate the degree of exposure and frequency of inundation with differing concentrations of soil chemical parameters from the sea to the land.

It has been suggested that the zonation of species is paralleled by changes in soil chemistry (Navalkar and Bharucha, 1949, 1950; Vieillefon, 1969; Kartawinata and Walujo, 1977; Kassas and Zahran, 1967. Previous experiments have been limited by the fact that they have been confined to one type of coastline. The present study has considered both an open accreting coast and an estuarine coast.

The results obtained in this study differ from those produced elsewhere. The trends which are displayed on the open accreting coast (Magnetic Island) are quite different from those found on an estuarine coast (Saunders Beach). At the former site the parameters tend to have a spatial variation through the mangal but a minimal seasonal trend. This contrasts markedly with data from the two Saunders Beach transects. Marked spatial and seasonal trends are found in the results with low concentrations in the wet season and high concentrations in the dry season. Although there appears to be a relationship between the timing of an increase in fresh water passing through the system and the lowering in concentrations it was not found that the abnormally wet period in September and October 1975 had any noticeable effect on the results. This applies to both sites. Davison (1950) and Chapman and Ronaldson (1958) found that in the swamps at Auckland precipitation and tidal cover probably affected elemental concentrations in the soil. Their results suggest that there is a short time lag between rainfall and its modifying influence being discerned. When applied to the seasonal pattern of rainfall such a hypothesis fits the Saunders Beach data, but does not fit the data from Magnetic Island so well.

A different conclusion is reached when the hypothesis is applied to short-term changes in the data. Multiple regression analysis was used in an attempt to predict the ground water salinity on Magnetic Island using height of the land surface, the distance landward, precipitation and exposure between sampling periods. A varying time lag was built into the latter two components. Statistically precipitation is not a significant variable. The duration of exposure between sampling is found to be significant but contributes to only a small proportion of the explained variance in the data. Distance landward and the height of the ground are found to be the most important variables in explaining the ground water salinity trends. The degree of explanation shows a considerable increase when landward stations influenced by fresh water seepage are not included in the analysis. The seasonal influence of fresh water at the inner *Ceriops* zone and the *Arthrocnemum/Avicennia* zone is also responsible for trends in the chloride and soluble sodium values which are similar to those at Saunders Beach. Other than that there is little similarity in the results from the two sites.

Differences observed at the two types of sites, estuarine and open coast accretion sites, reflect trends observed in Malaysia (Diemont and Wijngaarden, 1975). Not only is it apparent that there are marked differences in elemental concentrations between the Saunders Beach and Magnetic Island sites, but that there are also temporal variations which appear to depend on the volume of fresh water in put into the mangal. When this is taken into account greater differences are observed between the two types of coasts. It is apparent that in this situation, similar vegetation zones have contrasting elemental concentrations. Therefore in the Townsville region it is suggested that mangroves do not tend to grow in any particular set of conditions and that the environment in which they exist it cannot be generalised with respect to the chemical variables that have been considered. This is in direct contrast with the ideas initially suggested by Navalkar and Bharucha (1949, 1950).

Notwithstanding the differences in the raw data certain similarities are displayed by the factor analysis of the data. Over 50% of the covariance from Magnetic Island and from Saunders Beach sites are explained in terms of a salt factor and a pH factor. Approximately 30% of the remaining covariance is explained by a variety of factors, leaving about another 20% of the covariance unexplained.

Although environmental gradients have been derived using factor analysis it may be expected that stations containing a similar vegetation canopy at the same site would be located close together along the environmental continua. This is not found to be so when the stations are classified using a discriminant programme. The three stations under the *Rhizophora* canopy on Magnetic Island are classified as discrete units whilst the creek bank mixed vegetation on each transect at Saunders Beach is considered to have similar characteristics to either the inner *Ceriops* zone (transect 1) or to the landward *Ceriops* zone on transect 2. Similarly, the stations within the *Ceriops* zone on Magnetic Island are classified as being unrelated to each other, but this is not so for the Saunders Beach data. The reverse trend is apparent on the upper portion of the intertidal slope. The bare or sparsely covered zones on Magnetic Island are grouped together but those along the first transect at Saunders Beach are not. The *Avicennia/Sonneratia* fringe on Magnetic Island is classified with the bare lower intertidal slope to seaward.

The results above therefore suggest that there may be important differences between the mangals chemically, even though the overall vegetation pattern that is present is similar at Magnetic Island and Saunders Beach. An important factor that has to be taken into account when considering ecological information is time. A time lag response between landscape modification and a change in the vegetation has previously been suggested in the context of mangals (Thom, 1967). On a longer term the data collected from the various research sites suggest that the mangals have a complex evolution with many individual characteristics. Whilst it is possible to relate the development of coastal mangals on Magnetic Island to variations in sea level, this could not be done for an estuarine situation as has been suggested elsewhere (Bloom, 1977, p.D6).

Model of Mangal Development

Thus in the Townsville region the results indicate that each swamp is quite different with respect to the environmental details that have been analysed. This is in spite of apparent similarities in the vegetation zonation. Notwithstanding the uniqueness of the mangals it is still possible to construct a general model displaying the important features of mangal development and mangrove zonation. Initially this can be applied to the Townsville region. However, it may also be possible to apply the same logic to the study of other mangals.

One of the basic assumptions of earlier models which describe the general distribution of plants across the intertidal slope has been a relationship between the extent of plant cover and the type of climate. Thus in the humid tropics there is a complete mangrove cover from the lower intertidal slope to the upper limit of tidal water influence. As the amount of precipitation decreases and the duration of a dry season increases the mangroves reduce in height and gaps appear in the areal extent of the mangrove cover (Davies, 1972; Valentin, 1975; Saenger *et al.*, 1977). The logic used to explain this phenomenon is that hypersalinity develops in the dry season. Die-back of species is initiated and salt flats develop. This study suggests that the salt flats may be started in three ways: relative sea-level lowering; physiological drought with mangroves becoming further away from a water supply; localised breaks in the canopy. Consequently the role climate plays is one of reinforcing an existing trend. That is, once a break in the canopy occurs the increased insolation reaching the surface allows hypersalinity to develop. These conditions are not ameliorated to any great extent during the wet season. Therefore the re-establishment of mangroves is precluded. By recognising the limitations as well as the assets of the various models a more useful model of mangal development can be formulated.

Primary factors which influence the development of mangals can be diagrammatically represented (Figure 5.1). Four main components can be identified:

(i) Pre-existing conditions prior to colonization.
(ii) Colonizing conditions.
(iii) Historical factors.
(iv) Present-day environmental conditions.

The coast is a dynamic region which is continually being affected by a variety of short-term modifying influences within an overall long evolutionary trend of events (Wright and Thom, 1977). Prior to colonization of a coast of mangroves, the conditions cannot be suitable for the establishment of mangals or the community would have already established itself. The reasons precluding establishment of mangroves are varied. Conditions may be too energetic (McMillan, 1971); the sediment might not be of the necessary textural composition, since that may influence other soil characteristics (McMillan, 1975); there is not sufficient sediment being brought onshore from either a marine or a fluvial source; the intertidal slope may be too steep; or due to a lack of supply of hypocotyls.

Ultimately under suitable climatic conditions many stretches of coasts in tropical and subtropical land masses may develop mangals. The apparent conditions which are suitable for mangrove establishment vary between species depending on salinity, soil type, energy controls (Ding Hou, 1958; Giglioli and Thornton, 1965; MacNae, 1968; Baltzer and Lafond, 1971; McMillan, 1971, 1974, 1975). It is apparent form the literature that tidal regime need not necessarily play an important role. For example the Ord River, W.A. and Broad Sound, Qld, have tidal ranges of the same order of magnitude but quite different ranges in the colonizing extent of mangroves (Burgis, 1974; Thom *et al.*, 1975; Cook and Mayo, 1978). Contrasting conditions and heights with respect to tidal datum are experienced between this study and that in Cairns (Bird, 1970).

The initial character of the mangals depends therefore on the species present and their ability to cope with the conditions that pevail at that point in time. Once mangroves become established they exert a modifying influence on coastal processes. This has been illustrated in this study and their effect under high energy conditions has been noted (Hopley, 1974a). Under suitable conditions with a continuous input of sediment, the mangals will expand. As the microenvironmental conditions change, new species are able to colonize and establish themselves. The plants may need specific topographical conditions (Thom, 1967; Clarke and Hannon, 1969) or particular environmental conditions such as salt, shade, moisture, or lack of it (Chapman, 1944, 1966; Clarke and Hannon, 1970, 1971). The environment changes through time and the species composition and distribution will reflect these changes albeit with a time lag in response (Thom, 1967).

The mangals today therefore represent the response to the sum total of the changes in the environment that have been experienced through time. As environmental conditions change so will the inherent stresses that are imposed upon the mangroves. Mangals are continuously undergoing modification due to contemporary conditions. These, in turn, impose the most recent set of conditions on mangal development and ultimately affect the zonation of mangroves within the swamps. Present day factors can be subdivided into factors which are external to the swamp, e.g., macro-climate, offshore processes, sediment sources and supply; and factors which are internal to the swamp, e.g., micro-climate, soil characteristics, symbiotic faunal assemblages.

The model of mangal development allows a directional trend to be incorporated into it because the intimate details of plant response and the development of the zonation of mangroves is considered only in a minor way. The problems of zonation have only been alluded to by indicating that a zonation represents the response to the sum total of environmental changes and stresses imposed upon the mangroves in the past and which are currently undergoing continual modification. Considering the problem more specifically the factors that affect the zonation of mangroves are given in Figure 5.2. Using the data from this study, a further set of relationships can be identified, Figure 5.3.

Three interacting subsystems are thought to be of primary importance:

(i) the geomorphological subsystem;
(ii) the ecological subsystem;
(iii) the climatic subsystem.

The subsystems interact with each other as indicated in the diagram, Figure 5.2. A two-way interaction exists between the geomorphological subsystem and the ecological subsystem, and between the ecological and climatological subsystems. This is to say geomorphological processes influence the distribution of plants and animals across the intertidal slope but there is also a modification of these processes by the flora and fauna. Macro-climatological factors play an important role in selecting those species which are able to survive in a locality. In turn those which do survive affect the micro-climatology in the mangal, which may further influence the establishment of the species. A one-way interaction is indicated between the climatological and geomorphological subsystems; macro-climate influencing the latter's processes. The interactions are all operating within a temporal framework. The potentially complex development that mangals may go through has been effectively illustrated in Bloom's classification for coastlines (Bloom, 1965).

Many of the noted interactions, Figure 5.3, are derived from this study and represent relationships that appear to exist in the

Townsville region. Other interactions are of a more general nature and have a wider application. The macro-climate of a region affects the type and rate of weathering which operates there. In turn the climate affects the erosive processes and their intensities. Through time, this will influence the regional physiography which under some circumstances may affect the off-shore topography. Weathering and erosion affect the input of new material to an area. This in turn affects the type of substratum and the off-shore topography. The latter parameter also modifies the tidal regime and the local wave energy environment. Both these last two factors are also modified by the macro-climate. The local wave energy environment influences the input of new material as well as the amount of material that is transported across the intertidal slope. The type of substratum present will affect the conditions necessary for erosion and deposition to occur. A set of inter-relationships are found between the mangrove physiography and terrestrial influences and the amounts of material that are transported through a mangal and the rate of sediment accretion in the swamp. Under some circumstances fresh water influences play a significance role in the type of material supplied to parts of the swamp.

In addition to the influence of off-shore topography and climatic parameters, the tidal regime may also be affected by local geomorphic influences and the slope of the intertidal surface. Through the tidal regime they affect the frequency of inundation or the degree of tidal exposure experienced by any particular point on the intertidal slope.

Apart from the effect of vegetation physiognomy on the rate of accretion, there are other links between the geomorphological and ecological subsystems. The influx of fresh water and the frequency of inundation influence the soil moisture which can influence the soil forming processes and thus the soil chemical status. The latter variable is also modified by the type of substratum.

Links between the climatic subsystem and the ecological subsystem are quite varied. The microclimate is influenced by both the macro-climate and the vegetation cover. In turn, the micro-climate indirectly affects the soil forming processes via the insolation received at the ground surface and the organism activity. Micro-climate also modifies the ground water and soil water salinity which when hypersaline can be a limiting factor in the type of vegetation present and hence the cover given. Vegetation cover and organism activity influence the input of nutrients which modify the soil chemical status. Variations to the desiccation gradient through a mangal are due to soil moisture and the height of the water table. In turn desiccation affects the vegetation cover as well as the amount of material transported through the swamp.

The three models have therefore attempted to illustrate many of the important interrelationships which exist within the mangals in the Townsville region.. Although there are some similarities between the last model, Figure 5.3, and the holocoenotic complex described by Clarke and Hannon (1969), Figure 1.1, there are important differences. Tidal inundation and soil water salinity form the focus of their model. Whilst recognising the potential influence of soil water salinity, it is not necessarily of prime importance in affecting the distribution of plants within mangals of the Townsville region. The influence of tidal inundation on the soil forming processes has been emphasised as a posssibly more important causal factor in determining the distribution of mangals across this intertidal slope.

What the model does not illustrate is the importance of each component in affecting the overall zonational pattern. The model merely indicates the links which exist between various components. Mangals are treated here as a dynamic community affected by many external and internal factors. A constant response is taking place within the mangals as a result of the changing duration and intensity of imposed stresses within the systems. A time lag exists, however, between the changing intensity and duration of the stresses and the response as witnessed within the mangal.

The overall applicability and versatility of the models can be demonstrated by considering an example from a different location.

Mangals occur along a large extent of the Papua New Guinea coastline. It has been estimated that they may cover over one million hectares (Johnstone, 1978). Until recently there has been little research on the mangals since they have not been considered to be of economic importance with respect to harvesting on a commercial scale. Mangals occur under all climatic conditions experienced in coastal Papua New Guinea, ranging from the humid conditions of the Gulf of Papua to the seasonally dry climate of Port Moresby. It is perhaps appropriate to consider the basis of mangal development in this latter locality since climatically it is similar to Townsville. The major difference is that Port Moresby tends not to suffer from the direct influence of cyclones.

Johnstone (1978) considers that three types of zonation can be found in the mangals near Port Moresby. At Hood Lagoon just over 100km to the south-east there is what is referred to as the classical zonation. Here there is a mixed back zone near the shore with at least 10 species present. Progressively seaward there are zones dominated by *Avicennia "marina"; Ceriops tagal* var. *tagal; Rhizophora apiculata; Bruguiera gymnorrhiza; Rhizophora stylosa; Sonneratia alba;* and *Avicennia "marina."* Johnstone states that the zonation is probably a response to the tidal level since wave action in the lagoon is minimal and there are no significant inflows of fresh water into the lagoon.

The second zonational type is the river estuary with the distribution of the mangroves reflecting conditions such as tidal levels and drainage patterns. The example cited relates to a study by Paijmans and Rollet (1977) on Galley Reach, 50km north-west of Port Moresby. The zonation is divided into a mature mangrove; young mangrove; mangrove transitional to dry land vegetation; and mangrove transitional to fresh water swampland It may also be possible to identify a river bank "zone."

The last category is the open coast. Johnstone suggests that the zonation is in response to tidal level and wave action. This varies depending on whether the substratum is coral or non-coral.

In his brief statement concerning the causes of zonation within the mangal types he identified, Johnstone appears to have underestimated the significance of not only the energy environment within the mangals but also differences which exist between the geomorphology of the various areas. The presence of a river entering the sea may play a significant role in affecting, (i) the type of sediment brought down; (ii) where it is deposited under particular energy conditions; (iii) the distribution of the mangroves in relation to the dynamic nature of such an environment with its continually changing arrangement of dendritic channels (Allen, 1965; Baltzer, 1972; Boye *et al.*, 1975). Thus the geomorphological evolution of the mangals at Hood Lagoon would be relatively simple compared with that at Galley Reach. This is because there is minimal interplay between marine and fluvial forces at the former site. Where such interactions take place a complex picture emerges. This is clearly demonstrated at Galley Reach. Here the channel is bordered by all four zones. This produces a complex pattern of mangal evolution if it can be assumed that the usual sequence of mangroves is from young mangrove to mature mangrove and then to one or other of the transitional communities. Since the salinity values quoted for Galley Reach (Paijmans and Rollet, 1977) are at least two-thirds the concentration of samples taken from the *Rhizophora* zone on Magnetic Island, it suggests that the effect of salinity is less pronounced. Therefote other factors have to be considered when trying to explain the zonational sequence. This is also amply illustrated by the choice of sites to illustrate the open coast (Johnstone, 1978). On Haidana and Buna Motu Islands the number of species present are fewer than at Hood Lagoon and Galley Reach and their distribution is related not only to tidal level but also energy conditions. Since the geomorphology of the islands is relatively simple, sand bank on a coral reef, and a high island with a fringing reef respectively, historical factors may have only a limited influence.

These three examples, together with the data collected from the Townsville area, attest to the individuality of the swamps in terms of their development. Nevertheless certain similarities are expressed between the various sites with respect to the species composition and distribution. The common factors used to explain the distribution of species are water level, energy conditions and soil type. Salinity *per se* does not appear to be as important a controlling parameter as has been suggested in other studies. Marine energy conditions, are important primarily in the colonizing phase (McMillan, 1975) and therefore do not necessarily have any long-term effect, especially where there is an extensive mangal. Consequently one is left with the two factors of water level and sediment type. These have been indirectly incorporated in dynamic models such as those developed by Thom (1967, 1975) and Thom *et al.* (1975) which can be elaborated much further.

The sediment type and distribution in an area is a function of the geomorphological history of that area. This is a phenomenon which is unique to each mangal. However, once colonized and subjected to varying degrees of tidal immersion and emergence a suite of soil chemical reactions is initiated in response to the variable reduction and oxidation conditions. Such phenomena are common to all mangals. This study has shown that there is not a significant zonal relationship between the overlying mangroves and the soluble and exchangeable ions that were measured. This is in direct contrast to results obtained from other parts of the world. Therefore, it may be that other chemical parameters such as exchangeable aluminium, ion, phosphorus, nitrate-nitrogen, ammonia concentrations (Jones, 1972a, b) or other features (Chapman, 1966) are more important. The difficulties of obtaining satisfactory soil samples (Hesse, 1971) are often compounded by the conditions under which they are collected. Consequently it is doubtful whether meaningful results can be obtained from such chemically organically active environments unless sampling is undertaken by a major research programme concentrating on one area.

The models as they have been developed cater both for the individuality and the similarities of the mangals. From a short-term point of view Spenceley (1978) considers that the zonation of mangroves in the Townsville area is a function of the composition of species present and their ability to withstand the environmental stresses imposed across the intertidal slope and inter- and intra-specific competition.

Lugo *et al.* (1975) noted the complex changes that took place in a mangal in the photosynthesis, respiration, transpiration and gross productivity of individual species going from the sea to the land. The changes were suggested, in part, to be related to salinity. However, since environmental controls and requirements may be important controlling influences in species interaction (MacNae, 1968; Clarke and Hannon, 1970, 1971), and the net capacity of individual species to assimilate CO_2 varies between species with higher photosynthetic species requiring less water to produce one gram of dry matter than low photosynthetic species (Black, 1971), the moisture gradient in mangals (Vieillefon, 1969) and the associated soil chemical changes may have an importance that has not been fully recognised.

When considering the long-term causes of mangal development and the zonation of species within the mangal, both specific and generalised factors have to be taken into account. The results of this and other studies suggest that the most important parameters are:

(i) The available species pool.
(ii) The geomorphological history of the individual mangal.
(iii) The soil type and conditions with particular reference to the effect of a changing oxidation/reduction environment.
(iv) The controls in (iii) will have an increased effect on normal interspecific competitions.

The factors of prime importance will vary between mangals since an innumerable set of interactions are possible in response to the prevailing conditions. This will evoke a variety of reactions which are visible by the extent of the mangal and the distribution of species within the swamp.

CHAPTER SIX

GEOMORPHOLOGICAL AND ZONATIONAL DEVELOPMENT OF MANGALS, TOWNSVILLE REGION, NORTH QUEENSLAND: SUMMARY AND CONCLUSIONS

The present study has confirmed the complex nature of mangals. In particular it has highlighted the two-way interaction between the sediment, its physical and chemical characteristics, and the plant zonation within the mangals. This is most clearly demonstrated on Magnetic Island, since that was the site that was most intensively sampled. However, each of the other sites, Saunders Beach and Orpheus Island, provides significant additional information which reinforces conclusions reached from the evidence on Magnetic Island.

The pneumatophore experiment clearly demonstrated that, contrary to the much quoted idea, mangroves do not necessarily provide or create quiet conditions which allow material to fall out of suspension. Nor do mangroves actively trap sediment under normal conditions. Depending on the prevailing marine energy conditions, density of prop roots or pneumatophores, either localised scour or erosion might take place. For a grid of 6mm diameter metal rods, intense erosion may occur when the spacing between the rods is 5cm or less. A 10cm grid size did not undergo excessive erosion or deposition at any time. However, when conditions are suitable for deposition of material, the mangrove appendages probably assist the process by hindering water flow.

Greatest variations in erosion or deposition occur in the *Rhizophora* or creekward zones of the mangals and generally decline inland with an increase in height of the sediment surface. Often an increase is seen at the highest stations which are present on the upper intertidal slope within the bare salt flat, samphire or *Ceriops* zones. On a monthly basis the erosional and depositional sequences along a transect on Magnetic Island are unclear. However, if the data are amalgamated into three monthly units, the transect appears to undergo an alternate sequence of erosion and deposition with a net erosion during the period of observations. Such trends are not apparent at Saunders Beach or at Orpheus Island. At the former site net deposition is taking place whilst the latter site displays highly dynamic characteristics.

On Orpheus Island large variations in erosion and deposition occurred during two tidal cycles. However, since the mangal remains as a viable unit, a limiting factor must be present to restrict erosion. Under low to medium energy conditions erosion seems to be limited by the depth at which mechanical binding of the soil particles by fine rootlets takes place or alternatively the depth at which cohesion between sediment particles is enhanced by electrolytic attraction associated with plant root activities. Thus at Orpheus Island the upper sediment layer is able to move freely about the mangal. The physical role mangroves seem to play is that of stabilising the sediment, reducing losses in high energy conditions to a minimum. The surface is gradually raised when newly deposited sediment is bound by fresh growth of fine rootlets.

The increased activity that takes place on the upper intertidal slope is due to a number of factors. Movement of larger particles found in this part of the mangal on Magnetic Island has a greater impact on the results than movement of clay sized particles. The *Ceriops* zone on Magnetic Island is often subjected to overland flow and erosion in the wet season. The *Ceriops* zones are also usually emerged from tidal waters for long periods during the tidal cycles. Intercepted rain water may therefore flow down the tree trunks and become concentrated between the buttress roots, initiating local scour at the base of the tree. Alternatively, before reaching the ground, water drips from the tree trunk concentrating its energy on one particular spot. This eventually results in erosion.

A further reason is suggested from the bedload data. Variations in the bedload data essentially mirror the variations in the accretion rates. Greatest amounts are trapped in the seaward or creekward stations, declining inland. However, at both the Magnetic

Island and Saunders Beach sites an increase in amounts transported, in absolute terms and with respect to load per unit time covered, takes place at stations located at an elevation above the bare salt flats at approximately mean high water spring tides. Such a situation is also present in the landward *Ceriops* zone on the second transect at Saunders Beach. This feature is attributed to either local wind generated waves increasing turbulence and resuspending material or to the wavelet which forms the leading edge of tidal waters. The latter process is probably more applicable to the conditions in the mangals studied.

The influence that mangroves have on the average rate of accretion is clearly indicated by data relating to the evolution of the Magnetic Island swamp. Between about 7500 and 7000 C14 years BP conditions were suitable for mangroves to establish themselves. The mangal survived for a short period before it was destroyed. Prior to mangroves re-establishing themselves on the Island, from approximately 7230 to 1620 C14 years BP, there was an average sedimentation rate of about 30.3mm/100 years. Once mangroves recolonized, the average rate of sedimentation increased to 129mm/ 100 years until about 690 C14 years BP. From then until the present time the average sedimentation rate decreased to 36mm/100 years. Thus since it is unlikely that there has been an increase in the supply of sediment, the onset of mangrove recolonozation is probably accompanied by an increased stability of the intertidal slope. That is, more material is bound by mangrove rootlets, thereby restricting the resuspension of sediment. Contemporary processes suggest that the seaward section of the swamps, which is generally dominated by *Rhizophora* spp., possesses the greatest accretion rates. Assuming similar processes were operating in the past, the C14 evidence indicates that as the mangrove swamp extends across the intertidal slope, the area of maximum sedimentation shifts seaward. Since more material is fixed in position in this locality, less is available to be transported landward. Hence accretion rates decrease appreciably in the inner swamp.

Not only can it be seen that the rate and extent of marine processes across the intertidal slope are functions of the extent and type of mangrove cover, but the mangrove species distribution is also affected by the characteristics of the intertidal slope surface. Mangroves appear to require a certain depth of water before colonization can take place. The depth of water apparently varies between localities. In the Townsville area the probable complete zonational seqyence is, from sea to land:

(i) a narrow *Avicennia/Sonneratia* fringing strip which is replaced by a mixed mangrove community on the lower creek banks;

(ii) a *Rhizophora* forest with some *Bruguiera* trees;

(iii) a *Ceriops* forest with a variety of other genera, e.g. *Osbornia, Xylocarpus, Laguncularia* and *Avicennia,* on the landward fringe.

In the local area the most common variation is the presence of bare saline flats either within a zone or at the landward edge of the swamp. Evidence produced in this study coupled with data from the literature indicate that there are two major types of salt flats which are differentiated according to their origins. Relict flats are areas that have been abandoned by a relative fall in sea-level. Contemporary flats, however, have been formed since sea-level reached its present position. Two sub-divisions have been designated, the long-term and the short-term development flats. The former set are formed in areas of rapid sedimentation. Mangroves at the back of the swamp become progressively distant from a water supply for periods of the year and die out because of the induced drought conditions. Short-term flats can be caused by destructive influences such as cyclones. The break in the canopy layer allows greater insolation to reach the ground. This results in an increase in evaporation which induces hypersaline conditions to develop. In turn this tends to inhibit plant regeneration. Samphires may grow on the edges of salt pans.

The problems associated with the salt flat development are indicative of the complications relating to the causes of zonation within the mangals. A basic similarity in zonation has been recognised at Saunders Beach and on Magnetic Island. However, the more readily accepted factors affecting zonation, such as height of the land surface, ground water salinity and frequency of tidal inundation, cannot satisfactorily explain the zonation in the swamps. No common factor could be identified. The altitudinal extent of the various zones differs between the two swamps. Ground water salinity values are found to be related as much to the extent and type of vegetation cover as to the height of the land surface.

When data from all the zones on Magnetic Island are included in a multiple regression analysis, only 35.6% of the variance could be explained in terms of distance landward, height of the ground and the degree of exposure between sampling periods. With the inner *Ceriops* and *Arthrocnemum/Avicennia* zones omitted, 90.37% of the variance is explained by the designated variables. Although the degree of exposure is a statistically significant variable it plays a minor role in explaining the variance. Precipitation is not found to be a significant variable in either analysis.

Although species zonation appears to be associated with a variation in frequency of inundation, the precise relationship is more obscure. With an increase in the frequency and extent of emergence, soil forming processes change from reducing to oxidizing processes. Variations in the chemical variables that were measured indicate that the two swamps belong to two different environments. Spatial trends are displayed within the data. However the data from Magnetic Island display little seasonal variation, whilst most elements at Saunders Beach display large seasonal fluctuations. Low values are experienced in the wet season and high values in the dry season.

Statistical analysis of the data by factor analysis indicates a certain similarity between the results for Magnetic Island and Saunders Beach. In both sets of analyses the first two factors are a salt and a pH factor, explaining just over 50% of the covariance. Another 30% is explained in terms of a variety of other factors, leaving almost 20% of the covariance unexplained. Despite this similarity, a lack of association between the zones is revealed by the discriminant analysis. On Magnetic Island an association is indicated between the two *Arthrocnemum* zones, salt flat, *Sesuvium/Avicennia* and seaward *Ceriops* zones on the upper intertidal slope; and between the *Avicennia/Sonneratia* fringe and the lower intertidal slope. No other associations are indicated even within the *Rhizophora* zone. At Saunders Beach a similarity exists between the mixed creek bank community, the two *Ceriops* zones and the *Sporobolus virginicus* zone, transect 1; and between the mixed creek bank community and the *Ceriops* zone, transect 2. In part this is a function of the different evolutionary histories of the two areas. The core profiles indicate that each mangal is unique in this respect.

The temporal aspect has been incorporated into a generalised model of mangal development. The main interactions for the Townsville mangals have been incorporated into the model, together with others suggested from the literature. The initial limiting conditions to the species pattern in mangals is considered to be primarily controlled by the geomorphological evolution and the species pool that is available. Once established, the species distribution reflects the interaction between species along a continuum of environmental conditions from the sea or creek inland. It must be remembered that the mangroves grow in a dynamic environment, consequently there is a constant readjustment taking place between the plants and the land surface. However, a time lag exists between the changing environmental conditions and the response being indicated by the distribution of species.

Conclusions

This study has been concerned with the dynamic relationships which exist between mangroves and processes operating on the intertidal slope and high tidal flat. A number of questions were posed in the first chapter concerning:

(i) factors that influence mangrove zonation;
(ii) the role mangroves play in the sedimentary processes operating on the intertidal slope; and
(iii) the evolutionary history of the mangals.

More specific questions were asked, in amplification of the first question, concerning the relationship between the soil and its overlying vegetation.

(i) The vegetation/soil relationship is not as clearly defined as suggested by Navalkar and Bharucha (1950). The two types of coast studied produce contrasting trends in the soil chemical variables that were analysed. The chemical data from an open accreting coastline, Magnetic Island, displays a marked spatial trend but, on the whole, a lack of seasonality in the results. A seasonal trend is present for the water soluble chloride but this is primarily confined to the inner margins of the mangal and is related to the type of vegetation cover and the influence of ground water seepage of fresh water from the adjacent higher area. Marked spatial and seasonal trends are present in the data from an estuarine coastline, at Saunders Beach. This is related to the seasonal fresh water flow from Althaus Creek.

(ii) Although there is a basic similarity between the zonations along the transects studied, each zone is found at a different height and hence has a different tidal inundation frequency and duration of emergence from tidal waters. Nevertheless, using factor analysis over 50% of the covariance of the soil chemical data from the two sites can be explained in terms of a salt and a pH factor. The discriminant analyses indicate those zones which are chemically similar to each other. Although zones on the upper intertidal slope on Magnetic Island are grouped together, a similar association is not present at Saunders Beach. On Magnetic Island stations within the *Rhizophora* zone are not related to each other, nor are those within the *Ceriops* zone. However, stations within the *Ceriops* zones at Saunders Beach are related to each other. Thus groupings recognised along each transect are different from each other. Consequently the soil chemical variables that were measured cannot adequately explain the vegetation pattern displayed in the mangals.

(iii) Salt flats are not necessarily part of the "normal" zonational pattern in seasonally dry areas. Two types of flats, relict and contemporary, may be identified. Relict flats are caused by a relative lowering of sea level. Contemporary flats result from a break in the vegetation canopy rather than being a cause of such a break.

(iv) The relationship between mangroves and the sedimentary processes operating on the intertidal slope and high tidal flat is complex. Amount of sediment trapped per unit of time covered is greatest in the seaward or creekward zones, generally declining landward to the salt flat or approximately mean high water spring tide. Further landward there is an increase in the amounts trapped per unit time covered. This is probably related to the influence of the rippling wavelet at the leading edge of tidal waters.

(v) Concomitant with variations in bed load are changes in the rate and amount of accretion. Greatest fluctuations in erosion and deposition occur in the seaward or creekward vegetation zones. These decrease in intensity inland. Variations increase again on levels covered by vegetation above mean high water spring tides.

(vi) Mangroves do not necessarily create quiescent conditions suitable for sediment deposition. Pneumatophores and prop roots can create localised turbulent conditions which initiate scour in their immediate vicinity. Under certain circumstances mangroves may concentrate intercepted rainfall between buttress roots either by trunk flow or water dripping off the trunk, thereby eroding the sediment. Overland flow from the adjacent terrestrial environment can play an important subsidiary role in the landward portion of the mangal. Mangroves, however, remain viable even in a fairly dynamic environment.

(vii) The role mangroves play is one of binding the soil and protecting the coastline. They act as a buffer to the occasionally imposed high energy conditions, thereby limiting erosion. Data from the transects suggest that the mangal on Magnetic Island is undergoing a period of erosion, whilst that at Saunders Beach is undergoing deposition.

(viii) The evolutionary history of the swamps has been described. The most complete sequence of development is recorded for Magnetic Island, relating mangal development to the prevailing sea level conditions. It is apparent that each mangal has a unique evolutionary history.

(ix) A model of mangal development has been suggested. The main interactions within the Townsville mangals have been illustrated. The primary role of mangal evolution and species pool available on the contemporary pattern of species distribution are considered. Each mangal has a different evolution. It has also a different set of species available for colonization at any particular time. Hence each mangal develops a unique vegetation pattern in response to the continually changing environmental conditions.

LIST OF SPECIES

AIZOACEAE

Sesuvium portulacastrum L.

CHENOPODIACEAE

Arthrocnemum halocnemoides Nees var. *pergranulatum* J.M. Black

A. leiostachyum Benth. Paulsen

Suaeda maritima L.

EUPHORBIACEAE

Exoecaria agollocha L.

MELIACEAE

Xylocarpus australisicum Ridl.

X. granatum Koen.

MYRTACAE

Osbornia octodonta F.v.M.

SONNERATIA

Sonneratia alba J.E. Smith

RHIZOPHORACEAE

Bruguiera exaristata Ding Hou

B. gymnorrhiza (L.) Lamk.

Ceriops tagal (Perr.) C.B. Rob.

Rhizophora lamarkii Montr.

R. stylosa Griff.

COMBRETACEAE

Lumnitzera racemosa Willd.

MYRSINACEAE

Aegiceras corniculatum (L.) Blanco.

PLUMBAGINACEAE

Aegialitis annulata R. Br.

RUBIACEAE

Scyphiphora hydrophyllacea Gaertn.

VERBENACEAE

Avicennia eucalyptifolia Zip ex Miq.

POACEAE

Sporobolus virginicus L.

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