# HOLOCENE SEA LEVEL RECORD OF TONGATAPU, KINGDOM OF TONGA, FROM POLLEN ANALYSIS OF MANGROVE SEDIMENTS.

by

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From Pollen Analysis of Mangrove Sediments

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# ABSTRACT

Many Holocene sea level studies are imprecise owing to use of fossil sea level indicators that have a broad relationship with mean sea level, and lack of quantitative determination of this relationship from the present day environment. This study assesses the sea level record available from pollen analysis of mangrove sediments, from Tongatapu, Kingdom of Tonga, in the S.W. Pacific. Surface samples were taken across a transect in the largest swamp, on the fringes of the Fanga 'Uta Lagoon at Folaha, to show pollen assemblages representative of the mangrove species zonations that occur at different elevations. Eleven cores were pulled on this transect, and seven from other mangrove areas on Tongatapu to show stratigraphy related to sea level changes during the Holocene. Pollen analysis was carried out on two mangrove peat units, using elevations of the modern analogue surface samples to give a high resolution sea level reconstruction for these periods.

Early Holocene sea level rise is shown, with calcitic mud of terrestrial pedogenic origins being encroached on by mangroves. This lower mangrove peat shows that a large mangrove forest existed at the Folaha site broadly from 7000 to 5500 radiocarbon years before present (BP), and pollen analysis shows that sea level rose during this period at a rate of 12 cm/100 years. This early mangrove forest has no known equivalent in the islands of the Pacific, attributable to the sheltered conditions at Folaha. A mid-Holocene highstand of sea level is shown by presence of lagoon sediments at the site, estimated between 4500 and 2500 years BP, before sea level fell towards present levels. A more recent sea level fall of less than 50 cm allowed mangroves to again occupy the area. Pollen analysis of these upper peats shows a sudden shift of zonations that indicates a tectonic event, and alien pollen present and review of early charts of the lagoon identify an earthquake in 1853 as the cause.

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## The Origin of Features of the Tongatabu Lagoon

This story is about the fish of the Tui Tonga Fatafehi in Nukuhitulu, who had premises named Keafata. At that place lived two old priestesses. The names of these two priestesses were Hava and Ila.

The two old women went shellfishing for the meal of the Tui Tonga. Hava returned with her basket full of fish, but Ila came with white crabs and various other crabs. The Tui Tonga, however, wished for fish. Hava only had fish and Ila had no fish. Hence they again went shellfishing on that afternoon. Ila went along one shore and Hava went along the opposite shore.

As evening came on Hava put her torch on a mangrove tree to burn there, while she went to a cave. There she pushed aside a big stone and placed her basket under the opening. Mullet dropped from the opening into her basket until it was full. The she promptly closed the opening with the big stone.

While Hava was doing this, Ila, who had also left her torch burning on a mangrove tree, was standing close by watching her. Hava, however, thought that Ila was still fishing on the opposite shore. Then Hava went on her way, gathering shellfish along the shore. Ila now went to the cave, pulled the large stone aside for the mullet to pour out, and filled her basket. Then Ila went away, but did not close the opening of the cave. Therefore, the fish poured out, making a sound like thunder in their exit. Hava heard the noise made by her escaping fish. She hastened back to the cave, but found the entrance open and the fish gone.

The name of the cave was Lokofa, and it was situated on the island of Nuku. Upon finding her school of mullet gone, Hava pulled forward the island of Mokohunu, and she also pulled forward the island of Kanatea (in the bay of Pea, Tongatabu) to block her escaping fish, but it was too late for they had gone. Then she ran and pulled forward Lokupo and also pulled forward Nukuhua to stop her fish. This, too, was without effect. Again she hastened forward and pulled forward Kaunga and also Houmaniu, but it was useless. Still she hurried on and pulled forth Fonuaeiki and she also pulled forth Angina, but without avail, for she could not halt the fish. Next she pulled forward Toa and at the same time she pulled forth Faihavata, yet she could not head off the fish. She again ran forward and tried to block the fleeing fish by placing Muihaaloausi and also Umusi in their path. Onca again she tried to head them off by placing Mataaho and shouted to Nukunukumotu and Fasia, which are situated in the passage connecting the great lagoon of Tongatabu with the ocean. She called upon these islands to stop her fish, but in vain.

In her chagrin, Hava jumped into the lagoon at Palalafa and turned herself into a stone. When Ila realised that she had done wrong in so carelessly releasing the fish, she threw her basket of fish away. Then she ran forth, jumped into the lagoon near Hava and, like her, turned into a stone. They are both still standing in the passage at Palalafa. When the mullet leave the lagoon of Tongatabu they go aground, while one small fish leaps the barrier and obtains permission at Lokofa for the school to depart. When the messenger returns the school of mullet can pass on their way. This habit is still continued by the mullet, the fish of Hava.

A Tongan myth, translated by Sione Tupou,
given in Gifford (1924, p.95-6).

# CHAPTER 1: PROBLEM DEFINITION AND LITERATURE REVIEW.

## 1.1 Introduction.

Polynesia was so named by James Kelly in 1824, meaning "many islands". Located to the east of Wallace's line (Wallace 1880), these islands are oceanic throughout geologic history, the absence of land bridges causing depauperate floras and faunas (Usinger 1963).

Pacific islands have been regarded by many as "graduated measuring rods that record their own movement or shifts in the level of the sea around them" (Ladd 1962). They have even been viewed as the best place to study eustatic fluctuations in sea level, uncomplicated by factors of isostatic downwarping experienced on continental coasts (Bloom 1967, 1970; Walcott 1972; Nunn 1987a).

A great many sea level studies have been, and continue to be carried out on the shorelines of small Pacific islands. This dissertation reviews the record of Holocene sea level change established for the South West Pacific, and critically evaluates the accuracy and resolution of techniques employed. The Holocene sea level record of Tongatapu, Tonga is then examined from lagoon and mangrove stratigraphy, and the record available from mangrove peat is refined by the technique of pollen analysis. Environmental advantages of the Tonga location, as described in Chapter 2, enable the contribution of this technique to sea level studies, as established by Grindrod (1983, 1985) to be assessed.

## 1.2 Holocene sea level in the region.

Changes in sea level can result from variation in the volume of ocean water (eustatic change) or tectonic movement of the land or ocean floor (isostatic change). Periods of rapid eustatic change cause lithospheric adjustments to redistribution of weight of ice (glacioisostatic change) or water (hydroisostatic change), and separation of these factors involved in sea level change over these periods requires complex correlation of different indicators and sites (Farrell & Clark 1975, Shennan et al. 1983). Holocene sea level change in the south- west Pacific region can be attributed to three factors: post-glacial eustatic rise, mid- Holocene hydroisostatic adjustment of the Pacific basin to this rise, and local tectonic movements.

## Post-glacial eustatic rise.

During the last glacial maximum, sea levels in the east Australia area were at a level of around 130 m below present in the period 20 000 to 15 000 BP (before present) (Chappell 1974). With the onset of the Holocene, around 10 000 BP, sea levels were some 40 to 70 m below present in the south- west Pacific (Nunn 1987b).Rates of sea level rise during the glacial collapse and early Holocene were extremely rapid. By 9400 BP sea levels had reached 22 m below present in New Zealand (Suggate 1968), and -17 m by 8000 BP.

The causative climatic changes of the time are shown more directly on the mountains of the region. The ice cap disappeared from Mauna Kea 9080 BP (Porter 1979). In New Guinea, the Sirunki pollen diagram from a swamp at 2500 m shows vegetation change from fern woodland, sedge and grasslands of a cooler climate to rainforest between 9000 and 8000 BP (Flenley 1979). In north- east Queensland, the Lynch's Crater pollen diagram from a crater lake at 760 m shows change from *Eucalyptus* /*Casuarina* forest 9000 BP to full rainforest by 8000 BP (Kershaw 1976).

## Mid-Holocene sea levels and hydroisostatic adjustments.

A sea level curve is a time/ depth diagram derived from isotopic dating of some deposit that has a relationship with sea level. With the discovery of the $^{14}$C dating method, a world wide search was initiated for a curve of global relevance, with the assumption that the interconnected oceans would share a common history (Kidson 1982). In the Pacific, Holocene studies of the 1960's and early 1970's grouped in support of either the Shepard (1963) model, arguing that the post- glacial rise was continuous, at a rate diminishing in time to the present day, or the Fairbridge (1961) model, arguing that the rise was spasmodic and inclusive of stands higher than present.

A continuous steady rise in sea level to stability at present levels was identified in Europe (Jelgersma 1961, 1966) and the Caribbean (Scholl 1963, 1964), and found support in the Pacific principally from the CARMASEL expedition to Micronesia (Shepard et al 1967; Curray et al 1970; Newell & Bloom 1970; Bloom 1970). In the mid- 1970's such global comparisons were shown to be invalid, with the recognition of the role of hydroisostatic deformation in altering regional sea level(Walcott 1972, Chappell 1974). In Australia, sea level was at present levels around 6000 BP, considerably earlier than the Atlantic, which was still rising before 3700 BP, and these major differences were attributed to isostatic processes (Thom & Chappell 1975).

Ideas of a spasmodic rise were supported by studies on temperate shorelines where glacio- isostatic rebound was a component of Holocene sea level change (Tooley 1974, 1982, Shennan 1982). Sea level stands identified higher than the present lent credence to the possibility of a climatic optimum in the early to mid-Holocene (Cranwell & Von Post 1936, Morner 1969). Raised shoreline features of some 2 to 3 m had long been noticed on Pacific islands (Sollas 1904, Ladd & Hoffmeister 1927, Ladd 1962), and later empirical dating of different raised indicators of sea level accumulated a great weight of support for a mid- Holocene highstand in the south- west Pacific (Schofield 1960, 1964, 1977a, Coudray & Delibrius 1972, Buddemeier et al. 1975, Sugimura et al. 1983, Bourrouilh 1985, Pirazzoli et al. 1985, Pirazzoli & Montaggioni 1986, and Scoffin et al. 1985). Data from these sources are presented in Figure 1, showing a general trend for the highstand to increase in magnitude from the equator south. However, caution in comparisons is necessary owing to different sea level indicators used, different expressions of height of these above present sea level, and errors of dating. These will be expanded in the next section 'Evidence of sea level' to point out improvements in the accurate measurement of past sea levels offered by this thesis.

The mid-Holocene highstand of sea level in the south- west Pacific has been attributed to hydro-isostatic factors. Isostatic adjustment between the crust and the asthenosphere to a eustatically rising sea result in ocean basin depression, as sub-Pacific plates subside in the asthenosphere beneath the increased weight of water. This causes mid- oceanic islands to experience a slight fall in sea level in post- glacial time (Walcott 1972, Chappell 1974).

### Local tectonic movements.

Eustatic or hydro- isostatic components of sea level change in the south- west Pacific can be masked by local tectonic movements. While areas with longterm, steady rates of uplift such as the Huon Peninsula, Papua New Guinea (Bloom et al. 1974, Chappell & Polach 1976, Neef & Veeh 1977), can be used to record eustatic and hydro- isostatic change, other islands move more sporadically. Taylor et al. (1980, 1981) record uplift of the north part of Malekula Island, New Hebrides from a sequence of thrusting- type earthquakes in 1965. Differential degree of movement of semi- independent morphotectonic blocks caused the maximum uplift of 1 m to be quite localised, contouring to 0 m uplift within a 30 km radius. Doyle et al. (1979) record uplift rates of islands in the Southern Kermadec group of 10 cm/year for the last 190 years, from radiocarbon dating

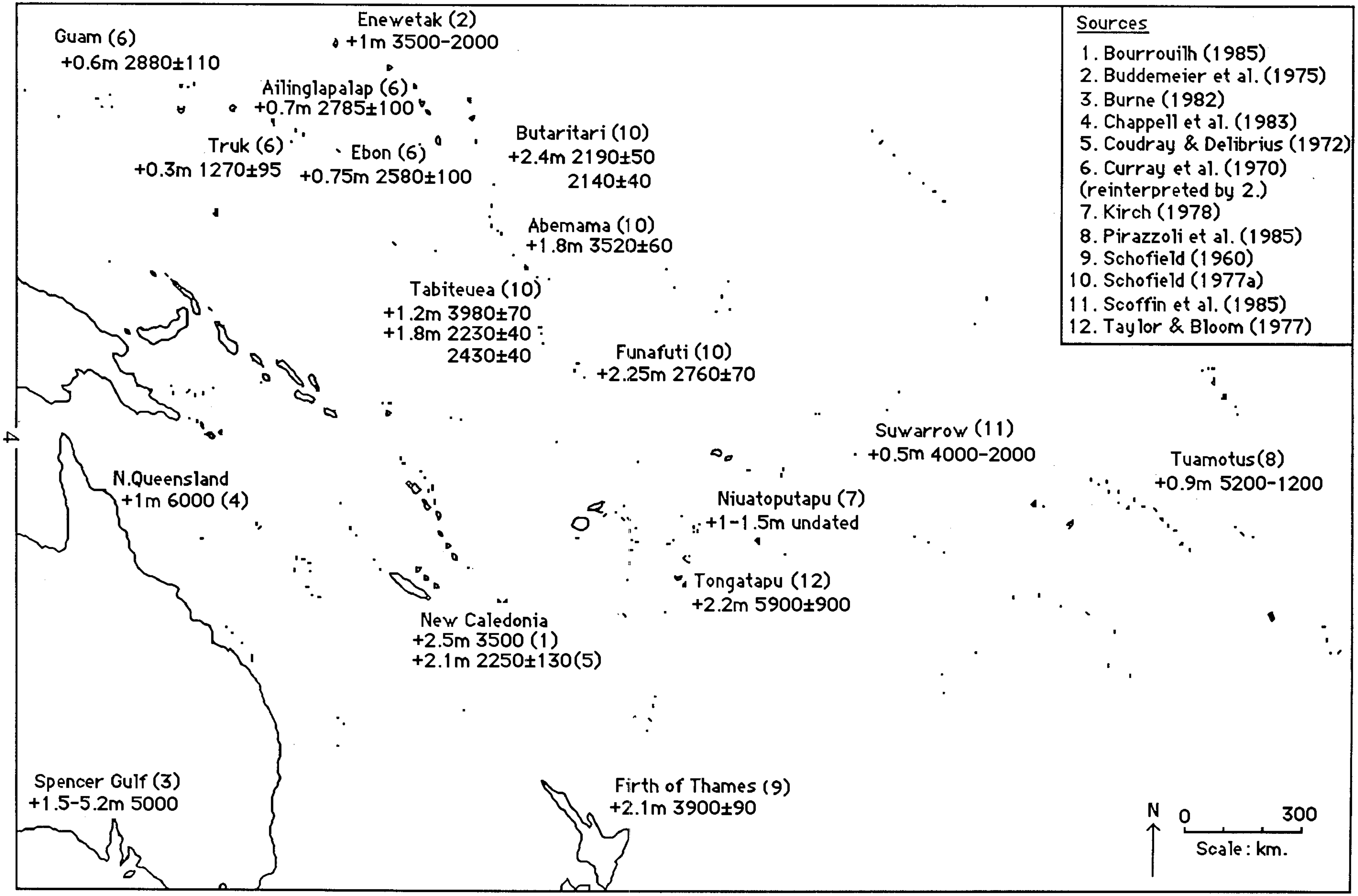


Figure 1 : Mid-Holocene sea level in the S.W. Pacific (height above present MSL, years BP).

barnacles on a terrace 18 m above present sea level. Schofield (1981) records a 3.5 m recent uplift of Raoul Island, Kermadec, though this is contested by Anderson (1987). Tonga is located on the same tectonically active frontal island arc as the Kermadec group, and tectonic movements there are discussed in later sections. Erratic tectonic uplifts are most noticeable in more recent times, and it would seem that such movements apparent in the late Holocene become averaged in the longer term record (Bloom & Yonekura 1985).

## 1.3 Evidence of sea level.

The level of the surface of the sea is not a constant reference plane, but rather is statistically defined. Hence different workers use mean sea level (Schofield 1977a), or mean low water (Curray et al. 1970), or lowest low water (Buddemeier 1975) as a datum plane, or do not indicate it at all. Both the present and past reference points should be clearly defined.

Evidence of sea level is some feature, erosional or depositional, abiotic or biotic, that formed during a period it was when under the influence of intertidal processes. Sources of most use in indicating past sea levels are features where this relationship with the intertidal zone can be empirically calibrated from a modern analogue, and when some material can provide a date related to the time at which the sea level was in that position.

Erosional features such as notches and wave-cut platforms are visually convincing remnants of a former sea level. However, the relationship with mean sea level (MSL) will vary according to the dominant process of formation. Wetting and drying processes are most powerful mid- intertidal, while abrasion is at a maximum in the lower shore zone (Trudgill 1985). Intensity of action of intertidal bio-eroders may vary with predator pressure (Underwood 1978), and notch symmetry is a function of the presence or absence of sand (Trudgill 1976). Hence the correspondence of notch vertex with former MSL (Pirazzoli et al. 1985, Pirazzoli and Montaggioni 1986) must be established, not assumed. Attempts to date such erosional features are few, and the technique is complex (Bourrouilh 1985).

Coral reefs are widely used to date sea levels by $^{14}C$ or $^{230}Th/^{234}U$ isotopic methods. The vertical growth of reef coral is usually limited by mean low water spring level (Pirazzoli and Montaggioni 1986), though the survival ceiling varies between species (Taylor et al. 1981). Below this limiting elevation, coral specimens can grow within a wide range of depths, for example 0 to -20 m for *Porites lobata* in the Tuamotus (Faure and Laboute 1984, Pirazzoli and Montaggioni 1986). Consequently, raised dead coral can date a higher sea level (Scoffin et al. 1985), but the actual height of the sea surface is difficult to determine. Few go to the lengths of Taylor et al. (1980, 1981), using relative elevations of live and dead individuals of each species to establish the degree of sea level fall. Sea level results not taking such variations into account cannot provide accurate information on the position of former sea levels, but must still be regarded as directional sea level criteria of some value (Pirazzoli and Montaggioni 1986).

Reef growth results from three constituent phases of coral growth, storm fragmentation and algal cementation to provide a higher surface for new coral growth. Hence the time of death of reef material at the same depth will differ, resulting in care taken to select "coral in growth position" for sea level related isotopic dating. This may yield a younger date if recrystallized with exposure to fresh water (Chappell et al. 1978). Reefs may grow to "catch up" with a rising sea level and so bear a poor stratigraphic relationship with past levels, or may "keep up" with the sea level and so bear better evidence (Neumann and Macintyre 1985). Most reefs are of the former type (Pirazzoli and Montaggioni 1986). Reef cores may encounter irregular reef stratigraphy from previous lateral growth or slumping, that may even result in inversions or duplications of dates with depth (Pirazzoli and Montaggioni 1986).

Intertidal deposition occurs during a sea level fall, material being moved onshore as active current areas are deepened to the new equilibrium (Bruun 1962, Schwartz 1968). By this principle, beach ridges in the south- west Pacific have been taken as evidence for a late Holocene sea level fall (Schofield 1960, 1964, 1967a, 1973, 1975a, 1975b, 1977a, 1977b). Schofield (1977a) used raised beach deposits to date a maximum stand of +2.4 m, 2760 radiocarbon years BP in the Gilbert and Ellice Islands. Curray et al. (1970) dated similar deposits in the Caroline and Marshall Islands, though interpreted them as evidence of stormier conditions 3000 to 2500 years BP as opposed to a higher sea level, owing to a "high energy window" as described by Hopley (1984). Buddemeier et al. (1975) reinterpreted these dates as a higher sea level, with confirming evidence from dating of reef materials on Enewetok.

Kidson (1982) criticised the use of transported debris, such as marine shells to date Holocene sea levels above that of present. Mobile carbonate material could have been reworked or rejuvenated by contamination, resulting in dubious $^{14}$C ages and erroneous sea level indications (Geyh et al. 1979).

The only wholly reliable sea level indicators are organic remains in growth position where relationships to sea level can be determined within acceptable limits (Kidson 1982). While coral reefs give a general indication that contributes to knowledge of Pleistocene sea levels, it is shown that for detail in the Recent period individual species must be examined. This is also true for use of mangrove peat as a sea level indicator, reviewed in the next section, "mangroves and sea level". This peat forms within the intertidal range, enabling greater accuracy of calibration against statistical sea level than coral reefs. Further refinement of the sea level record can be obtained by establishing which mangrove species were contributing to peat formation, by examining the pollen record contained.

## 1.4 Mangroves and sea level.

Mangroves are a taxonomically diverse group of tropical tree species that grow in the upper intertidal zone of sheltered shores. Mangrove species show high fidelity to a particular habitat, owing to special physiological and morphological adaptations to a stressful environment. Mangrove species are rarely found outside the intertidal area, and mostly occur between mean sea level and mean high water spring tide (Lear and Turner 1977, Belperio 1979).

Mangrove peat formation results from vegetative detritus accumulating beneath the trees. Mangrove peat also contains faunal remains and allochthonous inorganic and organic matter brought in by the tides. Its formation within the upper half of the tidal range renders it a useful sea level indicator (Scholl 1963). In Townsville, Queensland, for example, modern mangrove deposits occur from 1.5 to 3.0 m in a tidal spectrum which varies from 0 to 3.8 m above tidal datum. Ancient mangrove deposits therefore provide an indication of mean tide level within ±1 m (Belperio 1979).

### Species zonation.

Species zonation in a mangrove community is the formation of different assemblage units from sea to land. This phenomenon has been extensively catalogued and commented upon, forming a literature exceeding 7000 titles (Snedaker 1982). Classic works are Davis (1940) and Chapman (1970, 1976), and Fosberg (1947) and Macnae (1968) in the south-west Pacific. More recent assessments from Australia have included Jones (1971), Bunt & Williams (1981), Bunt et al. (1982, 1985) and Semeniuk (1985). This zonation is caused by differential ecological performance of individual species across environmental gradients of frequency of inundation, salinity and waterlogging of the soil.

Two schools of thought have developed on the significance of zonation to community dynamics over time. The successional model envisages zonations as Clementsian seral stages to a high ground climax, a temporal sequence induced by the plants themselves

(Davis 1940, Chapman 1976). The opportunistic model explains zonation as a response to external geomorphological conditions, species colonising their preferred sites within the elevational range (Thom 1967). The opportunistic model is also supported by evidence of tidal sorting of propagules according to size and flotation ability, resulting in seedling germination at different elevations to give species zonation (Rabinowitz 1978a, 1978b).

In both models, zonation is a function of the inherent capabilities of each species to perform at different elevations. As stated by Snedaker (1982), the whole basis of the successional argument seems to hinge on the ability of *Rhizophora mangle* to build and colonize new land (i.e. primary succession) by trapping water- borne debris within its arching prop root system.

### Mangrove pollen.

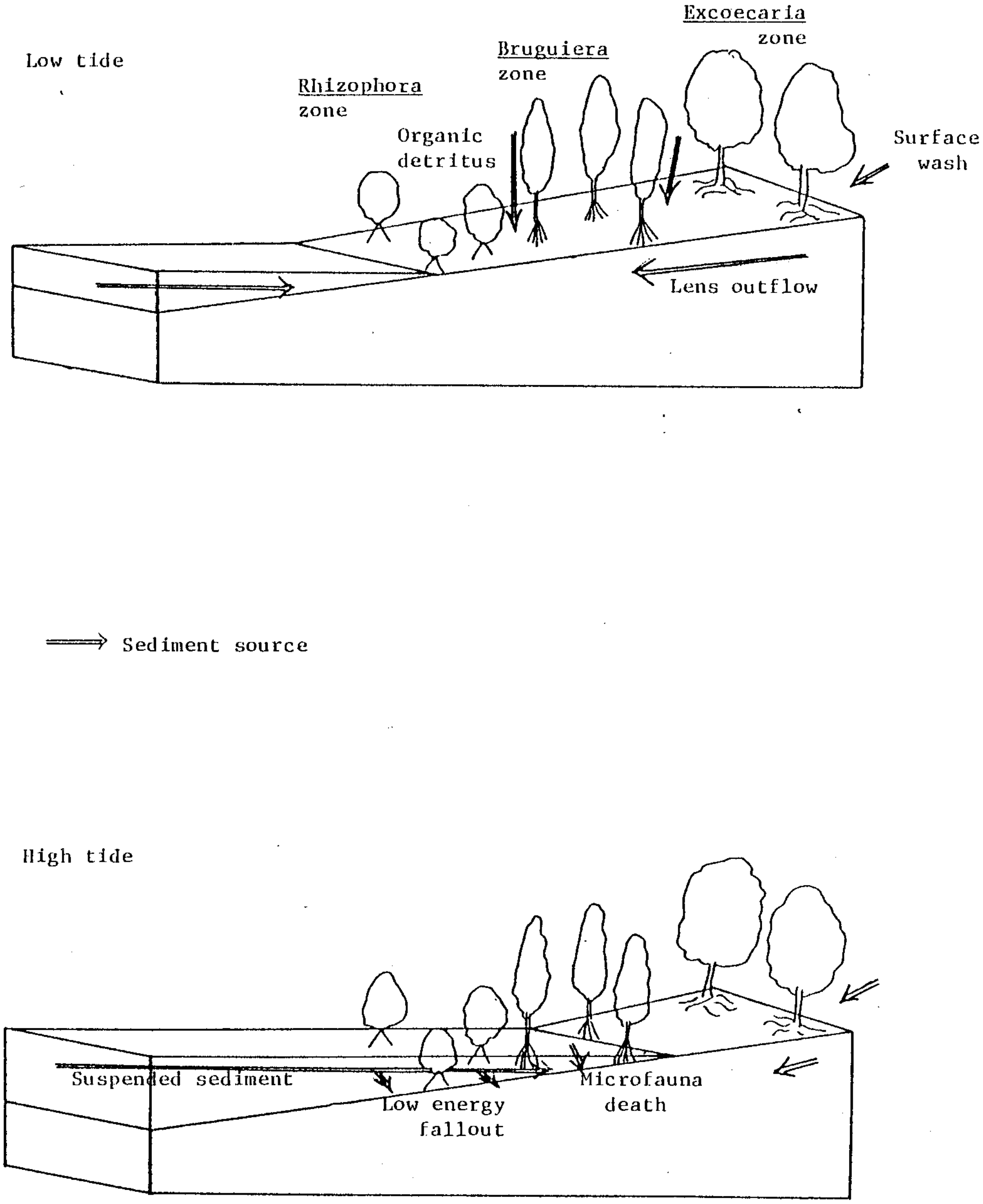
Zonation of mangrove species gives potential for the sea level record from mangrove peat to be refined by pollen analysis. If patterns of pollen deposition are congruent with zonation of the plants, and a time/ depth relationship of fossil assemblages is maintained by macro- organic and abiotic sedimentation as shown in Figure 2, then a sea level interpretation is possible.

A pollen grain is the male gametophyte of a flowering plant, while a spore is the gametophyte producing cell of a lower plant. According to dispersal strategy, the quantity produced varies between species. Both pollen and spores have an outer covering that is resistant to decay in anaerobic conditions, which by features of shape, size, aperture type and ornamentation can be identified. Most pollen analysis research has examined sequential fossil pollen deposits for reconstruction of past vegetation patterns adjacent to the lake or bog core, with climatic change implications.

Mangrove pollen has been used as an indicator of past sea levels by several researchers. The genus *Rhizophora* provides the most abundant evidence, being an anemophilous species producing prolific amounts of pollen. Muller (1959) examined distributions of pollen in sediments offshore of the Orinoco delta in Venezuela. He found high pollen abundance, and a high *Rhizophora* proportion in the coastal source area; high pollen abundance and a lower *Rhizophora* proportion immediately offshore; and low pollen abundance with a high *Rhizophora* further offshore as the limits of transport of pollen from other species are surpassed. These patterns were sustained by Van der Hammen (1963) on the Guyana coast.

Later studies of pollen in surface samples within the mangrove ecosystem also show that there is a high *Rhizophora* proportion in and immediately adjacent to the *Rhizophora*

Figure 2: Sediment sources to the mangrove fringe



zone. Spackman et al. (1966) analysed surface samples taken across a coastal swamp in Florida, showing how coastal domination by *Rhizophora* gives way to Chenopodiaceae inland. This they used to interpret a high *Rhizophora* proportion in fossil assemblages as representing marine coastal environments, and a low *Rhizophora*, high Chenopodiaceae assemblage as representing brackish or freshwater conditions. This was refined by Wijmstra (1969), who examined mangrove pollen from the Alliance well from Surinam, from Cretaceous through to Plio- Pleistocene sediments. He used modern surface samples from mangroves to interpret fluctuations of sea level over the period, identifying a 90% proportion of *Rhizophora* as a *Rhizophora* stand, and a 30% proportion as immediately adjacent to a *Rhizophora* stand, such as a seaward mud flat.

The Holocene transgression was shown by pollen analysis of mangrove cores in Guyana (Van der Hammen 1961, 1963, 1974) and Panama (Bartlett & Barghoorn 1973), with landward migration of mangrove taxa, particularly represented by a *Rhizophora* spike. Bartlett and Barghoorn (1973) interpreted a transgressive sea by the following conditions:

(i) The percentage of pollen of *Rhizophora* plus *Avicennia* in a mangrove swamp of these species may be between 45% and 95%.

(ii) Nearshore sediments seaward of mangrove swamps may contain from 30% to 50% *Rhizophora* pollen.

(iii) Sediments immediately landward of mangroves may contain 45% to 10% *Rhizophora* pollen, declining to less than 10%.

There is reason to expect that open-system intertidal and nearshore sediments would not offer the sensitive record of closed systems such as lakes and bogs where pollen analysis of past vegetations is traditionally performed. As pointed out by Chappell & Grindrod (1985) sediment mixing from turbulence and bioturbation could provide the means for extensive pollen redistribution. However, work carried out in Princess Charlotte Bay (Grindrod 1983,1985,1988) and Missionary Bay, North Queensland (Grindrod & Rhodes 1984), and South Alligator River, Northern Territory (Chappell & Grindrod 1985, Woodroffe et al. 1985, Woodroffe et al. 1987) fully established the value of pollen analysis of mangrove sediments to environmental reconstruction. At Missionary Bay, the patterns of *Rhizophora* pollen distribution reviewed above were confirmed, finding over 90% *Rhizophora* pollen in surface samples within the *Rhizophora* zone, and 44% to 59% immediately landward. At Princess Charlotte Bay, comparison of two cores showed how vegetational succession in association with extensive progradation of the shoreline can be interrupted by a more local geomorphological event, such as development of a chenier. At the South Alligator River, the Holocene transgression is shown, followed by progradation associated with fluvial sedimentation.

The clarity of sea level reconstruction from these Australian research projects was greatly hindered by three environmental factors. First, the large mangrove species assemblage of Northern Australia gives diverse zonations, for example, at least 35 arboreal species from 12 families in Queensland (Bunt et al. 1982). The assemblages include genera between which pollen is indistinguishable in the light microscope, such as *Bruguiera* and *Ceriops* (Grindrod 1988). Second, these areas are adjacent to the mouths of large rivers and consequently experience extensive progradation. This tends to obscure lesser magnitude sea level changes. Third, the Queensland and Northern Territory coasts are macrotidal, with an intertidal range of around 7 m, so causing sea level indicators including the *Rhizophora* dominated mangrove facies to occupy a broad elevational range (Grindrod & Rhodes 1984). Near Townsville, for instance, the *Rhizophora* zone occupies an elevational range of 1.5 m (Spenceley 1982). As pointed out by Kidson (1982), where tidal ranges are significant, the vertical spread over which marine processes operate become very wide and potential errors multiply. In macrotidal locations, differences in sea level within the Holocene are of a magnitude less than the present tidal range, hence are difficult to isolate. Moreover, creeks develop in areas of large tidal range, having the effect of complicating zonation, with edge species such as *Rhizophora* fringing creeks inside more landward zones.

This study uses pollen analysis to show mangrove community change in response to variation in sea level through the Holocene, in a location where these complicating factors are much reduced. As described below, the island of Tongatapu, Tonga, has a reduced number of mangrove species owing to isolation, limited sediment sources, and is microtidal. This results in narrow elevational ranges of mangrove species zones, low diversity of constituent components of these, simple parallel species zonation with lack of creeks, and reduced shoreline change as a result of progradation. This allows direct assessment of the contribution of pollen analysis of mangrove peat to sea level questions.

# CHAPTER 2: THE STUDY AREA.

## 2.1 Tongatapu Island.

The study area selected is Tongatapu Island (Figure 3), the largest of a group of islands that form the Kingdom of Tonga in the South West Pacific Ocean (Latitude 21°08'S, Longitude 175°11'W). The island has an area of 245 $km^2$, its longest diameter being around 35 km from east to west. The topography is generally flat or undulating, the highest point in the south- east is around 65 m.

## 2.2 Climate.

The climate of Tongatapu is tropical, with two seasonal divisions. The warmer wet season is from November to April, which is also the cyclone season, and the cooler dry season is from May to October.

**Winds:** The Kingdom of Tonga lies within the extensive tropical trade wind belt of the South Pacific Ocean. The south- east trades show remarkable constancy of direction, at Tongatapu winds blowing from the eastern quadrant for 64.8% of the time (Thompson 1986). Wind speeds average 12 to 13 knots, declining across the island, and tend to be stronger during the cyclone season from November to April.

**Temperature:** Temperatures show limited seasonal variation, the coolest mean monthly temperature being 21.2°C in August, and the warmest mean monthly is 26.1°C in February. Diurnal variations can be more marked according to cloud cover.

**Rainfall:** Rainfall shows marked seasonality being largely derived from convective processes, two- thirds falling in the summer wet season. Mean annual totals diminish across Tongatapu from windward to leeward coasts, around 2050 mm $a^{-1}$ in the Folaha area, and Nuku'alofa records since January 1947 show a range between 838 and 2655 mm. There is a large variation in rainfall from year to year in both seasons, including periodic droughts, but there is no recorded completely dry month.

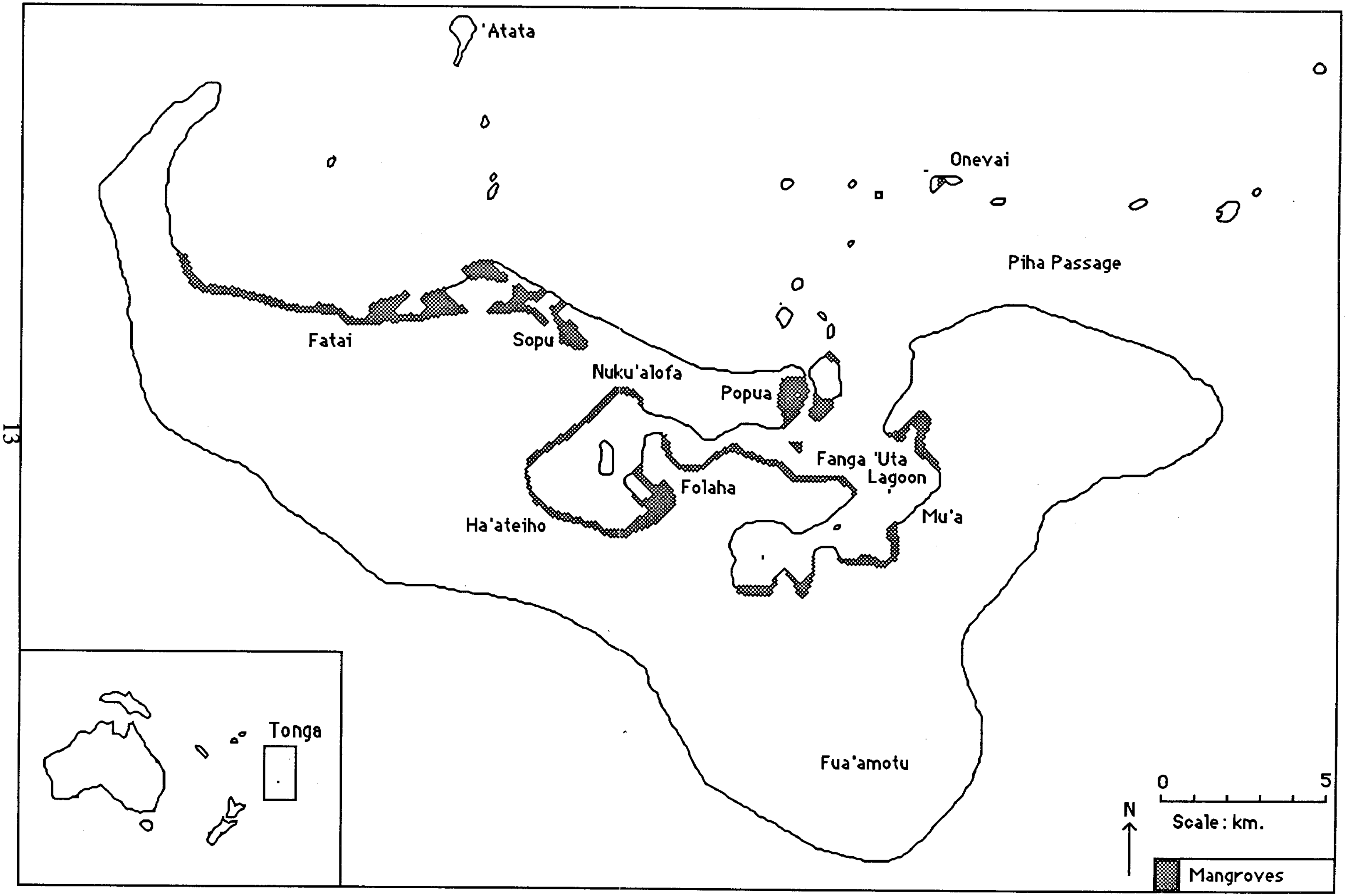


Figure 3: Map of Tongatapu showing distribution of mangroves, and places mentioned in the text.

**Droughts:** Drought patterns in Tonga have been analysed by Thompson (1986). Nuku'alofa experiences an average of 18 dry spells per decade, these being periods of at least 15 consecutive days with less than 1 mm of rain per day, and 7 very dry spells per decade, of 15 or more days with no rain. The majority of these conditions were observed during the dry season, especially in the latter part of the season. Droughts occurred in 1926, 1930, 1931, and September 1977 to January 1978 (Lewis 1978), also, there was eleven months of drought in 1983 (Finau 1985).

**Cyclones:** Cyclones during the historic period show periodicity of 20 to 30 years (McLean et al 1977, Oliver and Reardon 1982) with moderate to severe cyclones affecting Tongatapu 1874-1883, 1912-1913, 1930, 1964 and 1982.

The most severe storm damage in recent years came with cyclone Isaac, tracking south- west through the Tonga group in early 1982 (Thompson 1986, Revell 1982) This affected Tongatapu most severely on the 2nd and 3rd of March, with winds moving from south- easterly, through easterly, then strongest winds from the north- east and north on the 3rd, with gusts of 92 knots recorded at 1345 on that day. On Tongatapu, most low-lying northern areas were badly affected by floods from high seas and a heavy swell (Oliver & Reardon 1982, Woodroffe 1983). Variability in damage was a function of aspect, and degree of protection within the central lagoon and behind reefs.

## 2.3 Tongatapu: Geophysical Setting.

The Pacific plate subducts obliquely beneath the Indo- Australian plate at the Tonga-Kermadec trench. This extends to 9000 m depth, but shallowing to less than 6000 m around 26°S where the Louisville Ridge enters into subduction, and is characterised by lack of sedimentary infilling (Pontoise et al. 1986).

The Tonga group is a double chain of islands formed in association with this tectonic scenario, situated on the Tonga Ridge at the edge of the Indo- Australian plate. The ridge runs parallel to the trench, trending NNE to SSW. On the eastern margins is a line of larger islands, of entirely coral such as Vava'u, Lifuka and Tongatapu, or sedimentary volcanic material and coral such as 'Eua (Lister 1891). On the western margins is a line of active andesitic- dacitic volcanic cones (Ewart et al. 1973), 160 km distant from the subduction trench, comprising 9 active volcanoes, and at least 6 shoals.

Volcanic activity is frequent, averaging every four years this century (Bryan et al. 1972), and is catalogued by Phillips (1899), Hoffmeister et al. (1929), Richard (1962), Melson et al. (1970), Bryan et al. (1972), Ewart & Bryan (1973) and Ewart et al. (1973). Some of these eruptions include ash and pumice as well as lavas, for example, Phillips (1899) described detritus in the water for miles around the 1885 eruption of Falcon Island. Drift pumice on beaches in Fiji and the cays of Queensland probably originated from Tonga (Bryan 1968), and is common on the beaches of Tongatapu (Straatmans 1954). Earthquake acitivity in the subduction zone is frequent, with a history of strong shocks (Gutenberg & Richter 1954, Schofield 1967b).

The geological evolution of Tongatapu is described by Taylor & Bloom (1977), Taylor (1978) and Bloom (1980), commencing in Pliocene times, when coral capping the ancient frontal arc was uplifted to produce a paleoisland of some 30 m height in the southwest of the present island. During the early Pleistocene, a reef developed to windward, extending particularly to the north and west of the paleoisland, and patch reefs developed behind this. In the mid- Pleistocene, this system was raised to close to present elevations, the southwest paleoisland reaching 65 to 70 m in the Fua'amotu area, and the reefs forming the present south coast ridge at 25 m (the Vaini formation). Subsequent sedimentary infill linked the leeward former patch reefs, but remain as distinct hills around the lagoon and on the north shore, such as Mt. Zion in Nuku'alofa, the N.Z. High Commission Residence in Popua, Nuku island to the southwest of Nukuhetulu, and at Longoteme and Kauvai. Others have been quarried out, in Ma'ufanga and Vaini. More remote patch reefs remain islands, such as the north of Atata, and 'Euaiki.

While accretion continued to the northwest, erosion occurred on the southeast coastline, causing the present day rugged cliff topography. A 7 m narrow terrace above these cliffs was dated 135 000±18 000, so representing the Illinoian interglacial (the Utulau formation). Such evidence of sea level change was noted as early as the second European visit to Tongatapu, by George Forster (1968) on Cook's first visit in October 1773:

> "as we walked along (a sandy beach) towards the north point, we found it rose perpendicularly, and in some places it was excavated and overhanging. It consisted , however, entirely of coral, which is strong proof of some great change on our globe, as this rock can only be formed underwater. Whether it was left bare by a gradual diminution of the sea, or perhaps by a more violent revolution which our earth may formerly have suffered, I shall not venture to determine."

Such an observation, 60 years before Darwin deduced the atoll theory in the Society Islands, and over a century before Suess's concepts of eustatic sea level change, must be commended.

Evidences of a higher Holocene sea-level stand occur below this terrace, such as notches, algal platforms and sea caves, around 2 m above present sea level. Mid-Holocene notches are described by Taylor (1978), and the "excavated and overhanging" portions of the cliff noted by Forster could have been these. The impressive raised algal ridges of the Tongatapu south shore are described by Lister (1891), ocean rollers crashing on the wall beneath the ridge to throw high spray, while jets and spouts of water are forced up through fissures. The water falls into shallow basins on the ridge, with rims perfectly level and standing at different heights, such that water fills each basin and cascades from one to another. Ladd & Hoffmeister (1927) estimated that the platform was made at a time when the sea stood 15 ft. (4.6 m) above its present level. Sea caves at 2 to 3 m above MSL include Ana Hulu and Fua'amotu Cave (Lowe & Gunn 1986).

Isotopic dates of this mid- Holocene highstand have been carried out on associated features on the north shore of Tongatapu. At this time, the western arm of the Fanga 'Uta lagoon could freely exchange with the ocean through a channel where the capital, Nuku'alofa is now located (Taylor & Bloom 1977). Coral in growth position at the Nuku'alofa streets site gave U-series dates of 6200±300, 7600±800 and 6200±300 (Bourrouilh & Hoang 1976), and 5900±900, and a $^{14}$C date of 6240±110 (Taylor 1978). From these, Taylor proposes 2.2±0.3 m emergence of Tongatapu since 6000 BP. The interpretation was one of local tectonics, despite the considerable coincident evidence throughout the southwest Pacific (Figure 1). Other $^{14}$C dates are 4490±60 on a 53 cm raised microatoll in Sopu (Woodroffe 1983), and 6670±90 and 5940±90 on 2 m old shoreline deposits beneath the To-Pe-21 midden in Ha'ateiho (Spennemann 1986 and pers. comm.).

## 2.4 Tongatapu: Biotic Environment.

### Soils.

Soils of Tongatapu have chiefly been analysed by Gibbs (1976) and Orbell (1983). They are traditionally classified by differences in parent material, the widespread *kelefatu* soils developing on volcanic ash, and more localised *tou'one* soils developing on coral sands. The *kelefatu* soils occur over most of the island, highly friable and well drained, to a depth of 0.5 to 5 m (Pfeiffer & Stach 1972). They have been subdivided according to age of the ash deposits: a more recent active volcanic period about 6000 to 5000 BP deposited ash on western and central areas of the island, and Vaini soils cover these areas. Eastern areas have soils developed on older ash, and are termed Lapaha soils.

*Tou'one* soils occur mainly on raised beach areas of the north shore, developed since the late Holocene sea level fall. Waterlogged soils of mangrove areas are also recognised, termed Sopu soils.

### Vegetation.

The natural vegetation of inland Tongatapu has been cleared for *Cocos* plantations and intensive small-holder agriculture, as described by Thaman (1975), except for a small forest near Fua'amotu airport. Natural littoral forest fringes the rugged south coast, and occurs on the northern islets (Stoddart 1975, Woodroffe 1983, Ellison, In press). Mangrove forests fringe the north shore and the central Fanga 'Uta lagoon, the largest area and most developed ecosystem in terms of species diversity and organisation being the Folaha swamp (Figure 3). Large mangrove areas also occur on the north shore at Popua and between Sopu and Fatai, but these are partially disturbed by reclamation (Straatmans 1954, Wolterding 1983).

Polynesia is on the eastern margins of the Indo- Malayan (Old World) centre of mangrove diversity. Isolation has greatly reduced the number of mangrove taxa present in Tonga to seven, listed in Table 1. By comparison, the Eastern Queensland coast has a species assemblage of over 35 arboreal mangrove taxa, from 12 families (Bunt et al 1982). Notable absences in Tonga are the genera *Avicennia* and *Sonneratia* . The effect is low diversity species zones, especially of the seaward *Rhizophora* zone.

Of the 58 km of Fanga 'Uta shoreline (Figure 3), 44.5 km are covered by mangrove tidal forest at present (Zann 1984). The coverage is greater on the western sector , being about 30 to 35 km, as compared with about 14 km on the eastern sector's 24 km circumference. The southern coast of this sector is comprised of raised limestone and hence, is less suitable for mangrove growth; where present, the mangrove zone is very narrow.

The largest area of mangrove in Tongatapu is south of Folaha village, extending in a tombolo linkage to the island Nuku beyond Nukunukumotu village, and eastwards to the lagoon peninsula shoreline, on the western arm of the Fanga 'Uta lagoon. This was selected as the primary study area because greater size reduces extra-mangrove pollen rain, indications of simple species zonation, absence of freshwater lens discharge from the low peninsula, and proximity to a benchmark.

Table 1: Mangrove species present in Tonga.

Common: *Rhizophora mangle* L. (Rhizophoraceae).
    pseudonyms: *R. samoensis* (Hochr.) Salvoza.
        *R. mangle* var. *samoensis* Hochr.
*Rhizophora stylosa* Griff. (Rhizophoraceae).
    pseudonym: *R. mucronata* Lamk. var. *stylosa* Schimp.
*Bruguiera gymnorrhiza* (L.) Lamk. (Rhizophoraceae).
    pseudonyms: *B. rheedii* Blume.
        *B. conjugata* Merr.
*Excoecaria agallocha* L. (Euphorbiaceae)
Rare: *Lumnitzera littorea* (Jack) Voigt. (Combretaceae).
*Xylocarpus granatum* Konig (Meliaceae).
*Heritiera littoralis* Dryand. (Sterculiaceae).

Sources: Yuncker (1959) and Whistler (1987) for species in Tonga, mangrove taxonomy from Tomlinson (1986).

## 2.5 The Fanga 'Uta lagoon: Physical characteristics.

The Fanga 'Uta lagoon (Figure 4) is composed of two branches separated from each other and from the ocean by a complex system of reefs and channels. The western branch is a broad, shallow basin surrounding Kanatea Island, that during the mid-Holocene high stand connected directly with the ocean through the area now occupied by the capital, Nuku'alofa (Taylor and Bloom 1977, Taylor 1978). The time of closure of this passage as sea level fell has been dated at between 2650 and 2450 BP (Spennemann, pers. comm.) The western branch now connects with the eastern branch through the wide, sinuous Fanga Kakau lagoon. The eastern branch is deeper north of Mu'a, then further south is a shallow basin with dense seagrass cover (Zann 1984).

Information on lagoon bathymetry, dimensions, circulation and tidal patterns is available from Kimmerer (1984). Not including the entrance channel, the lagoon encompasses an area of 27 $km^2$, with about half the area in each of the two branches. The lagoon is shallow, with a mean depth of 1.4 m, and a maximum of 6 m. The western arm has a mean depth of 0.8 m and a maximum depth of 2.5 m; the Fanga Kakau passage has a mean depth of 1.5 m and a maximum of 3.2 m.

The main lagoon entrance, between Nukunukumotu Island and Nukuleka, is constricted by extensive reef flats with a single deep (5.6 m) channel through which strong tidal currents flow, of up to 2.6 knots. On the seaward side the reef breaks up into numerous patch reefs. A flood- tidal delta composed of fine calcareous sand and coral rubble has accumulated inside the lagoon entrance (Roy & Richmond, in press), with many channels leading into either the eastern sector, or into a pair of channels across another reef into the Fanga Kakau passage towards the western sector. These channels are as shallow as 53 cm below MTL, and the reef flats surrounding the side channels and the lagoonward end of the main channel become exposed at low tide. The wide, shallow entrance into the Fanga Kakau passage is in areas colonised by *Rhizophora* seedlings, most successfully around Talakite and Mata'aho Islands, which are largely pure stands of *Rhizophora* with little dry land.

The geometry of the reef flats and tidal channels constrains tidal circulation in the lagoon, with a decreased range and a time lag on ocean tide. Ocean tides at Nuku'alofa are semi-diurnal with a slight diurnal inequality. The mean tidal range is 1.07 m, and the spring range is 1.22 m (US National Oceanic and Atmospheric Administration 1986).

From comparative observations during the spring tide cycle of 23 June 1978, Richards and Dumbleton (1978) showed an ocean tidal range of 1.72 m, while a tide

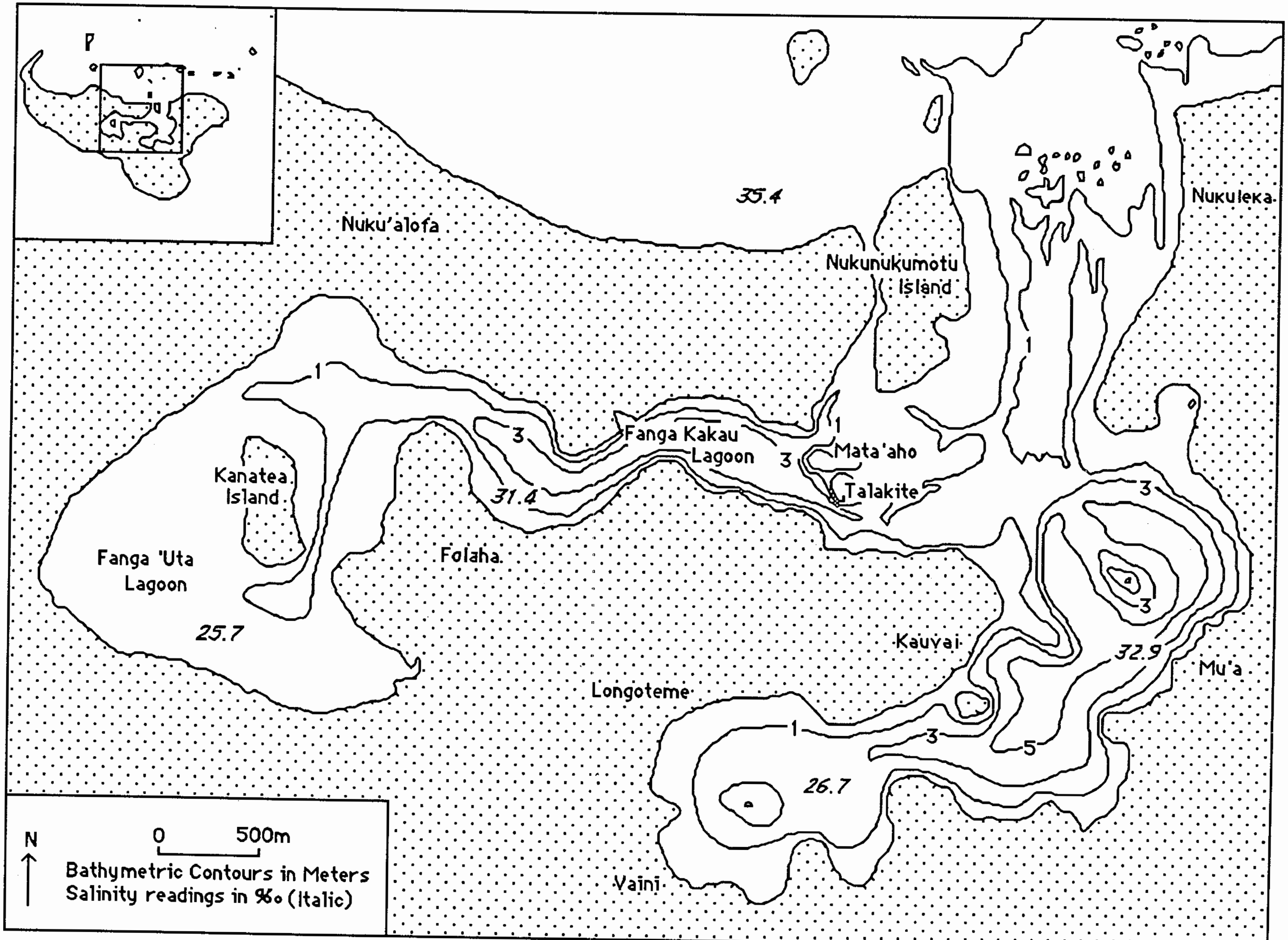


Figure 4: Physical Characteristics of the Fanga 'Uta Lagoon.

guage on the north shore of the western lagoon showed a range of 0.26 m. Tide in the lagoon peaked 3 hours 6 minutes after the ocean. Braley (1979) found a 28 to 38 cm tidal range in the western lagoon on the south Nuku'alofa shore, at full moon, and a delay of nearly an hour. Belz (1985) took tide guage readings from the same location over a three month period in 1981, and these show that the lagoon does reliably follow the ocean's semi-diurnal spring/neap pattern, only on a reduced range. Kimmerer (1984), again on the south Nuku'alofa lagoon shore, found a mean tidal range of only 0.13 m, and a lag of 3 to 4 hours. Richards and Dumbleton (1978) calculate that MTL in the western lagoon is 24 cm higher than that of the ocean. However, with such a constricted outlet, lagoon level is subject to rainfall conditions, heavy rain thought to be capable of raising lagoon level up to 1.22 m, with a considerable dwell period.

The importance of fresh water input into the lagoon is supported from salinity measurements (Pfeiffer & Stach 1972, Kimmerer 1984), which show a tendency of decreased salinity with distance from the ocean outlet, as shown in Figure 4. Fresh water input into the lagoon is largely from the groundwater lens, though contributions come from direct precipitation and saturated overland flow. Average input is 26 000 $m^3$ per day, of which 85 percent enters through diffuse subsurface springs, and 15 percent from solution channels on the shore.

Kimmerer (1984) combined computer model studies with measurements of fresh water content and current velocities to produce a freshwater budget for the lagoon. This enabled an estimate to be made of a mean residence time of oceanic water in the lagoon of about 23 days. From this it can be deduced that tidal mixing of ocean and lagoon waters results in exchanges of 1/23 or about 4 percent of the lagoon's volume with the tides, with mixing of water on each tidal excursion being only about 12 percent complete; that is, most of the water coming in on the flood leaves on the following ebb tide without mixing.

Owing to the shallow character of the Fanga 'Uta lagoon, change in MSL of small magnitude would result in considerable shoreline transgression or recession. With recent tectonic movements shown for other islands in the area, it was undertaken to review maps and documents that describe the lagoon in the Historical period, since the seventeenth century. This is the substance of the next section, "The Fanga 'Uta Lagoon: Historical record", and a significant shoreline change established from these is discussed in the subsequent section, "Question of a recent sea level fall in the Historical period".

## 2.6 The Fanga 'Uta lagoon: Historical record.

The narrow passage through reefs into the Fanga 'Uta lagoon keeps out all larger shipping vessels. Only outboard fishing boats, canoes, and the occasional yacht seeking refuge in the cyclone season venture inside. This caused many early explorer ships to omit charting the lagoon, while their maps of the offshore reefs and islands are quite detailed, owing to the difficulty of reaching the deepwater Nuku'alofa anchorage through these (Ellison 1987).

The first European visitor to Tongatapu was Tasman in January 1643 (Sharp 1968), who anchored off the northwest shore, and named the island "Amsterdam". He estimated a tidal range of 7 to 8 foot. Having drifted off anchor in winds, he decided to proceed north to Ha'apai, and did not investigate the north shore. His charts show the island as triangular, with no awareness of the lagoon.

These charts were adopted by the next visitor, Cook in October 1773 during his second voyage (Cook 1967), though he used the Tongan names. On this occasion Cook spent less than a week at Tongatapu, anchored in the northwest, and remarked that the north shore needed survey owing to the many offshore islets (Stoddart 1975). He returned during his third voyage in June 1777, making the first chart of the approach to the Nuku'alofa anchorage through the Piha Passage from the east. He visited the then capital of Mu'a, in the eastern lagoon, but crossed from the Nuku'alofa anchorage in a small boat, and did not chart the lagoon.

D'Entrecasteaux visited the area in March and April 1793, and the chart of the harbour was revised by Beautemps-Beaupre in 1807 (Stoddart 1975). This again does not show the lagoon. In 1797 the mission ship *Duff* called, and the chart (Wilson 1799) is the first to show the lagoon. The Folaha/ Kauvai/ Longoteme peninsula separating the western and eastern sectors is not shown, but charted are four islands (Figure 5). Ten missionaries were disembarked, and these record an earthquake on 28th June 1797:

> "About a quarter past three o'clock in the morning we were much alarmed by the shock of an earthquake, which lasted about a minute, during which time the earth kept a continual trembling; it was sensibly felt by us all. Our consternation on this occasion was much increased by the natives around us, who seemed quite panic-struck, and set up loud cries; and the surf on the beach made a greater noise than we ever heard before. This we considered as a wonderful exertion of divine power, and a sign at which we beheld those who dwell at the uttermost parts of the earth tremble. May the time hasten when they shall learn to know and love Him of whom they are afraid! Early in the morning we were visited by some of the natives, to whom we

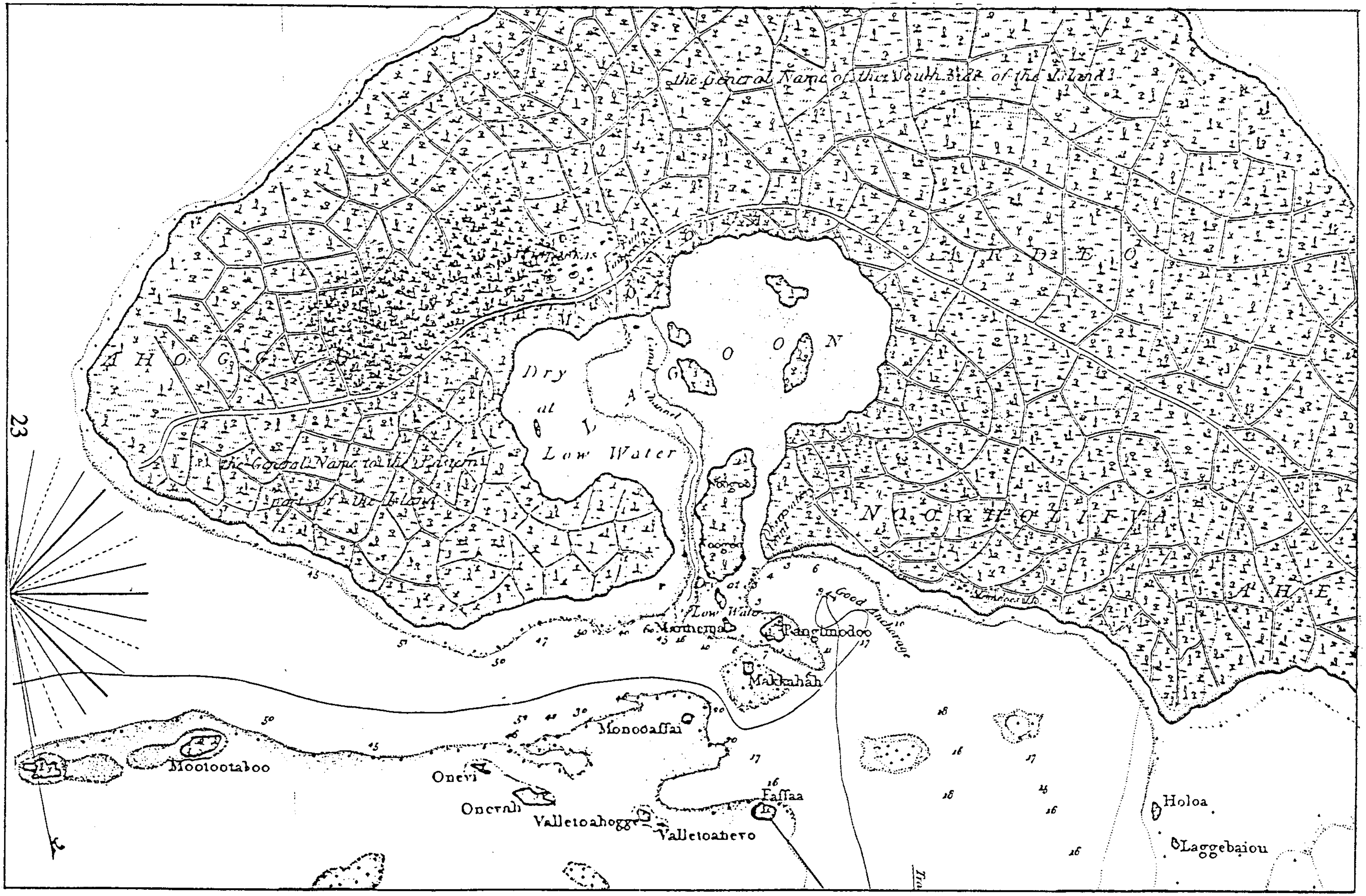


Figure 5: Wilson's chart of the Fanga 'Uta Lagoon, Tongatapu, in 1797 (Wilson 1799).

> mentioned the earthquake; the impression it made upon them seemed to be but momentary; they imputed it to the odooa (or spirit), of which they seem to have very confused notions, ascribing every thing to it which exceeds their comprehension, and of which they know not the immediate cause. Ambler says that it is the fourth shock since he landed here about eighteen months ago."
>
> (Wilson 1799, p.257-8).

In 1827 the *Astrolabe* visited under the command of d'Urville, and Paris (1833) added to Wilson's chart. He saw no reason to correct the shape of the lagoon (Figure 6).

In 1840 the United States Exploring Expedition called, under Wilkes. He mentions the lagoon:

> "Several of the officers visited Moa. In order to reach it, it is necessary to pass in boats through a large shallow lagoon, and it must be crossed at nearly high water, or the channel will be found to be very tortuous"
>
> (Wilkes 1845,p.185).

However, his charts do not include it (US Exploring Expedition 1850).

The third map to show this substantial change in the shape of the Fanga 'Uta lagoon is drawn by Heath, Acting Mate under the orders of Captain Home of the *H.M.S. Calliope*, visiting Tongatapu in 1852, and published as a British Admiralty Chart (Heath 1855). This is on a larger scale and in greater detail to the Wilson/Paris map, obviously independently surveyed. The peninsula area is shown to be a complicated group of islets and shallow water, the islets grouped into four areas as on Wilson's map. (Figure 7).

Heath shows a deeper channel across the eastern lagoon between Mu'a and the ocean, as does Wilson. Cook describes this as being dredged by the people.

The lagoon was not charted again until 1875, and all maps made after this date show the peninsula as it is today. The 1888 chart by Aldrich (Aldrich 1890) of the British Royal Navy is the basic work from which modern charts have been updated. It shows more extensive forest fringes to the lagoon than at present.

## 2.7 Question of a sea level fall in the historical period.

Consideration of this sequence of maps poses the question as to whether there was some great change to the coastline between 1852 and 1875, or it may just be that the area was initially wrongly mapped, and this copied until corrected in 1875 (Ellison 1987).

Zann (1984) from evidence of dead microatolls in the lagoon entrance around Nukunukumotu Island, suggests a sudden tectonic uplift of the land of 20 to 40 cm. Dead microatoll coral heads of several species occur at this height above the level of presently

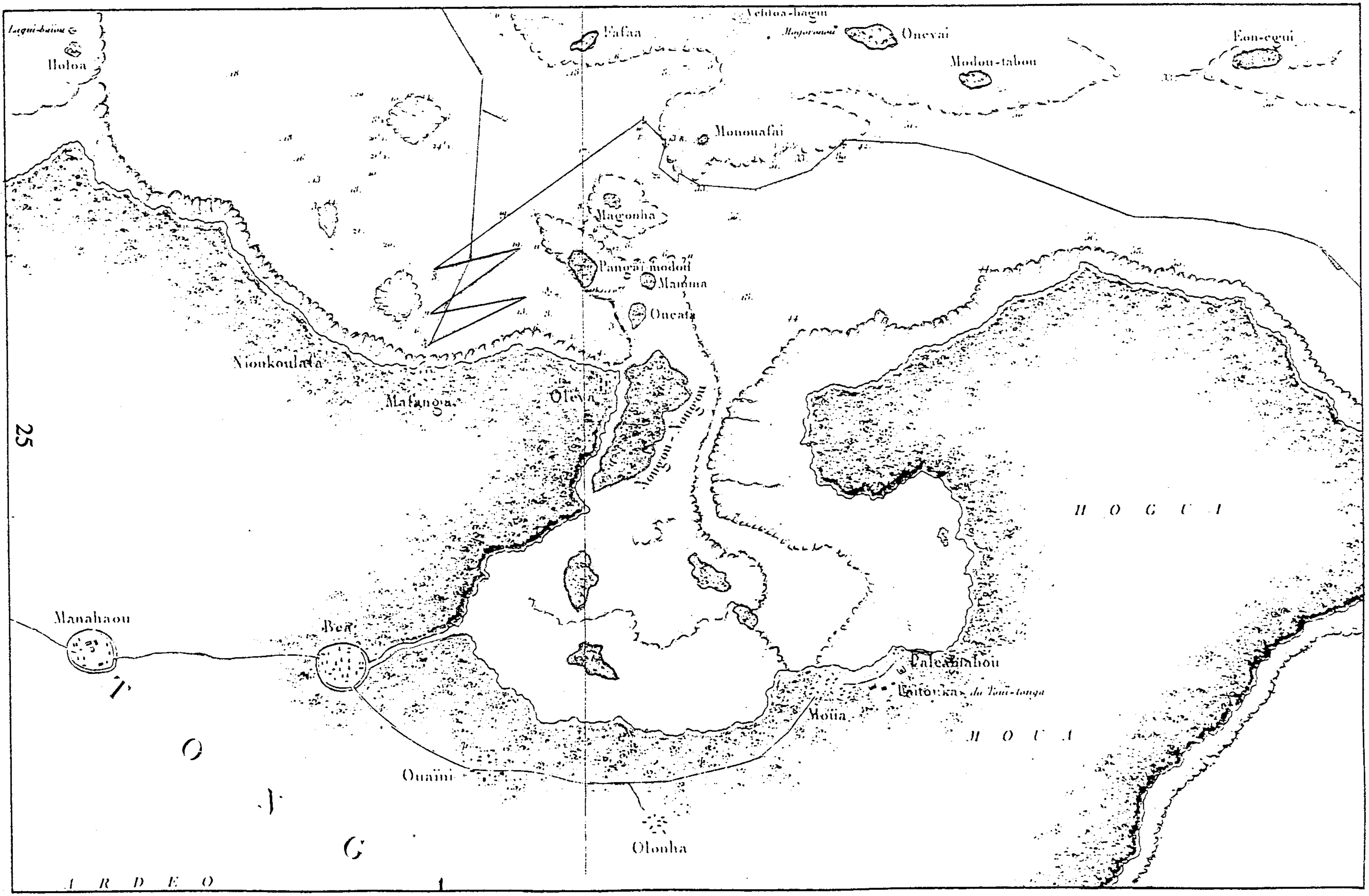


Figure 6: Paris's chart of the Fanga 'Uta Lagoon, Tongatapu, in 1827 (Paris 1833).

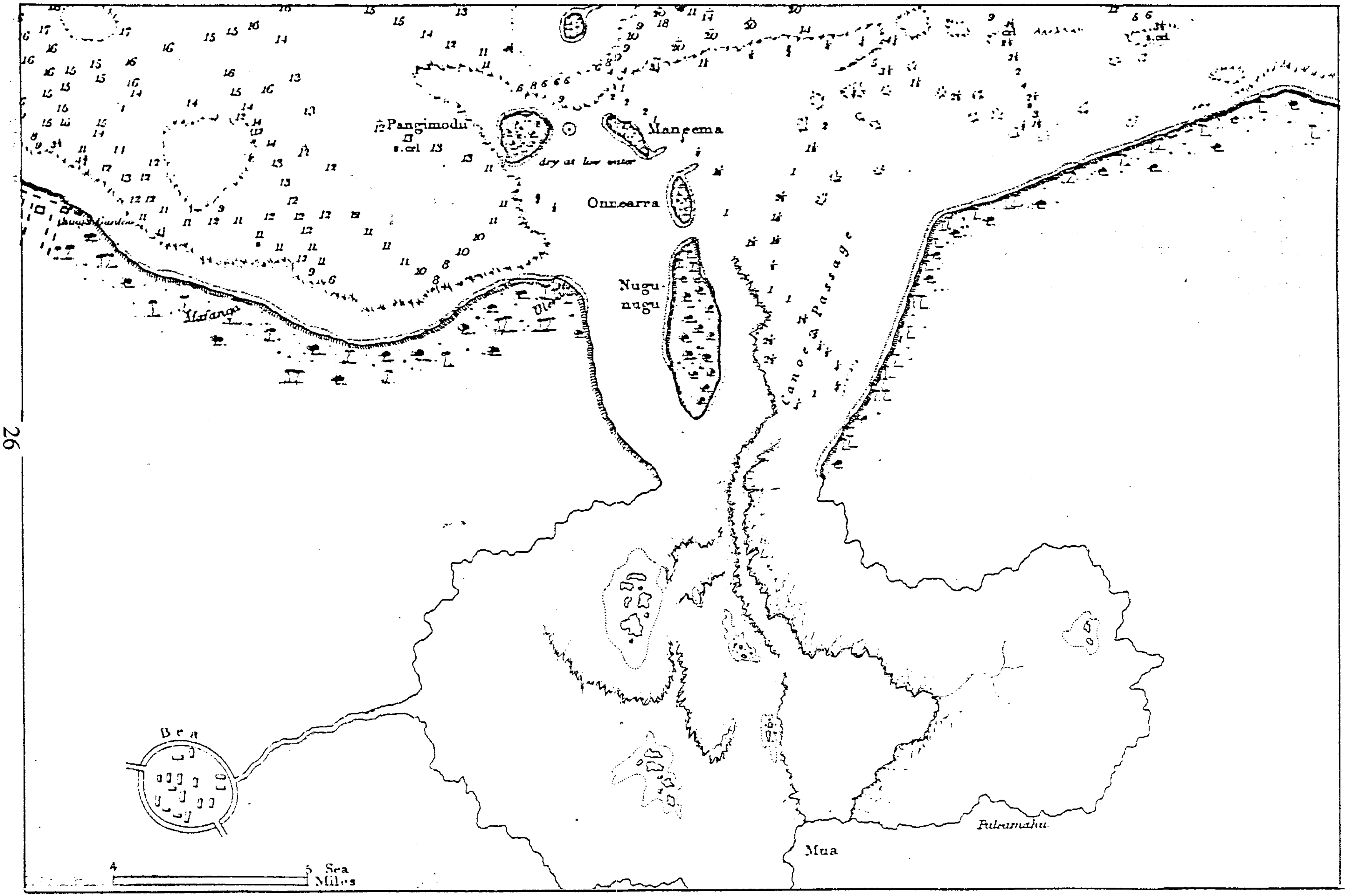


Figure 7: Heath's chart of the Fanga 'Uta Lagoon, Tongatapu, in 1852 (Heath 1855).

living coral. The time of death was not determined, but with little chemical alteration of the heads evident, and inner parts still white and crumbly, Zann gave an opinion that the heads were killed in very recent times geologically, perhaps between 40 and 200 years ago.

He suggests that the 1914 earthquake may have been responsible, but did not research other alternatives.

Owing to Tonga's location on an active convergent plate margin, earthquakes occur in association with vulcanicity along the western line of islands of the Tonga group, such as the Niuafo'ou eruption of 1946 (Rogers 1986). The frequency of volcanic and earthquake activity in Tonga has been established, and in the period of interest, earthquakes occurred in 1797 (Wilson 1799) as described earlier, 1853 (Sawkins 1856), 1865, 1917 and 1919 (Soloviev and Go 1984).

In the period 1852 to 1875 as identified from the map series, the 1853 earthquake seems likely to have caused an uplift of Tongatapu, as described by Sawkins:

> "Tongataboo, one of the Friendly Islands, was visited a few months previous to my sojourn there in 1854 by an earthquake, when the north-east portion was tilted down to an inclination sufficient to produce an encroachment of the sea for nearly two miles inland, gradually diminishing to the south-eastern shore as far as Nuku'alofa, where it now washes the roots of a tree that grew within a garden adjoining a house that has been entirely destroyed. The western coast has visibly risen some feet, and a spring of water has sunk below the surface.
>
> "The overflow of the sea on the northern and eastern sides of the island, and the elevation of the south and west are interesting in connection with the report of another island having appeared about this time to the westward. This fact was asserted by many, and among them a whaling captain who had often cruised over the same track, and who landed in an open boat with his crew on the western coast, having stranded his vessel on the said island, which he described as being only a few inches above the ocean (at a distance of thirty miles), and covered with black sand exactly like that on the shores of other volcanic islands in this and the Haabai group; he said that "tons of this sand were being levelled by the wash of every wave". I made particular inquiry of the natives of Tongataboo if they had ever before seen appearance of land in that direction, to which they replied, No,-but it was their belief that it rose on the night of the earthquake (Christmas-eve 1853), when the sea came over the land at Hihifo (the North Point)".

The 1865 earthquake affected Ha'apai more than Tongatapu, but was very large. Described from research by Soloviev and Go (1984):

> "On the 18th at 04:20 the English ship *John Wesley* ran aground near the small island (a coral reef) of Tau, but after several earthquake tremors was refloated completely. The ocean raged with such force that waves enveloped the deck.

> "At 05:40 there was a strong earthquake and the waves became even more dangerous. Twenty minutes later a terrible crack was heard on the ship and it immediately filled with water and sank in a depth of 1 m, but the crew and all passengers were saved.
>
> "The earthquake affected a huge area. It was severe on the islands of Ha'apai and rather severe on the islands of Lifuka and Vava'u, where furniture was displaced and the pendulums of clocks were stopped. On the open sea at 24° S and 173° 30" W, similar vibrations were experienced on the American ship *Siren* on the 18th at approximately 06:00 accompanied by a muffled rumble.
>
> "On the Tonga islands the earthquake was accompanied by a "sudden and violent movement of the sea", flooding the land and washing away everything in its path."

Indirect indications of a sea level fall could come from the Tongan myth "Origin of Features of the Tongatabu Lagoon" related by Gifford (1924). A translation in this work is given in the frontispiece of this thesis. The myth is analysed by Bataille (1980), mapping the route of a school of escaping mullet from a pond high in the Folaha swamp (Figure 8) that is now dry land. Her interpretation was that the story gives practical information on the movements of tidal currents within the lagoon, from HHW at points 2/3, to HLW at points 7/8, LHW at 9 and LLW at 15. However, she did not realise that tidal effects in especially the western sector of the lagoon are minimal, and the diurnal inequality is actually far less than indicated. An alternative interpretation could be that the escape of fish from the lagoon, and shoreline changes described are consequent from a fall in level of the lagoon. However, this is more likely to relate to the late-Holocene hydroisostatic fall than the small, recent tectonic fall examined here.

It was partially to investigate this interesting question of a recent sea level fall that the Folaha swamp was chosen as the location for this study, a key location in both analysis of the map series and the lagoon myth. Such evidence in the context of this work is little more than an enticement to investigate, and would stop at that point if the Folaha swamp were not also suitable for more practical reasons. It is the largest mangrove area in Tongatapu, with definite species zonations with elevation, so offering the best potential for mangrove ecosystem dynamics in response to sea level change.

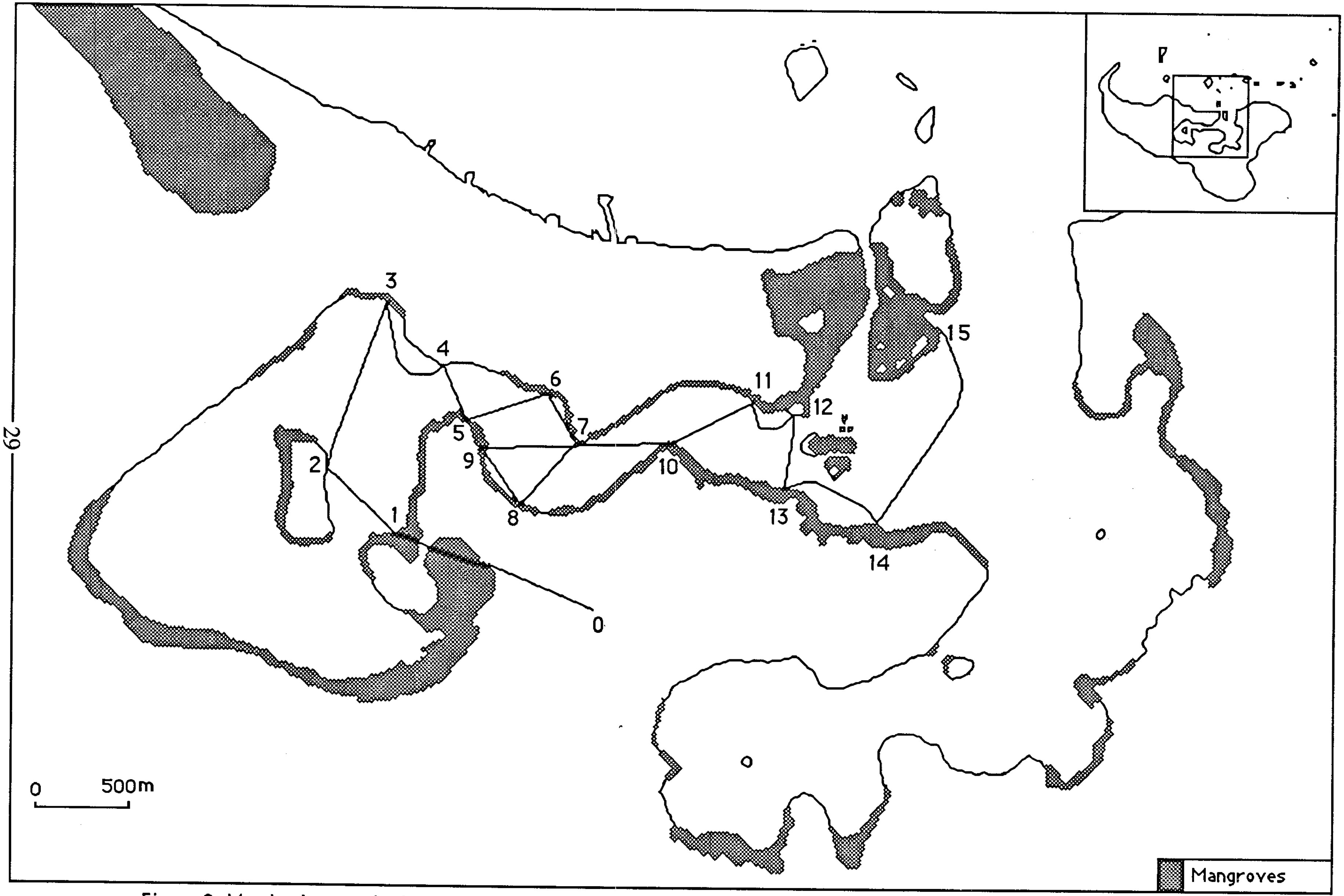


Figure 8: Map to show route described in the myth "Origin of features of the Tongatapu Lagoon" (from Bataille 1980)

# CHAPTER 3: METHODS.

## 3.1 Fieldwork design.

Owing to shortage of land on Tongatapu, and the custom in Tonga for each adult man to be given an eight acre field, the Folaha swamp has recently been allocated as agricultural land. This fieldwork was ideally timed in this development, preceding any clearance, but benefitting from the allocation surveys carried out in the swamp by the Department of Land and Survey in 1986. Straight lines were cut, and numbered concrete stones embedded at junctions of a grid system that runs perpendicular with elevation.

The transect established is adjacent and parallel to the main access line of this grid, from the south boundaries of the Nukuhetulu township across the centre of the swamp (magnetic bearing 200°, from stone 59461 to stone 58679). To avoid disturbance, all surface sampling and coring was done 50 m distant from this access line, at magnetic 110°. The grid system ceases 10 m higher than core 1, but the transect continues to the lagoon edge, successively with cores 9 and 10. This explains the disjunction of core numbers, which is maintained because core 1 was selected as the key core, for pollen analysis and radiocarbon dates.

The transect established therefore is located in the centre of the Folaha mangrove area, running perpendicular against elevation from the lagoon shore to the upper wet grassland. The length is 1 km, and surface samples and cores were taken at 100 m intervals.

Techniques can be divided into four sections: vegetation mapping, coring, levelling and pollen analysis.

## 3.2 Vegetation mapping.

Principal assemblages of the mangrove zones at Folaha were mapped from the 1981 1:12 000 air photo series (N.Z. Aerial Mapping Limited). The major and minor constituents of these were established during fieldtrips daily from May to August 1987, and periodically during labwork until January 1988.

### 3.3 Coring.

The lagoon/ mangrove stratigraphy to be expected from the Holocene sea level record in Tonga, of post- glacial transgression to a mid- Holocene highstand of about 2 m before fall to present levels, is shown in Figure 9. This is developed from Holocene mangrove stratigraphic records elsewhere (Scholl 1963, Bloom 1970, Woodroffe 1981).

All cores in the Folaha area were pulled using a Hiller sampler of diameter 3 cm. The Hiller was used for ease of penetration through sand facies. Cores were taken at low tide on rainless days, and sub-sampled at 10 cm intervals from each 50 cm section. Sample contamination was prevented by washing the corer each time with tap water carried into the swamp, also wiping spatulas used for sub-sampling. To avoid contamination from upper layers, the sampler was washed off before opening the cylinder. During cutting, air bubbles rose through the hole, indicating that the chamber was even air tight before opening. The hole maintained itself well while the sampler was out, the peat and marine units being well consolidated. In fact, all holes were still open to some depth as long as six months later. Colour of stratigraphic units was determined in the field by comparison with Munsell Soil Color Charts, and lagoon silt and lagoon sand distinguished by feel.

I attempted to extract cores in the swampy grassland area above the present day mangrove forest. The peat here is subject to periodic drying, so is more compact than under the mangroves. Core 11 was taken in this upper area, near where the Folaha/Vaini Research Farm road crosses. This was achieved by first hitting a cylindrical soil auger through the upper hardened layer, then taking over with the Hiller.

For comparisons of stratigraphy, reconnaissance cores were taken in other mangrove areas on the Fanga 'Uta lagoon and the north shore.

### 3.4 Levelling.

The elevations of the tops of all cores, and the elevational ranges of principal mangrove species zones were levelled using the Land and Survey 3 m benchmark in Folaha village (BP 3127, in front of Kelepi Po'olovati's house). Mean sea level as set by the Ministry of Lands and Surveys is 0.164 m higher than that set by the Hydrographic Department, Ministry of Defence, United Kingdom. Tidal observations show that the Hydrographic Department's mean sea level is the more accurate (Belz 1985, Appendix 1), so for this study the Folaha benchmark is taken to be 3.164 m above MSL. The Public

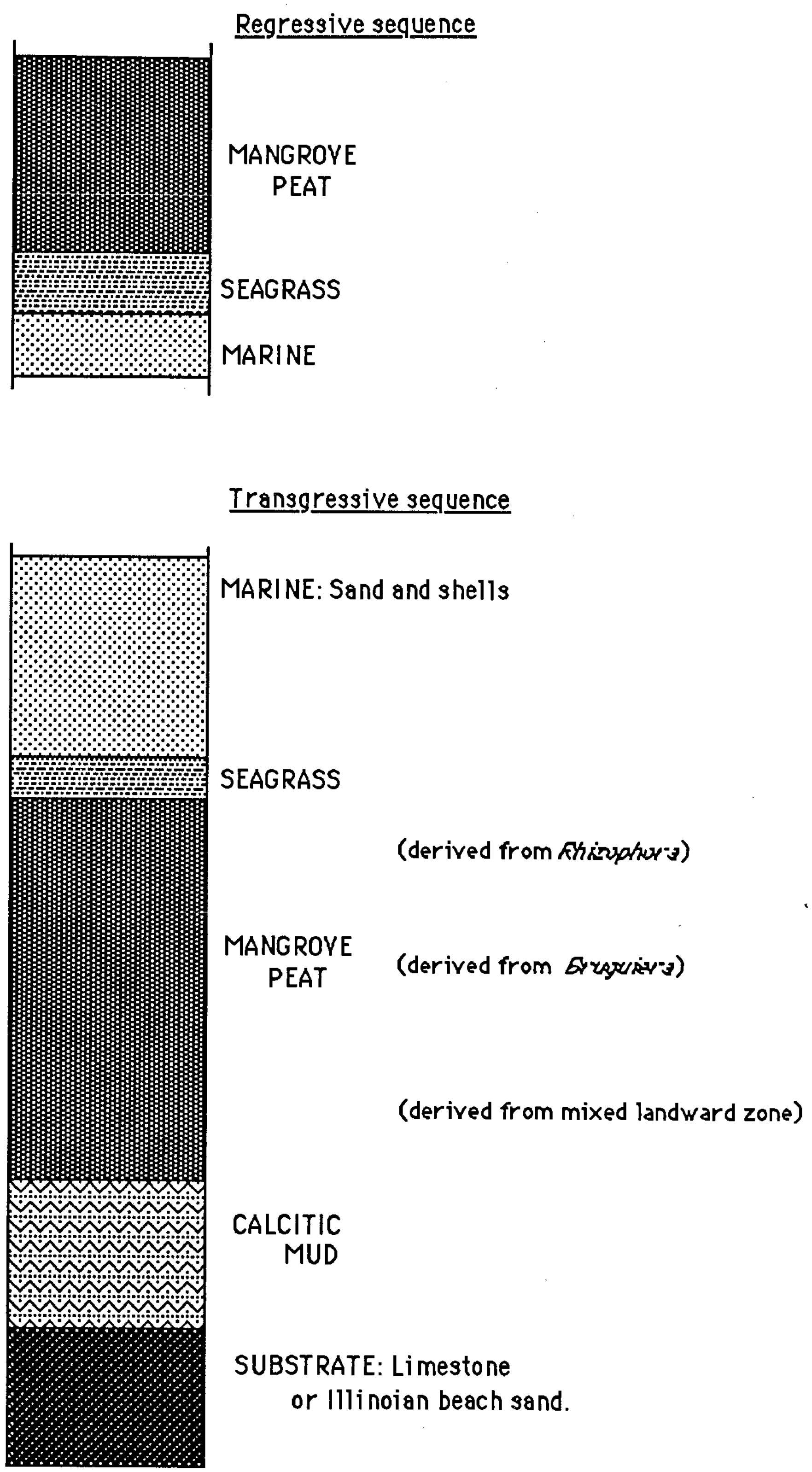


Figure 9: Schematic profile of mangrove stratigraphy.

Works Department Wild level was used principally, but occasionally a Sokkisha Automatic was also used. Temporary benchmarks were created of all Land and Survey stones along the access line used, and all legs between these and the benchmark were closed, and repeated if necessary. *Bruguiera* knee roots proved excellent spots to place the staff, and the tripod was usually positioned straddling the path for length of leg, but wedged into adjacent rooted consolidations of the mud. The benefits of access allowed by this pre-existing survey line, plus concrete buried stones cannot be over-stated, allowing legs of 20 to 25 m, and secure temporary benchmarks for this fieldwork period. This was realised when levelling just 50 m from the survey line to the core datum points through uncut mangrove forest.

## 3.5 Pollen analysis.

Pollen from reference samples was processed, and surface and core samples concentrated at 'Atenisi University in Nuku'alofa. Distilled water was obtained from the Public Health Laboratory at Vaiola Hospital.

The concentration procedure is designed to eliminate non-pollen matter in the peat, by solution agents that will act on these but not affect the pollen. These techniques broadly follow standard chemical treatments as described by Erdtman (1969) and Faegri & Iverson (1975), but refinements of these are necessary for the peculiarities of mangrove peat (Grindrod 1985). As mangrove vegetative matter is particularly resistant, an oxidation stage is included, using bleach. This necessitated that pollen was later stained to render it visible. Silicone oil was used to mount pollen so that it could be turned over for identification. This approach is needed to distinguish pollen types within the Rhizophoraceae.

Grindrod (1985) determined absolute pollen concentrations by volumetric sampling methods. He encountered problems with samples containing coarse sediments, and with losses from the sample during laboratory preparation. He suggested that the technique can be improved by determination of absolute pollen concentration from the addition of a known amount of exotic pollen grains (Benninghoff 1962). This is used in the following manner:

$$\underset{(\text{grains/cm}^3)}{\text{Concentration}} = \frac{\text{Total no. exotics added}}{\text{No. exotics counted}} \times \frac{\text{No. fossil pollen counted}}{\text{Volume of subsample}}$$

This technique was therefore adopted for accurate determination of pollen concentration. Pollen pills each containing 11300±400 *Lycopodium* spores were added to the 1 $cm^3$ sediment sub- sample prior to the pollen concentration technique. *Lycopodium* species occur in Tonga, but only on higher islands with inland lakes, not Tongatapu (Yuncker 1959).

Change of liquid between stages was achieved by centrifuging at 2000 r.p.m. for five minutes, and decanting the supernatant into running water. Eight samples could be run at once, owing to the capacity of the centrifuge, and the procedure as described below took around ten hours.

A sub-sample of $1cm^3$ of the refrigerated core or surface sample was placed in a 15 ml polypropylene test tube, used throughout the procedure.

Two exotic pollen tablets were added, each containing 11300±400 *Lycopodium* spores in a $CaCO_3$ matrix.

Calcium carbonate was removed by adding 10% HCl to test tube, and stirring with a wooden applicator stick while placed in a warm water bath. This was repeated until effervescence ceased, as many as five times for peat samples near a facies boundary with the calcareous lagoon sediment. The strong reaction of lagoon sediment with HCl precluded study of microfossils contained to a few reconnaissance sub-samples. Distilled water was used to wash samples after the HCl stage.

For removal of humic compounds, 10% NaOH was added, and test tubes placed in a hot water bath for 15 minutes, stirring and adding distilled water to prevent increased concentration by evaporation. Then washing was repeated until the supernatant ran clean, as many as eight times for the mangrove peat. Difficulty in cleaning at this stage proved to be an indication that the sample had at some stage been oxidized.

Dispersed by NaOH,, the sample was then passed through a 250 μm sieve to remove large organic fragments. The sample was then reconcentrated.

The HF treatment to remove silicates was not used, as it was desirable to keep sedimentary records of ash falls and deposition of siliceous sponge spicules for examination. There was little abiotic siliceous matter in the lagoon and mangrove environment, Tongatapu being composed of limestone.

For acetylosis, samples were first washed in glacial acetic acid, then a 9:1 mix of acetic anhydride and concentrated sulphuric acid added. Test tubes were placed in a hot water bath for up to ten minutes, then washed with glacial acetic acid, then distilled water.

For oxidation, 3% bleach was added, and diluted and removed according to the speed of the reaction. The sample was then washed.

For dehydration, 50% ethanol was added, then two drops of safranin stain, then 75% and 95% ethanol. Then Tertiary Butyl alcohol was added, test tubes centrifuged and decanted, and transferred to a glass storage vial with TBA. Silicone oil was added, and vials left at 47°C to evaporate the TBA.

For preparation of reference material, flower parts were subjected to the above procedures of hydrolysis of humic compounds, acetylosis and dehydration.

## 3.6 Other laboratory techniques.

**Percent organic determination:** Cores 1, 3, 5 and 7 were systematically sampled at 25 cm intervals for determination of organic fraction by loss on ignition. Samples were dried at 105°C for 24 hours, weighed, then ignited at 450°C for a minimum of four hours, the loss in weight giving the organic proportion.

## 3.7 Carbon-14 dates.

Samples of mangrove peat adjacent to the upper and lower boundaries of the lower peat unit in core 1 were $^{14}$C dated to establish the time of formation of this peat. Samples were extracted from the cavity of the Hiller with a clean metal spatula, and wrapped in aluminium foil. Only 5 to 10 g could be obtained from a specific depth, owing to the capacity of the sampler. Samples from 1-295 and 1-200 levels in core 1, the upper and lower boundaries respectively were submitted to the radiocarbon laboratory in the Department of Archaeology at Simon Fraser University. Carbonate content of the peat was removed, and remaining organic matter dated by traditional decay counting techniques. There was insufficient sample for $\partial^{13}$C determination, so samples were corrected for fractionation by the standard ∂13C= -25°/oo.

## 3.8 Pollen identifications.

A dichotomous key to the pollen and spores occurring in the Folaha mangrove area was developed, by building a reference collection from the flowers of species, and using existing descriptions from elsewhere. This is given in Appendix 1.

### 3.9 Pollen counting.

Sub- samples at 10 cm intervals from peat units of Folaha cores 1, 3, 5 and 7 were subjected to pollen concentration, then core 1 was selected as the key core for pollen analysis and radiocarbon dating.

Pollen and spores were identified and counted from slides by systematic transects. For modern analogues to be established, surface sample counts were continued until the total was over 200, while over 150 were counted from fossil assemblages. This methodology is comparable with that used by other researchers (Spackman et al. 1966, Grindrod 1983, 1985, for example).

Pollen results are expressed in percent of pollen, preferable to use of absolute concentration data, as it has been established that mangrove pollen as a sea level indicator is shown by relative presence of taxa of different zones. Similarly, relative presence of spores is necessary to interpret mangrove zonation present, hence data is expressed as percent of spores, with percent of pollen and spores also given.

# CHAPTER 4: RESULTS.

## 4.1 The Folaha mangrove species assemblage.

The Folaha mangrove forest extends between the elevations 0.4 and 0.9 m above MSL. Owing to low diversity of the Tongatapu mangroves, zonation is simple and marked. Five zonations of different species assemblages are recognisable within this range: lowest at the lagoon edge is *Rhizophora*, then *Bruguiera*, *Bruguiera / Excoecaria*, *Bruguiera / Excoecaria / Hibiscus*, then a diverse assemblage before wet grassland above the swamp. These are shown in Figure 10 and Plate 1.

Assistance with identifications allowed a complete compilation of species present (see acknowledgements). The elevational range of each species was noted during levelling, and by reference to surface pollen analysis key indicators of sea level were discovered. These have a narrow and limited location in the zone, and produce large quantities of pollen or spores that are deposited in the immediate vicinity of the parent. Particularly useful in this way are *Rhizophora mangle*, and the epiphyte *Stenochlaena palustris* (Polypodiaceae). The Folaha species assemblages are described below, and these two pointed out at this stage for guidance. Mangrove binomials are taken from Tomlinson (1986), and other species from where they occur in Yuncker (1959), Stemmerman & Proby (1979) and Smith (1979-1981).

The lowest zone consists of a pure *Rhizophora mangle* (Rhizophoraceae) stand that fringes the lagoon to a width of 50 to 75 m. Only three individuals of *Rhizophora stylosa* were seen, which indicates the intolerance of the latter for brackish water (Chapman 1970) as it is frequent along the north shore of Tongatapu, where freshwater influence is slight. *Rhizophora* occurs between the elevations of 0.4 and 0.7 m above MSL, and *Lumnitzera littorea* (Combretaceae) is occasional along the upper boundary of this zone. The only herbaceous species this low in the swamp is the epiphyte *Taeniophyllum fasciola* (Orchidaceae) which grows on the stems of *R. mangle*.

The *Rhizophora* zone gives landwards to *Bruguiera gymnorrhiza* (Rhizophoraceae), with occasional *Lumnitzera littorea* on its lower margins. Common understorey species are *Polypodium scolopendria* (Polypodiaceae), *Acrostichum aureum* (Pteridaceae), and occasional *Davallia solida* (Polypodiaceae) and *Derris trifoliata* (Papilionoideae).

This *Bruguiera* zone becomes interdispersed with *Excoecaria agallocha* (Euphorbiaceae) towards land from 0.75 m elevation, and this co-association has a more

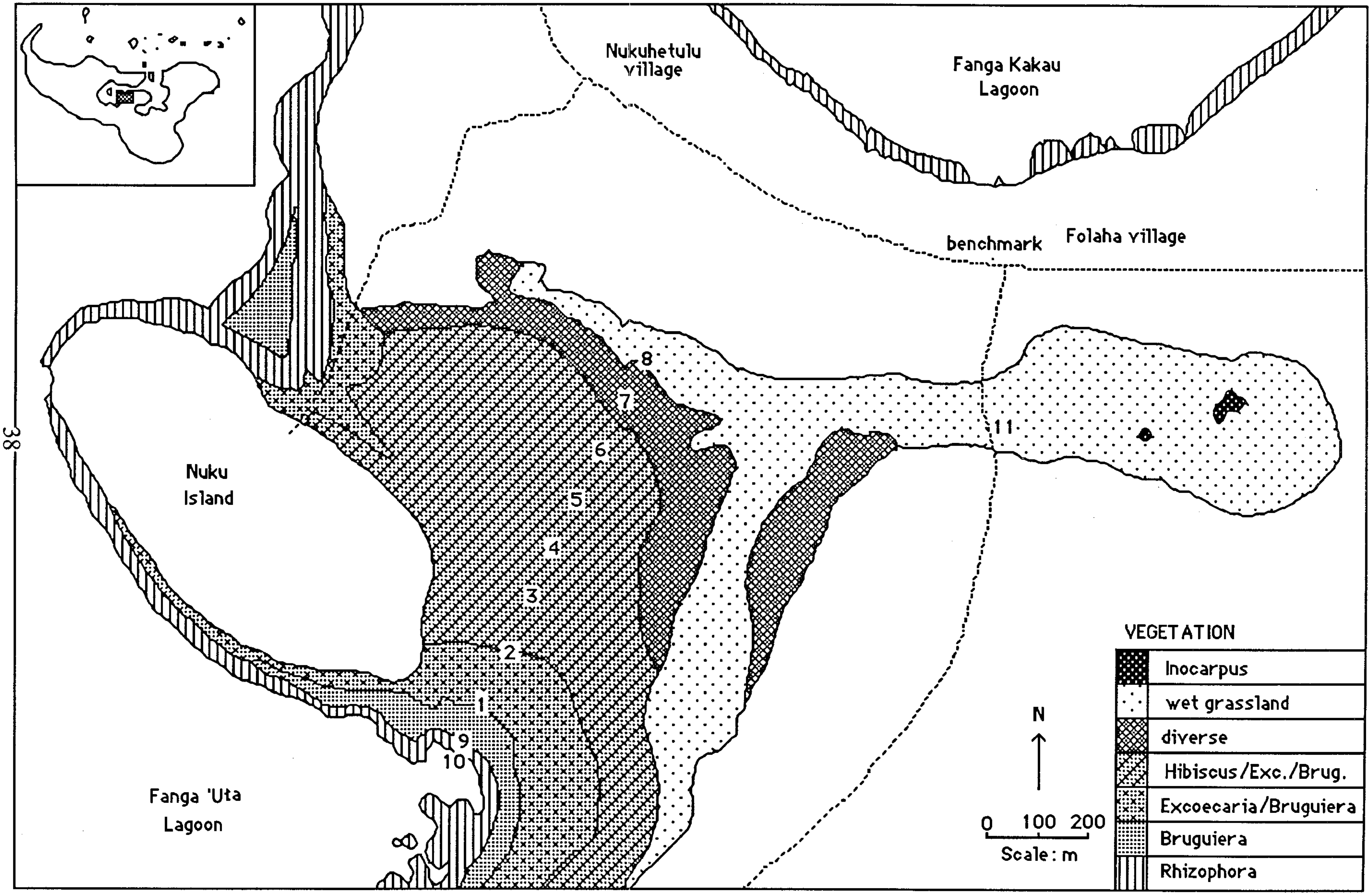


Figure 10: Map of Folaha mangrove zonations and core locations.

# PLATE 1

Oblique air photograph to show mangrove vegetation zonation at Folaha, Tongatapu.
(photo: Dirk Spennemann)

diverse assemblage of understorey species. These comprise *Acrostichum aureum*, locally widespread with disturbance, *Derris trifoliata, Davallia solida*, and occasional *Polypodium scolopedria*, *Clerodendrum inerme* (Verbenaceae), *Hoya australis* (Asclepiadaceae), *Asplenium nidus* (Aspleniaceae) and *Dalbergia candenatensis* (Papilionoideae).

Just above the reach of mean high tides, the *Bruguiera/Excoecaria* co-association becomes interdispersed with *Hibiscus tiliaceus* (Malvaceae), above 0.8 m elevation. The understorey ferns *Polypodium scolopendria* and *Davallia solida* do not extend into this zone. Common understorey species comprise *Stenochlaena palustris*, *Acrostichum aureum*, *Derris trifoliata, Clerodendrum inerme*, and occasionally, *Asplenium nidus*, *Hoya australis*, *Morinda citrifolia* (Rubiaceae), *Xylocarpus granatum* (Meliaceae), *Stachytarpheta urticaefolia* (Verbenaceae), *Pandanus tectorius* (Pandanaceae), *Lantana camara* (Verbenaceae) and *Mariscus javanicus* (Cyperaceae).

The upper edge of the mangrove forest, abutting wet grassland, has increased diversity for a zone around 50 m in width, and reaching elevations of 0.9 m. The co-dominant *Bruguiera*, *Excoecaria* and *Hibiscus* remain, and other trees present comprise *Pandanus tectorius*, *Pittosporum arborescens* (Pittosporaceae), *Xylocarpus granatum*, *Morinda citrifolia, Syzygium clusiifolium* (Myrtaceae), *Geniostoma insulere* (Loganiaceae), *Cocos nucifera* (Palmae),and *Psidium guajava* (Myrtaceae). Understorey species comprise *Acrostichum aureum*, *Stenochlaena palustris*, *Clerodendrum inerme*, *Dalbergia candenatensis*, *Stachytarpheta urticaefolia*, *Lantana camara*, *Mariscus javanicus*, *Wollastonia biflora* (Compositae), and *Panicum maximum* (Poaceae).

The wet grassland above the mangrove forest is of variable width, and is a common supra-mangrove vegetation in Tonga, particularly in the Sopu/Muifonua Point area. At Folaha it comprises a diverse mixture of sedges, grasses, weeds and vines. Chief of these are *Cyperus alternifolius* subsp. *flabelliformis* (Cyperaceae), *Paspalum vaginatum* (Gramineae), *Panicum maximum*, *Mimosa invisa* (Leguminosae), *Ludwigia octovalvis* (Onagraceae), *Passiflora foetida* and *Passiflora quadrangularis* (Passifloraceae), *Psidium guajava*, *Salix babylonica* (Salicaceae), *Eleocharis dulcis* (Cyperaceae) and in occasional patches, *Inocarpus faegifera* (Fabaceae).

As the land rises towards the relict 2 m shoreline the dry inland woodland includes species such as *Cocos nucifera*, *Rhus taitensis* (Anacardiaceae), *Leucaena leucocephala* (Leguminosae), *Psidium guajava, Mangifera indica* (Anacardiaceae) and *Citrus maxima* (Rutaceae) and subdominants *Sphaerostephanos invisus* (Thelypteridaceae) and *Stachytarpheta urticaefolia* as well as other weeds (Whistler 1983). While cultivated areas have crops standard elsewhere in Tonga (Thaman 1975), the semi- natural inland woodland on the Folaha/ Longoteme/ Kauvai peninsula of the lagoon is noticeably less diverse than elsewhere on Tongatapu.

## 4.2 Surface pollen distributions.

Pollen counts from surface peat samples give the modern analogue to which fossil assemblages can be compared and contrasted. Results from the Folaha transect, in relation to the zonation of source species, are presented in Figure 11. Trends in the data are discussed below. As surface samples were taken at core locations and are used for the upper level in core pollen diagrams, they are coded core number/ zero depth, *i.e.* 1-0 for the surface sample at core 1.

### POLLEN.

***Rhizophora* pollen:** The *Rhizophora* zone extends from core 10 to midway between cores 9 and 1. Between cores 10 and 9 it occurs as a single species stand, and above core 9 it is interdispersed by *Lumnitzera littorea* and *Bruguiera gymnorrhiza.* There was a consistent domination by *Rhizophora* pollen in samples 10-0 and 9-0, totalling 50% of pollen counted, declining to 19% at 1-0, located 50 m above the upper *Rhizophora* zone boundary. At 150 m upswamp distance from this boundary, at 2-0, Rhizophora had declined to 7% of pollen counted, and beyond this comprised 0-5% of the count, not occurring at all at 6-0 and 7-0. The genus therefore shows high pollen production, but relatively localised deposition. The percentage of *Rhizophora* pollen in surface samples within the *Rhizophora* zone is not as high as results of 80 to 90 % from elsewhere (Grindrod & Rhodes 1984), reflecting the narrow *Rhizophora* zone fringing a semi-brackish lagoon. However, changes in the proportion of *Rhizophora* pollen representation are shown to be significant, but of a lower magnitude.

***Bruguiera* pollen:** *Bruguiera* is the most common species occurring in the Folaha swamp, extending from the upper *Rhizophora* zone at core 9 to the upper swamp diverse assemblage above core 7. Pollen showed a comparable presence in surface sample assemblages, totalling 10% of pollen at 10-0, rising to 15% at the lower range of the species at 9-0, 24% at 1-0, then 32 to 55% higher on the transect.

***Excoecaria* pollen:** *Excoecaria* is also of common occurrence in the Folaha swamp, from core 1 to core 3 in association with *Bruguiera,* and from core 3 to core 7 in

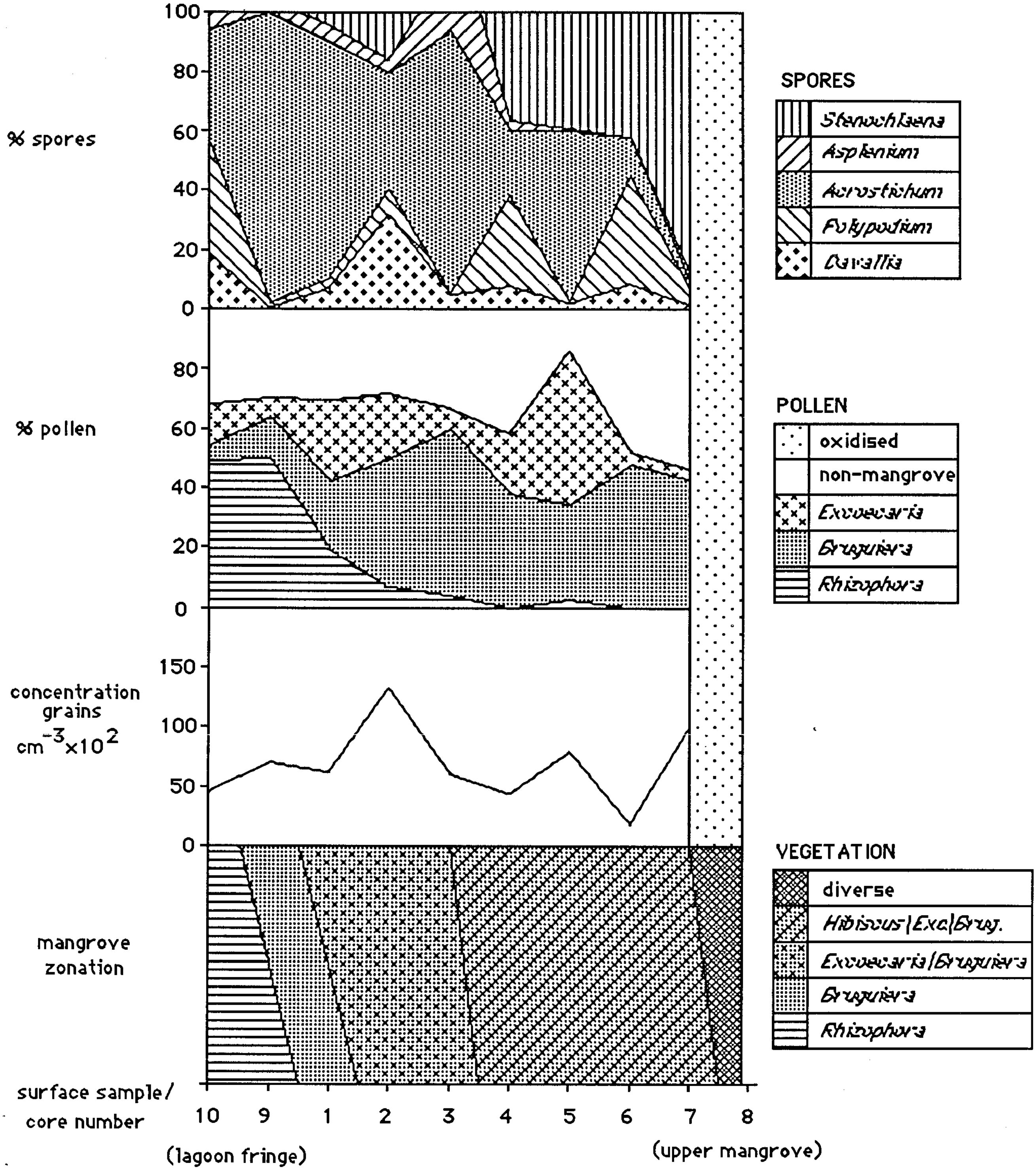


Figure 11: Surface pollen distribution related to vegetation zonations, Folaha transect.

association with *Hibiscus* and *Bruguiera.* Pollen was present in all surface samples, generally less than 10% of pollen outside the range of the source plant, and 21 to 26% within the zone. Variable results occurred within these trends, such as a low count of 7% at 3-0, and 50% at 5-0. All counts from surface and recent peat samples showed a higher *Excoecaria* proportion than expected from previous research, though the species was characteristically poorly represented in mid-Holocene peats.

***Lumnitzera* pollen:** *Lumnitzera* had only occasional occurrence in the Folaha swamp, in patches on the upper *Rhizophora*/ lower *Bruguiera* boundary area, between cores 9 and 2. Pollen showed a correspondingly low and localised representation in surface samples, from 3 to 8% of pollen counted from 10-0 to 4-0, and less than 1% at 5-0 and not at all higher in the swamp.

***Hibiscus* pollen:** *Hibiscus tiliaceus* was co- dominant in the Folaha swamp especially between cores 4 and 6, slightly less common above core 6 and from its lower boundary at core 3. Surface samples within these areas showed very infrequent occurrence of the pollen of 0.6 to 3%, and none outside the zone excepting one at 10-0, which must have resulted from drift in the lagoon.

**Non- mangrove pollen:** Non- mangrove taxa infrequently occur as subdominants in the upper areas of the Folaha swamp, above core 6, invaded from grassland and woodland vegetations on higher land. In the lower swamp, there is a fairly constant 30 to 35% of pollen from non- mangrove sources, increasing to 47% at 6-0 and 54% at 7-0. These pollen can be analytically classified into two types according to trends in the surface sample data. First, uniform if low presence in all surface samples were indicative of more extra- local pollen deposition, such as Cyperaceae, Gramineae, *Psidium guajava* and *Cocos nucifera.* Second, consistent increase landwards on the transect showed more localised deposition, such as *Pandanus tectorius, Syzygium clusiifolium, Geniostoma insulere, Rhus taitensis* , *Wollastonia biflora* and *Morinda citrifolia.*

SPORES.

***Acrostichum* spores:** *Acrostichum* was a common understorey fern in the Folaha swamp at lower elevations between cores 9 and 3. It did not occur in the *Rhizophora* zone, and was present but less common above core 3. Within this general pattern its abundance is locally variable, reflecting colonisation of disturbed areas where it restricts recolonisation by mangrove seedlings (Sukardjo 1987). It is a prolific producer of spores, the fertile pinnae at the ends of fronds being completely brown with them on the abaxial surface. The occurrence of spores in surface samples was correspondingly high but variable, depending on the local disturbance patterns and corresponding species distributions, but particularly high at 9-0 (54% of pollen and spores, 98% of spores) and 1-0 (11% of pollen and spores, 79% of spores).

***Stenochlaena palustris* spores:** *Stenochlaena palustris* is a common sub- dominant in the upper mangrove *Bruguiera /Excoecaria /Hibiscus* zone, an epiphyte growing on the stems of trees. The occurrence of its spores in surface samples shows high production and localised deposition, between 8 and 16% of pollen and spores from 4-0 to 6-0 (38 to 42% of spores), rising to an impressive 78% of pollen and spores at 7-0 (90% of spores). Outside of these areas it occurs infrequently, such as 2% of pollen and spores at 2-0 (16% of spores).

**Other Pteridophytes:** Other ferns sub- dominant in the mangrove ecosystem, *Davallia solida*, *Polypodium scolopendria* and *Asplenium nidus*, all show low and constant representation of spores in surface samples that reflect their numerical occurrence in the swamp.

### OTHER MICROFOSSILS.

Other microfossils common in autochthonous mangrove peat include fungal ascospores and sponge spicules (Cohen 1970).

**Fungal ascospores:** Fungi are an important element of the cycle of nutrients in mangrove ecosystems (Blum 1988), and fungal species diversity in these environments greatly exceeds that of higher plants (Kohlmeyer & Kohlmeyer 1979). Little work has been done on the occurrence of different species in the insular Pacific, and none in Tonga. Ascospores of the following species were present in surface and fossil peats at Folaha, identified from Kohlmeyer & Kohlmeyer (1979): *Halosphaeria quadricornuta*, which grows on several mangrove species such as *Rhizophora mangle* and *Hibiscus tiliaceus*, also occurring in Fiji (Kohlmeyer 1968); *Cytospora rhizophorae*, host specific to *Rhizophora mangle* and *Rhizophora racemosa*, also occurring in Papua New Guinea and Hawaii (Kohlmeyer & Kohlmeyer 1979); *Phoma sp.*, which grows on many mangrove species, of wide distribution including Hawaii and Japan.

**Sponge spicules:** Fragments of siliceous sponge spicules of diameter 8 to 10µm commonly occurred. Several species are mentioned from Palau by Laubenfels (1954), but it is not known which are present in Tonga. Some spicules had rounded ends, characteristic of *Cliona sp*. (Rutzler 1974). Surface samples at Folaha showed that spicule fragments were common lagoon sedimentary material, occurring in peats of lower mangrove zonations, hence their relative abundance could give a broad indication of relationship of fossil horizons to former sea levels.

**Unidentified "cysts":** Large subspherical cyst- like microfossils occurred in peats throughout the Folaha transect, though more common in lower zonations, in association with *Rhizophora* pollen. These were 110 -115 x 80-90µm, constricted on the equatorial axis, foveolate and transparent.

## 4.3 Stratigraphic results.

Along the Folaha transect, ten cores were pulled and top elevation determined by levelling. Each was 100 m apart, except for core 10, which was 50 m from core 9, at the *Rhizophora* / lagoon water fringe. The depth correlation of cores along this transect is shown in Figure 12. Reconnaissance cores pulled in mangrove areas elsewhere on Tongatapu are shown in Figure 13. Sedimentary units encountered are described below, in relation to Holocene mangrove stratigraphy described elsewhere (Scholl 1963, Bloom 1970, Woodroffe 1981).

### Limestone base.

Cores around the eastern arm of the Fanga 'Uta lagoon and on the north shore encountered the limestone base directly. At Nukuleka and Beulah, the hard limestone was overlain by a loose white mud containing angular pieces of weathered limestone, through which the auger could break. Bloom (1970) found the Sapuk swamp, Truk underlain by a bench of carbonate rock, either recemented coralline beach rubble or a former reef flat.

The base of Folaha cores, and all other cores in mangrove areas surrounding the western arm of the Fanga 'Uta lagoon, was a hard plastic calcitic clay. This limited penetration by the Hiller to 15 to 20 cm, but rock could on occasion be felt below by vertical knocking with the corer.

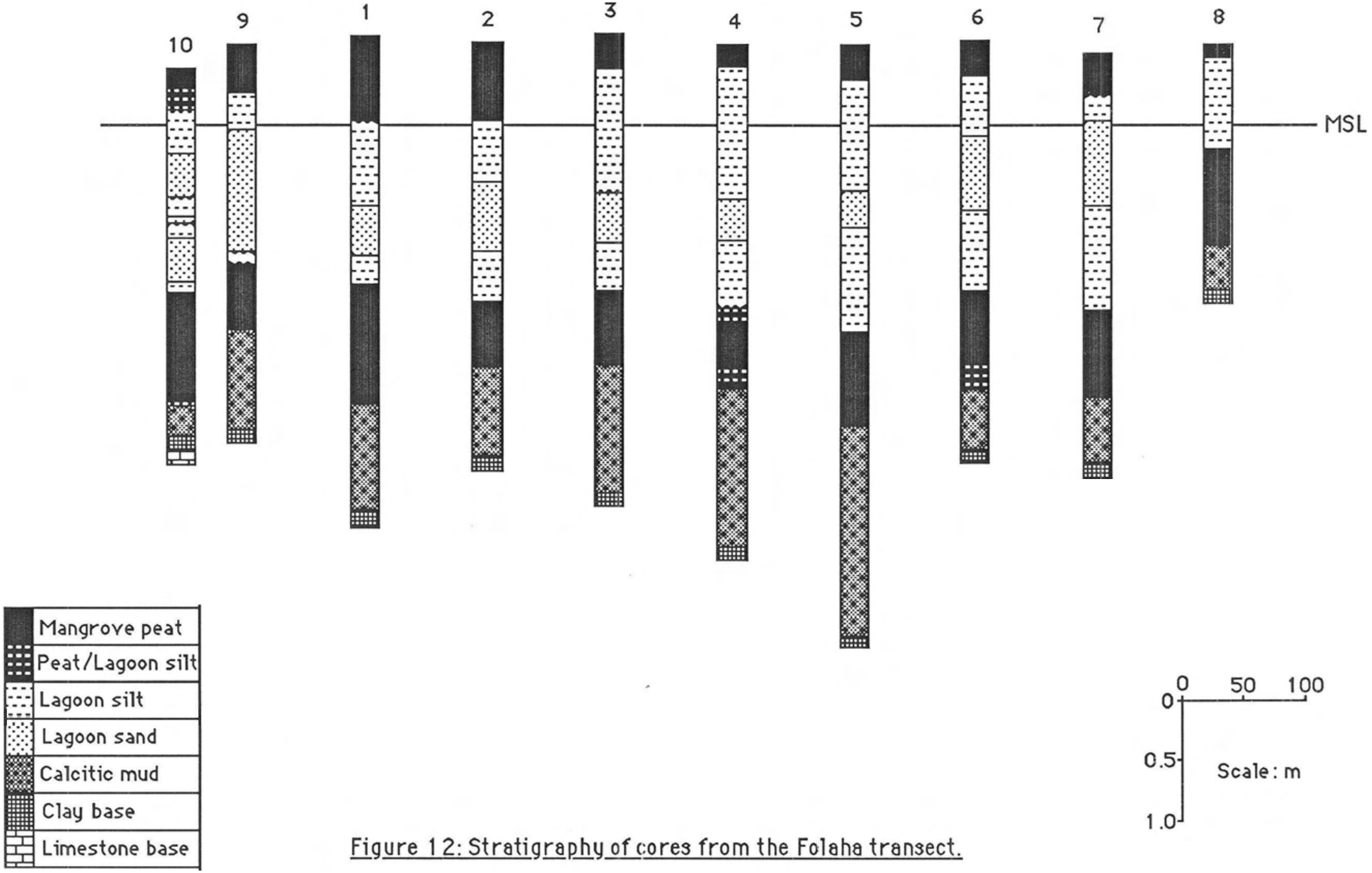


Figure 1 2: Stratigraphy of cores from the Folaha transect.

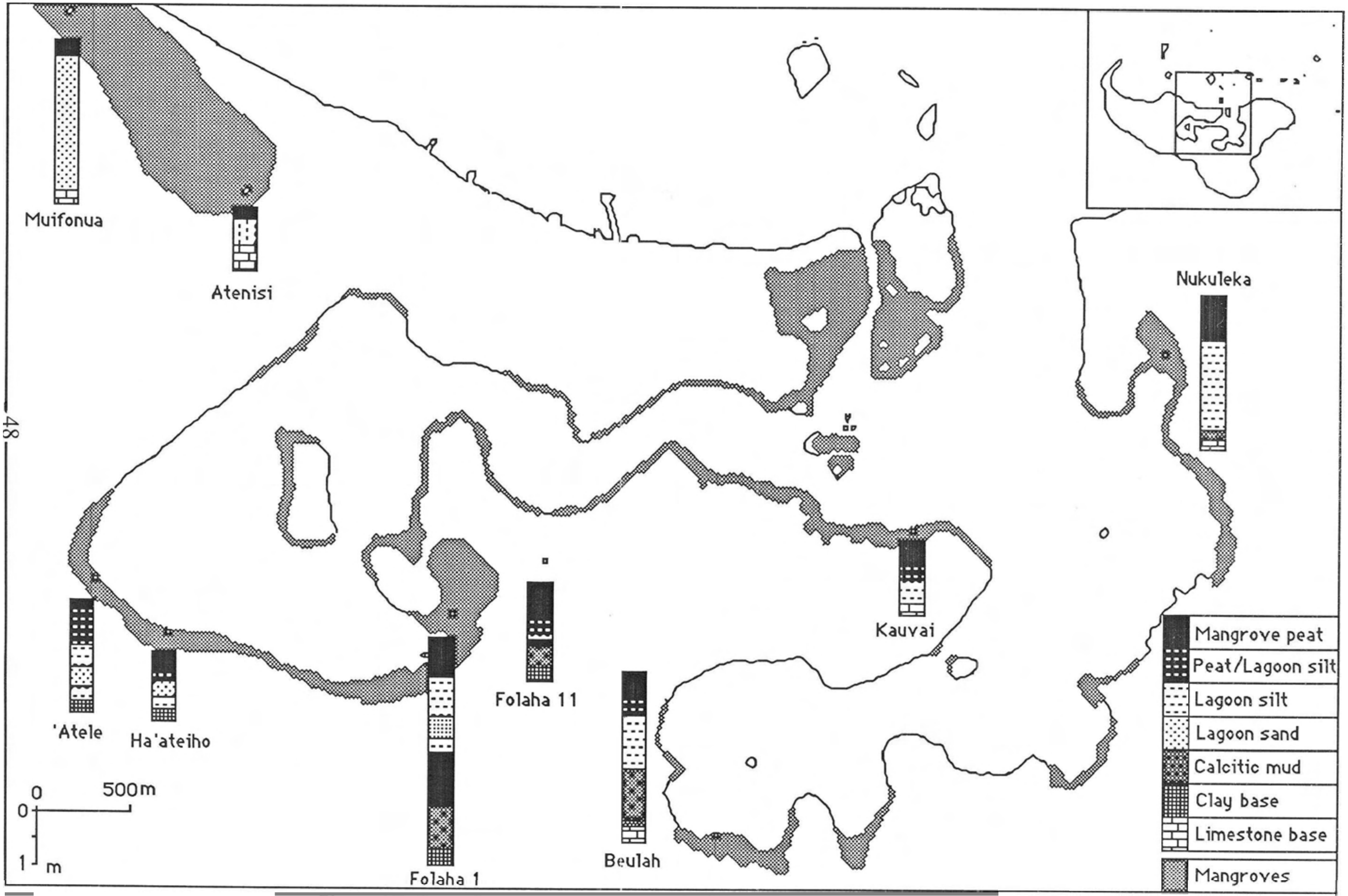


Figure 13 : Cores in mangrove areas, central Tongatapu.

### Calcitic mud.

The calcitic clay unit graded upwards into a looser silty clay. These units are similar to the green plastic mud described by Woodroffe (1981) and the basal calcitic mud described by Scholl (1963), a pedological deposit forming in seasonally flooded environments of slightly higher elevation to mangroves.

In Folaha, the colour of this clay was dark olive (5Y 3/2), and loss on ignition was 5.3-9.4% (mean 7.9%), while the silty clay was the same colour, and loss on ignition 5.7-10.2% (mean 8.5%).

### Lower peat unit and $^{14}C$ dates.

In the Folaha cores, a mangrove peat of around a meter thickness occurs above the calcitic mud, between 2 m and 1 m below present MSL. Exploratory cores taken offshore of the transect line at spring low tide showed that this peat unit continues under the lagoon. No corresponding unit was found at any other Tongatapu location, except for peat fragments near the base of the Beulah core.

Lower and upper facies boundaries of this peat are distinct, and it is smooth and compact, with red woody fragments particularly in the upper part. The red colour is characteristic of the cortex of root material of *Rhizophora mangle* (Woodroffe 1980). The peat was a very dark greyish brown colour (10YR 3/2), and loss on ignition was 22.0 to 56.4% (mean 32.9%). This unit occurs at slightly higher elevations from land to sea along the transect (Figure 12).

$^{14}C$ results gave the time of formation of this unit from the Folaha core 1. Sample 1-295 of peat adjacent to the lower facies boundary with calcitic mud gave a date of 6870±90 radiocarbon years BP. Sample 1-200 of peat adjacent to the upper facies boundary with lagoon silt gave a date of 5650±80. As samples were 2 to 5 cm within the peat unit, to avoid excessive carbonate contamination, these dates slightly underestimate the time of existence of the ancient forest at the Folaha 1 site. These $^{14}C$ dates were of all organic matter present, the lower sample would have been subject to more recent contamination while the ancient forest was in existence, with penetration by roots from above. Therefore the real time of initiation of this forest may be older than indicated by the date at 1-295. At the upper facies boundary, mangroves ceased to exist at this site at the time of facies change, hence the date is more secure.

Mangrove peat characteristically has a $\partial^{13}C$ value close to -25$^{o}$/oo, six samples from cores in Cayman (Woodroffe 1981) giving values of -26.2 to -27.1$^{o}$/oo. Hence correction for fractionation should be minimal, or real ages are slightly younger. As carbonates were removed before samples were placed in the count chamber, any hardwater effect of the limestone island and reservoir effects of a mid-Pacific location are limited to that gained by the plants through exchange with lagoon waters. The correction factor for dates on shells from Tonga recommended by the A.N.U. radiocarbon laboratory is 450 years, but would be far less for mangrove organic matter as plants are primary producers. Hence these dates are acceptable.

### Lagoon sediment.

Above the lower peat unit at Folaha, and calcitic clays and muds at other core locations, lagoon sediments occur. Mostly these are silts, but in cores around the western arm of the Fanga 'Uta lagoon a lagoon sand unit occurs between two silt units (Figure 13). The most exposed location cored, at Muifonua, showed only sand between the limestone base and modern peat.

At Folaha, the lower silt was a shelly, calcareous silt of dark grey colour (5Y 4/1), with loss on ignition of 5.9 to 9.4% (mean 7.5%). It is similar to the shelly, calcareous sediment of marine origins described by Woodroffe (1981). The shells were mainly translucent bivalves, between 0.5 to 0.75 cm diameter, occasionally both halves remaining together. The sand was dark grey (5Y 4/1), with loss on ignition 4.0 to 5.8% (mean 4.8%), with fewer shells than the silt. The upper silt was the same dark grey (5Y 4/1), with loss on ignition 4.1 to 11.3% (mean 7.5%), again containing many shells. At core 7, the upper 20 cm of this unit was a more yellow colour (2.5Y 5/6).

### Upper peat.

The lagoon sediment is overlain by a peat unit, related to the mangrove environments in which all cores were taken. At Folaha, this is less consolidated than the lower peat, but is the same very dark greyish brown colour (10YR 3/2), with loss on ignition of 32.6 to 69.3% (mean 51.9%). It is surprisingly shallow considering the above ground productive forest, ranging from 19 to 70 cm, but usually around 30 cm. At other locations around the lagoon it is of a similar depth, generally 30 to 50 cm. At Muifonua, the unit recorded is more an organically stained sand than peat as found in the lagoon. At Folaha, this peat occurs slightly lower elevations from land to sea along the Folaha transect (Figure 12), and is deeper at cores 8 and 11 in the grassland area behind the present mangroves.

## 4.4 Fossil pollen results.

Pollen was counted from 10 cm subsample intervals through the upper peat horizons of cores 1, 3 and 5; and the lower peat unit of core 1. The pollen diagrams are presented in Figures 14 and 15. Depths of samples are in cm. below the ground surface, the 0 datum or surface sample of the core. Elevations against MSL can be obtained by subtracting the height of the core datum point shown in Figure 12. For example, sample 1-260 means core 1, 260 cm depth below the present surface, which would be 188 cm below present MSL as core 1 was at +72 cm elevation. Trends in the pollen analysis results are described below.

### LOWER PEAT UNIT.

Pollen results are described here from core 1, 200 to 300 cm depth below the surface, as shown in Figure 14. This peat is underlain by a calcitic silty clay of pedological origins, and overlain by lagoon silt.

***Rhizophora* pollen:** The proportion of Rhizophora is low from 1-300 to 1-240, 4 to 11% (mean 7.0%) of pollen. At 1-230 it increases to 17%, then to 31% at both 1-220 and 1-210, and 41% at 1-200.

***Bruguiera* pollen:** From a low of 9% of pollen at 1-300, the *Bruguiera* proportion rises to 42% at 1-290, then a lower 22 to 29% at 1-280 and 1-270, then high again from 1-260 to 1-240 comprising 32 to 54% (mean 43.7%). As the *Rhizophora* proportion increases higher in the unit, *Bruguiera* declines through 1-230 and 1-210, 25 to 31%, to 17% at 1-200.

***Excoecaria* pollen:** The proportion of *Excoecaria* pollen is low throughout the lower peat, and shows slight variability. It does not occur at 1-300, then higher from 1-290 to 1-280 at 5 to 6% (mean 5.6%); low from 1-270 to 1-240 at 0.5 to 1% (mean 0.6%), then higher from 1-230 to 1-200 at 5 to 7% (mean 5.9%).

***Lumnitzera* pollen:** The proportion of *Lumnitzera* pollen is very low in this unit, most consistently present from 1-250 to 1-240 at 2 to 3% (mean 2.5%). At other levels it is absent or less than 1%, except for a sporadic 3% at 1-280.

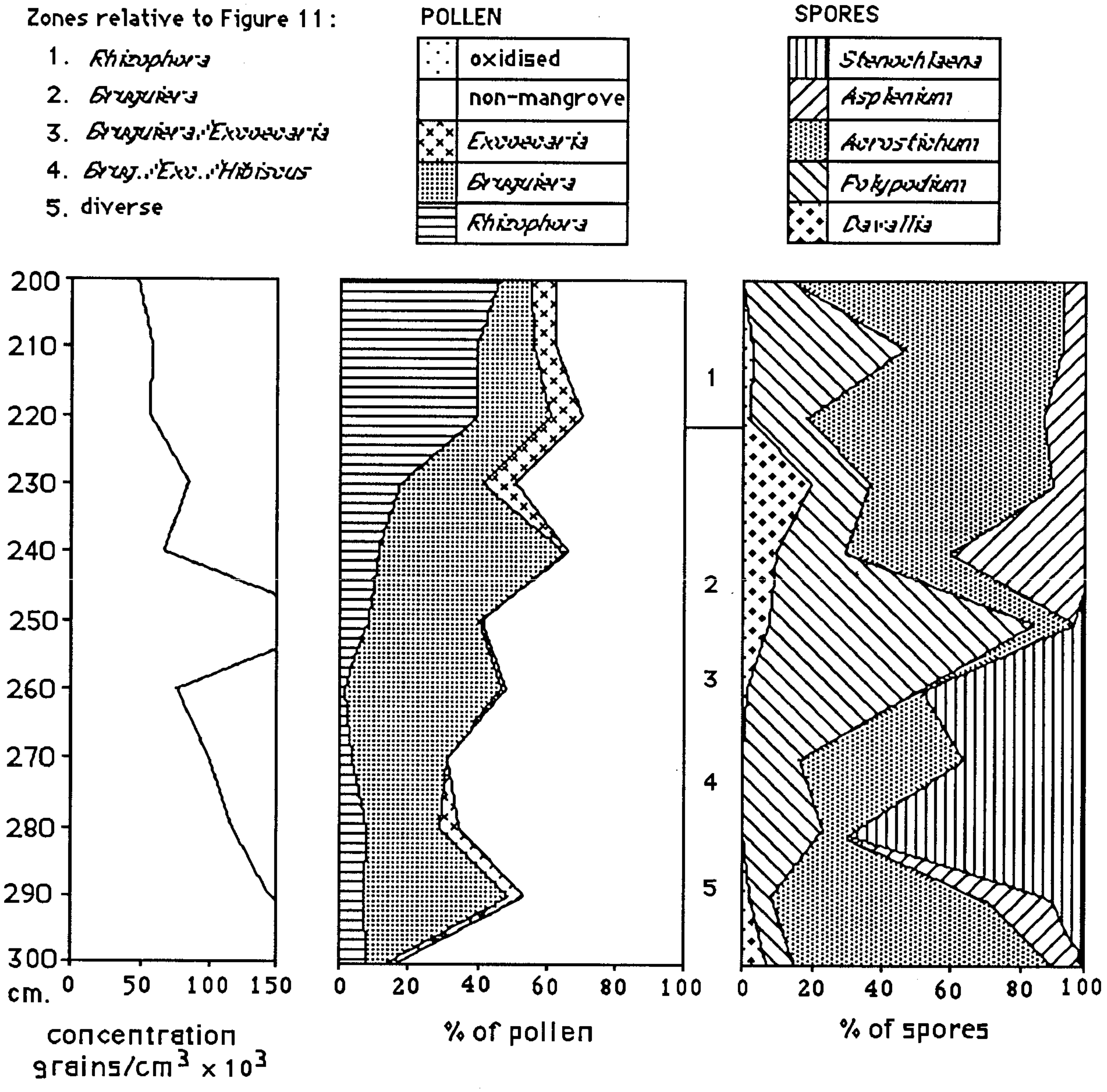


Figure 14: Pollen diagram of the lower peat unit, core 1, Folaha.

**Other common pollens:** Several pollen types showed greater frequency of occurrence in the lower peat than in surface or upper peats.

Cyperaceae comprised 50% of pollen at 1-300, 10 to 30% (mean 20%) from 1-290 to 1-260, then lower from 1-250 to 1-200 at 4 to 20% (mean 10.7%).

*Pandanus sp.* was higher from 1-280 to 1-230, 4 to 24% (mean 14.0%) of pollen, and lower from 1-300 to 1-290 at 0-6% (mean 3.0%), and from 1-220 to 1-200 at 0 to 1% (mean 0.6%).

*Syzygium clusiifolium* was higher from 1-290 to 1-240 at 3 to 15% (mean 8.8%), lower at 1-300 at 2%, and from 1-230 to 1-200 at 3 to 6% (mean 4.2%).

**Extra-local pollen:** These pollen types showed a constantly low presence throughout the lower peat, but increased substantially at 1-300. Hence pollen distribution was extra-local, but increased when the source was adjacent. *Cocos nucifera* comprised 8% of pollen at 1-300, and 0 to 4% (mean 1.6%) at upper levels; Gramineae comprised 8% of pollen at 1-300, and 0 to 4% (mean 1.6%) at upper levels.

**Upper mangrove pollen types:** Species occurring in upper mangrove areas with low pollen production had occasional presence of pollen at lower levels, from 1-300 to 1-260. These species included *Derris trifoliata*, *Hibiscus tiliaceus*, *Pittosporum arborescens*, *Clerodendrum inerme*, *Geniostoma insulere*, *Wollastonia biflora* and *Rhus taitensis*.

**Absent pollens:** Species commonly represented by their pollen in surface and upper peats at Folaha, but absent from similar sample sizes from the lower peat were the guava *Psidium guajava*, the Indian mulberry *Morinda citrifolia*, and the weeds *Lantana camara* and *Stachytarpheta urticaefolia*.

### Spores.

*Stenochlaena palustris* spores show high localised representation from 1-280 to 1-260, 6 to 16% (mean 12.4%) of pollen and spores, 12 to 68% of spores (mean 51.3%). The proportion is lower at adjacent levels, 0.6 to 4% at 1-300 and 1-290, and 0.6% at 1-250. At 1-240 and above, it does not occur.

*Acrostichum aureum* shows high representation at the upper and lower margins of the lower peat unit, reducing towards the center. At 1-300 it comprised 50% of pollen and spores, 83% of spores, reducing through 20% of pollen and spores at 1-290 (61% of spores), and 1 to 7% at 1-280 and 1-270 to be absent at 1-260. It then increases through 2 to 3% at 1-250 and 1-240, 9 to 20% (mean 14.6%) from 1-230 to 1-210, to 21% of pollen and spores at 1-200 (76% of spores).

*Polypodium scolopedria* shows high representation at 1-260, comprising 16% of pollen and spores, 76% of spores. At all other levels it shows a low and consistent presence of 2 to 12% (mean 5.1%) of pollen and spores.

*Davallia solida* shows consistent presence between 1-250 and 1-210, 0.5 to 5% (mean 1.8%) of pollen and spores, 4 to 19% of spores. It is also present at 1-300, comprising 5% of pollen and spores, 8% of spores. At other levels it is very occasional or absent.

*Asplenium nidus* occurs with low and consistent frequency in upper sections from 1-240 to 1-200, comprising 1 to 4% (mean 2.8%) of pollen and spores. It is absent from 1-300 to 1-250, excepting a sporadic 6% of pollen and spores at 1-290.

**Other microfossils:**

Fungal ascospores common in the lower peat unit included *Halosphaeria quadricornuta*, *Cytospora rhizophorae* and *Phoma sp.* Other ascospores occurred infrequently. *Cytospora* occurred consistently in association with *Rhizophora* pollen, 1200 to 4200/cm$^3$ (mean 2347/cm$^3$) from 1-230 to 1-200, and occasional at lower levels. *Halosphaeria* was also most common in association with *Rhizophora* pollen, 2600 to 6100/cm$^3$ (mean 4233/cm$^3$) from 1-230 to 1-200, and occasional at lower levels. *Phoma sp*. occurred most consistently from 1-300 to 1-250, 2800 to 40700/cm$^3$ (mean 12757/cm$^3$), and was occasional at higher levels.

Sponge spicules were abundant from 1-220 to 1-200, and occurred occasionally at lower levels. They included the *Cliona sp.* type.

The cyst-like microfossils were most common from 1-230 to 1-200, and occasional at lower levels.

Volcanic ash occurred throughout the lower peat unit. As HF was not used in the pollen concentration procedure, spherical black ash particles of 10 to 30 µm diameter could be seen on slides. However, two heavier ash falls were apparent in core 1 and other cores, with greater abundance and larger ash particles, to 25 µm diameter. In core 1, these levels were 1-300 to 1-290, and 1-210 to 1-200. This would correspond with the more recent period of ash fall of 6000 to 5000 BP identified by Gibbs (1976) and Orbell (1983), that forms the parent material of Vaini soils.

UPPER PEAT UNIT.

Pollen results are described here from core 1, 0 to 70 cm; core 3, 0 to 20 cm; and core 5, 0 to 10 cm, from the pollen diagrams in Figure 15. The transitional 5-20 level was oxidised, so gave no pollen results. These depths of surface peat are underlain by lagoon silt.

***Rhizophora*** **pollen:** In core 1, the *Rhizophora* proportion was comparable with the surface sample to 40 cm depth (1-40), 13 to 19% (mean 16.8%) of pollen. From 1-50 to 1-70, the proportion increased to 25 to 36% (mean 31.9%), before the peat gives to lagoon silt at 72 cm. In core 3, there is 4 to 5% of *Rhizophora* pollen in 3-0 and 3-10, increasing to 18% at 3-20. In core 5, the *Rhizophora* proportion remains at 3% or less.

***Bruguiera*** **pollen:** In core 1, *Bruguiera* pollen is most abundant between 1-10 and 1-40, 48 to 60% (mean 51.2%) of pollen. From 1-50 to 1-70, the proportion decreases to 14 to 36% (mean 23.2%), this being where *Rhizophora* is more abundant. The surface sample also has a lower *Bruguiera* proportion of 23%, with increased *Excoecaria* at this level. In core 3, the *Bruguiera* proportion is high at 55 to 57% in 3-0 and 3-10, decreasing to 40% at 3-20. In core 5, the *Bruguiera* proportion is consistent at 33 to 44%.

***Excoecaria*** **pollen:** The surface sample of core 1 has 27% *Excoecaria* pollen, but the proportion is lower from 1-10 to 1-70, 5 to 14% (mean 10.2%). In cores 3 and 5 patterns were more consistent, with 7 to 17% and 32 to 50% respectively.

***Lumnitzera*** **pollen:** In core 1, Lumnitzera pollen was infrequent but consistent, higher from 1-20 to 1-50 at 4 to 10% (mean 5.8%). In core 3, occurrence at all levels was a constant 3 to 6%. In core 5, occurrence was lower, 1 to 2%.

**Extra-local pollen:** Trends established from the surface samples showed conformity in the upper peat unit, with consistent but low extra-local pollen rainout. In core 1, *Cocos nucifera* comprised 0 to 6% of the pollen total, *Psidium guajava* 2 to 5%, Cyperaceae 2 to 10% and Gramineae 0 to 5%. Similar patterns occurred in cores 3 and 5.

**Upper mangrove associates:** Species that occur in the upper mangrove area, and have a low pollen production, were absent or very occasional in core 1. These include *Hibiscus tiliaceus*, *Derris trifoliata*, *Clerodendrum inerme*, *Syzygium clusiifolium*, *Pandanus*

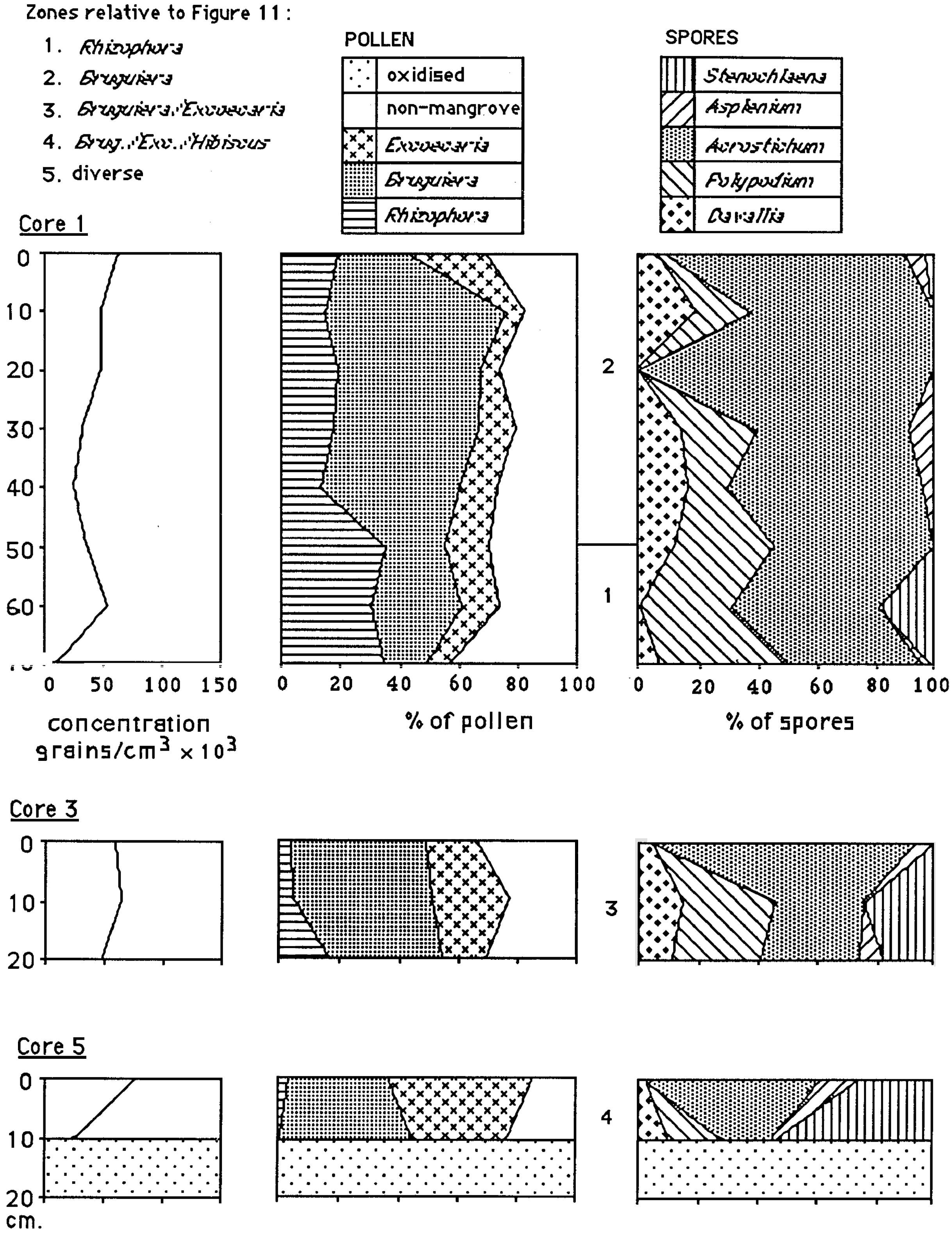


Figure 15: Pollen diagrams from upper peat units in Folaha cores.

*tectorius*, *Wollastonia biflora*, *Geniostoma insulere*, *Pittosporum arborescens* and *Rhus taitensis*. This non- occurrence was similar in core 3, but upper mangrove species showed a stronger representation in core 5.

## Spores:

The occurrence of *Acrostichum aureum* spores was common and consistent in all upper peat cores, in core 1 at all levels from 1 to 14% of pollen and spores (50 to 100% of spores), in core 3 was 2 to 8% of pollen and spores (31 to 90% of spores), and in core 5 was 1 to 12% of pollen and spores (18 to 58% of spores).

*Stenochlaena palustris* occurred infrequently in core 1, usually not at all but comprising less than 2% of the pollen and spores total at 1-40 and 1-60. In core 3, similarly less than 2% of the pollen and spores total at 3-10 and 3-20, and not at all at 3-0. In core 5, it was more frequent at 4 to 8% of pollen and spores (38 to 55% of spores).

*Davallia solida* showed consistent presence in core 1, 0 to 5% of pollen and spores (0 to 19% of spores). Similarly, in core 3 consistently 0.5 to 2% of pollen and spores (5 to 15% of spores), and in core 5 0.5 to 1% of pollen and spores (2 to 9% of spores).

*Polypodium scolopendria* had a higher occurrence, showing more variance by depth than by core location. In all cores, it was more common at lower than upper levels. In core 1, was consistent from 1-0 to 1-60 at 0 to 6% of pollen and spores (0 to 33% of spores), increasing at 1-70 to 10% of pollen and spores (52% of spores). In core 3, was absent at 3-0, but 2 to 3% of pollen and spores at 3-10 and 3-20 (29 to 31% of spores). In core 5, was absent at 5-0, but 1% of pollen and spores (18% of pollen) at 3-10.

*Asplenium nidus* showed no or very occasional presence in all of cores 1, 3 and 5 upper peat.

## Other microfossils:

Fungal ascospores occurring were most commonly those of *Phoma sp.* and *Cytospora rhizophorae*. In core 1, none occurred from 1-0 to 1-30, rising to 348 /cm$^3$ at 1-40, 1507 /cm$^3$ at 1-50, 29953/cm$^3$ at 1-60 and 10594 /cm$^3$ at 1-70. In core 3, 9662/cm$^3$ occurred at 3-0, 435/cm$^3$ at 3-10, and 19265/cm$^3$ at 3-20. In core 5, none occurred at 5-0, and 166/cm$^3$ at 3-10.

Sponge spicules showed conformity with patterns established in the surface samples, tending to occur in highest frequency in association with *Rhizophora* pollen. In core 1, they were common from 1-40 to 1-70, and infrequent above. In core 3 they were infrequent, and in core 5 did not occur.

The cyst- like microfossils described showed conformity in occurrence, in association with *Rhizophora* pollen. They were common at 1-70 and 1-60, occasional at 1-50 and 1-40, and did not occur higher in core 1 or in cores 3 and 5.

Volcanic ash did not occur in the surface samples, and in the upper peat, only occurred at 1-70.

# CHAPTER 5: DISCUSSION.

## 5.1 Discussion of pollen sedimentation in the intertidal zone.

Tauber (1967) categorised pollen deposition according to source, local if from within a few hundred meters, extra- local if more distant but not beyond 10 km, regional if from within 10 km and 100 km away, and long distance if from over 100 km away. West (1971) showed exponential decline in pollen quantity with distance from source. Local and extra- local pollen movement would be by canopy and trunk- space air movements, while regional and long distance pollen movement would be by meteorological winds and rain (Tauber 1967). Grindrod (1983) modified Tauber's model for the mangrove environment, showing pollen transport in regional and local winds and air movements. However, few clear and consistent trends in representation of taxa with distance from the coast were evident in pollen trap data.

Pollen trap data provides information on the process of wind transport of pollen. As fossil pollen assemblages from cores are derived from sedimentation on the peat surface that are buried over time, then the direct analogue for their interpretation is surface peat samples. This distinction is particularly important in the intertidal area, as pollen is transported both by water and by air movements.

Pollen analysis of lake sediments has shown that heavier grains tend to settle nearer the edges, while smaller, lighter grains move towards central deeper areas (Lundqvist 1927). The differential settling rates of grains of different morphology was shown from aquarium experiments by Wasmund (1931), with tricolporate *Salix* and triporate *Corylus* pollen grains sinking in less than an hour, while winged *Picea* pollen were still afloat after a month. Hopkins (1950) shows that conifer pollen abundance is highly variable in lake and marine sediments, subject to concentration by rafting. Such a phenomenon is unlikely to occur to such an extent in mangroves, all species having small tricolporate grains (Singh 1953, 1969). However, factors of tidal deposition of pollen must also be considered in this environment.

Clark & Patterson (1985) found that percentages of pollen along a salt marsh transect resulted from sorting by tidal action based on morphological characteristics. Muller (1959) investigated deltaic and marine transport and deposition of pollen in an environment of predominantly clastic sedimentation, finding that smaller, lighter grains such as *Rhizophora* tended to travel further. He found the effects of wind transport of pollen in the area small, and gradual subtidal variance in pollen sedimentation with distance.

This is not the case in the intertidal zone. The results from the Folaha transect, and from surface sample research reviewed earlier all show a sudden and marked decline of *Rhizophora* pollen in the upper reaches or just above the source zone. Such is unexpected for an anemophilous species, which should show gradual decline relative to other pollen types with distance from source. The pollen trap period 1 results of Grindrod (1983) showed fairly normal wind dispersal, with *Rhizophora* showing no stronger representation in seaward samples along a transect, while surface samples showed the usual sudden mid- swamp decline. He attributed this apparent lack of widespread landward dispersal to prevailing wind directions, and the dense forest canopy reducing local wind speeds and filtering air borne pollen.

The flowers of *Rhizophora* are held underneath the foliage, which is sufficiently dense to limit canopy and trunkspace air movements. This localises pollen deposition, as pointed out by Grindrod (1983), but not only due to air movement factors. As *Rhizophora* grows in the mid- tide zone, pollen released under the canopy will half the time fall onto water, especially if winds tend to be offshore. In the Folaha swamp, highest *Rhizophora* pollen deposition was within the ranges of normal high tides, with low deposition within the spring tidal range, and no *Rhizophora* occurrence higher in the swamp. This suggests that pollen deposition is predominantly tidal, with maximum deposition in the shallow waters of upper tidal reaches. Hence, the strong representation of *Rhizophora* pollen beneath the source plants is a result of the coincidence of the upper limit of the species (a function of limiting environmental tolerances and competition) and tidal sedimentation.

## 5.2 Holocene Sea level interpretation.

### Stratigraphic record of sea level.

Stratigraphic units of cores in mangrove areas on Tongatapu (Figures 12 and 13) show sea level changes throughout the Holocene. Pollen analysis of peat units encountered at Folaha shows in detail, by reference to the modern analogue of vegetation and pollen distributions across the transect, how mangrove zones migrate in response to a changing sea level.

Limestone was found at the base of all cores, though in the western arm of the Fanga 'Uta lagoon this was coated by a plastic calcitic clay. The variable depth of limestone, particularly apparent from core to core on the Folaha transect (Figure 12), suggests differential erosion of the karstic bedrock during the last glacial lowstand, as described by Trudgill (1985) and Scoffin et al. (1985).

The calcitic clays and muds found generally below 2 m in cores around the Fanga 'Uta lagoon (Figure 13) are pedological deposits forming in seasonally flooded environments that existed before the encroachment of mangroves, but probably covered by a low herbaceous vegetation (Woodroffe 1981). Scholl (1963) showed the environment of deposition as largely fresh-water by examination of molluscan fauna present. Grindrod (1988) describes stratigraphic results from similar environments in Queensland, termed 'high tide muds'. The modern analogue of this environment exists on the north shore of Tongatapu at Popua, Fatai and Onevai, where areas of herbs such as *Sesuvium portulacastram* occur on slightly higher ground within mangrove areas.

Latter stages of the early Holocene transgression are shown, with terrigenous environments represented by the calcitic mud unit becoming intertidal, recorded by development at Folaha of a mangrove peat. In core 1, this peat developed between depths of 2.3 and 1.3 m below present MSL, from 6870±90 to 5650±80 respectively (Figure 16). The core correlation diagram (Figure 12) shows that slow rise continued, with this lower peat unit becoming slightly higher in cores from land to sea. In this case, the time of deposition of the lower lagoon silt/ lower peat boundary would be progressively younger from core 10 to core 7 as mangroves colonise previously dry land.

The context of stratigraphic units between which this lower peat occurs, with a terrigenous pedogenic deposit below and lagoon sediments above, indicates that it formed in conditions of a rising sea level. This is confirmed by the pollen results, to be discussed in the next section, with the lower levels dominated by Cyperaceae and non-mangrove taxa similar to upper transect surface samples in the present swamp, and upper levels dominated by *Rhizophora* pollen similar to lower transect surface samples in the present swamp. Elevations of these communities determined from the transect can be used to determine the position of former MSL relative to the dated levels. At the lower boundary of peat with calcitic mud, 2.3 m below present MSL, the modern analogue of the upper mangrove fringe is appropriate, located at an elevation of 0.9 m above present MSL. Hence, the position of MSL 6870±90 radiocarbon years BP was 3.2 m below present MSL. At the upper boundary of peat with lagoon silt, 1.3 m below present MSL, the modern analogue of the lower mangrove fringe is appropriate, located at an elevation of 0.4 m above present MSL. Hence, the position of MSL 5650±80 radiocarbon years BP was 1.7 m below present MSL. The rate of sea level rise between these periods was 12.3 cm/100 years. Error margins on these elevations are discussed in a later section

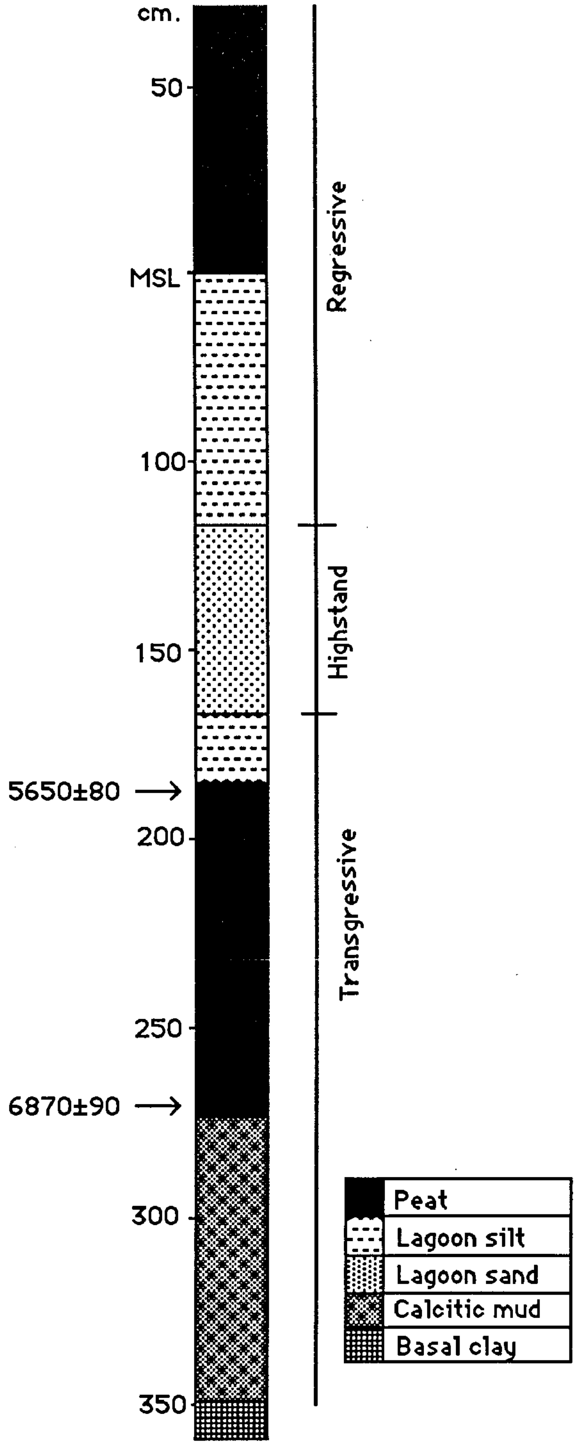


Figure 16: Stratigraphy and $^{14}C$ dates of the Folaha 1 core.

"Assessment of mangrove pollen stratigraphy as a sea level indicator".

No equivalent to this lower peat at Folaha was found elsewhere on Tongatapu, except for peat fragments at the base of the Beulah core (Figure 13). At two locations on Ponape, Bloom (1970) found similar traces of woody mangrove peat at around 5 m depth. The only similar deposit to the Folaha lower peat in the south- west Pacific is the large mangrove forest that existed from 6800 to 5300 BP in the South Alligator River area, Northern Territory (Woodroffe et al. 1985, 1987). Mangroves only become well established in calm and sheltered conditions, and the lack of records of mangrove environments in the mid-Holocene by comparison with the present reflects rougher coastal conditions, with growth of protective reefs lagging behind Holocene sea level rise (Hopley 1984, Neumann & Macintyre 1985).

The Folaha lower peat unit is overlain by lagoon sediment, showing that after 5650±80 sea level was higher such that the Folaha location was submerged by the lagoon. The lagoon silt contains many bivalves, molluscs that are common sedimentary contributors to a low energy tropical carbonate tidal flat (Hardie 1977), living on loose muddy bottoms from low tide to several meters below sea level (Sugimura et al. 1983). This sub- tidal sediment occurs at corresponding depths at all core locations in Tongatapu, though is sandier at more exposed sites, at Muifonua and Kauvai. Its modern analogue is the bed sediment beneath open water of the lagoon.

As sea level continued to rise, more turbulent conditions extended south into the lagoons as the the present north shore became submerged and islanded (Spennemann 1987). Direct exchange between the western arm of the lagoon and the ocean through the Nuku'alofa site was shown by the transition from silt to sand in all cores on that lagoon. The comparative sedimentary record shows that the western lagoon arm was more turbulent than the eastern arm at this time. The mid-Holocene highstand identified elsewhere in the South-West Pacific (Figure 1) is represented at Folaha by this sand unit, but owing to the wide elevational occurence of sub-tidal sands, a height of the highstand cannot be estimated from the Folaha stratigraphy. The $^{14}$C dates from the lower peat unit of core 1 show that the dates for this highstand as determined by Taylor & Bloom (1977) are too old, as indicated by their anomalous position to the regional pattern of mid-Holocene sea levels shown in Figure 1. Dates of the mid-Holocene highstand at Tongatapu need to be reconfirmed. It would seem from the Folaha dates and regional correlations that the highstand commenced more recently at approximately 4500 BP, and ceased with sea level falling to close the Nuku'alofa entrance to the western lagoon between 2650 and 2450 BP (Spennemann, pers. comm.)

Similar grey lagoon muds and sands are recorded from archaeological digs at sites around the Fanga 'Uta lagoon (Poulsen 1967, Spennemann 1986), underlying cultural deposits. These indicate the incursion of the lagoon over present dry land during the highstand. At the site To-Pe-21 in Ha'ateiho, a black lagoonal mud of 30 to 60 cm thickness was recorded beneath lagoon sediment (Spennemann 1986, Figure V.23). This had potential to represent mangrove peat deposited as sea level approached the highstand, and samples from lower and upper segments of the peat were run through the pollen concentration procedure. All pollen was shown to be oxidised, but presence of siliceous sponge spicule fragments could identify the deposit as a mangrove peat. The unidentified cysts of Folaha mangrove peats were also found here. The spicules were more abundant in the upper sample from this peat than the lower, indicating formation during a rising sea level. The unit is underlain by sand dated to 6670±90 (ANU-5730) (Spennemann, pers. comm.) and overlain by lagoon sediment, hence this peat must have formed as rates of sea level rise reduced towards the mid-Holocene highstand.

At Folaha, the late Holocene sea level fall is shown by return to lagoon silt above the sand. The facies boundary represents the time at which the Nuku'alofa passage closed, causing quieter conditions in the western lagoon.

Continued sea level fall allowed mangroves to extend into the Folaha transect area, so developing the upper peat unit. The occurrence of the unit at slightly lower elevations from land to sea along the transect indicates that it formed in conditions of a falling sea level. The shallow nature of this peat of around 30 cm indicated that extension of mangroves into this area of the lagoon has been relatively recent, and presence of the alien pollen *Psidium guajava* at all levels confirms this, as discussed below. The deeper upper peat in the grassland area behind the present mangroves, cores 8 and 11, indicates that this area was vegetated long before the lower Folaha transect.

## Comment on bioturbation.

The pollen and facies stratigraphies of Holocene sediments at Folaha show little loss of resolution by bioturbation. Facies boundaries were in almost all cases distinct, within 2 or 3 cm, though core 11 near the road crossing the upper wet grasslands showed disturbance of stratigraphy. Pollen analysis of 10 cm subsamples gave conclusive results. Accounts of serious bioturbation of mangrove peats (Semeniuk 1980, Havanodn 1987) are in locations with a diverse fauna of large mangrove inhabitants. The crabs present at

Folaha do not seem to have an effect that greatly disturbs beyond the 10 cm intervals used in this study.

### The sea level record from pollen analysis.

Greater detail of these sea level changes is given from the pollen analysis results of peat units occurring at Folaha, of the disjunct late transgressional and recent regressional periods. The following discussion of these units examines ecosystem dynamics as suggested from the pollen record in response to a changing sea level.

#### LOWER PEAT UNIT.

There is remarkable correlation between the pollen diagram for the core 1 lower peat unit (Figure 14) and the pollen diagram for surface samples transecting the present mangrove forest (Figure 17, developed from Figure 11). That these pollen assemblages have the same internal character and vertical order indicates that in response to a rising sea level, different mangrove zones occupied the core 1 location over time in the manner that they are distributed on different elevations of the present swamp.

The lower peat unit is effectively sealed from anthropogenic influences by a margin of 2420 radiocarbon years, human occupation of Polynesia resulting from the Lapita expansion from New Guinea 3500 to 2500 BP (White & Allen 1980), arriving in Tonga during the sea level highstand from 3150 BP (Poulsen 1977), when the lagoon sediment was being deposited at the Folaha location. The pollen results show communities that are undisturbed, particularly by comparison of the *Acrostichum* occurrence. In the ancient forest this species is common in the upper brackish marsh, which is its natural habitat (Stemmerman 1981), and the *Rhizophora* zone, where storm disturbance would be frequent. In the central mangrove zones *Acrostichum* dwindles to zero occurrence. Species not represented by their pollen in the lower peat unit at Folaha are weeds or domesticated crops, later introduced to Tongatapu by people.

At 1-300 the pollen assemblage shows a brackish marsh community, with dominance by Cyperaceae and *Acrostichum aureum*. Pollen concentration is very high, and mangrove taxa contribute only 18% of the pollen total. *Stenochlaena palustris* spores show low occurrence, 1% of spores. The modern analogue of this assemblage at Folaha would be the grassland above the mangrove forest where core 8 was pulled, but the surface sample showed oxidation. This would suggest that the droughts of the historic

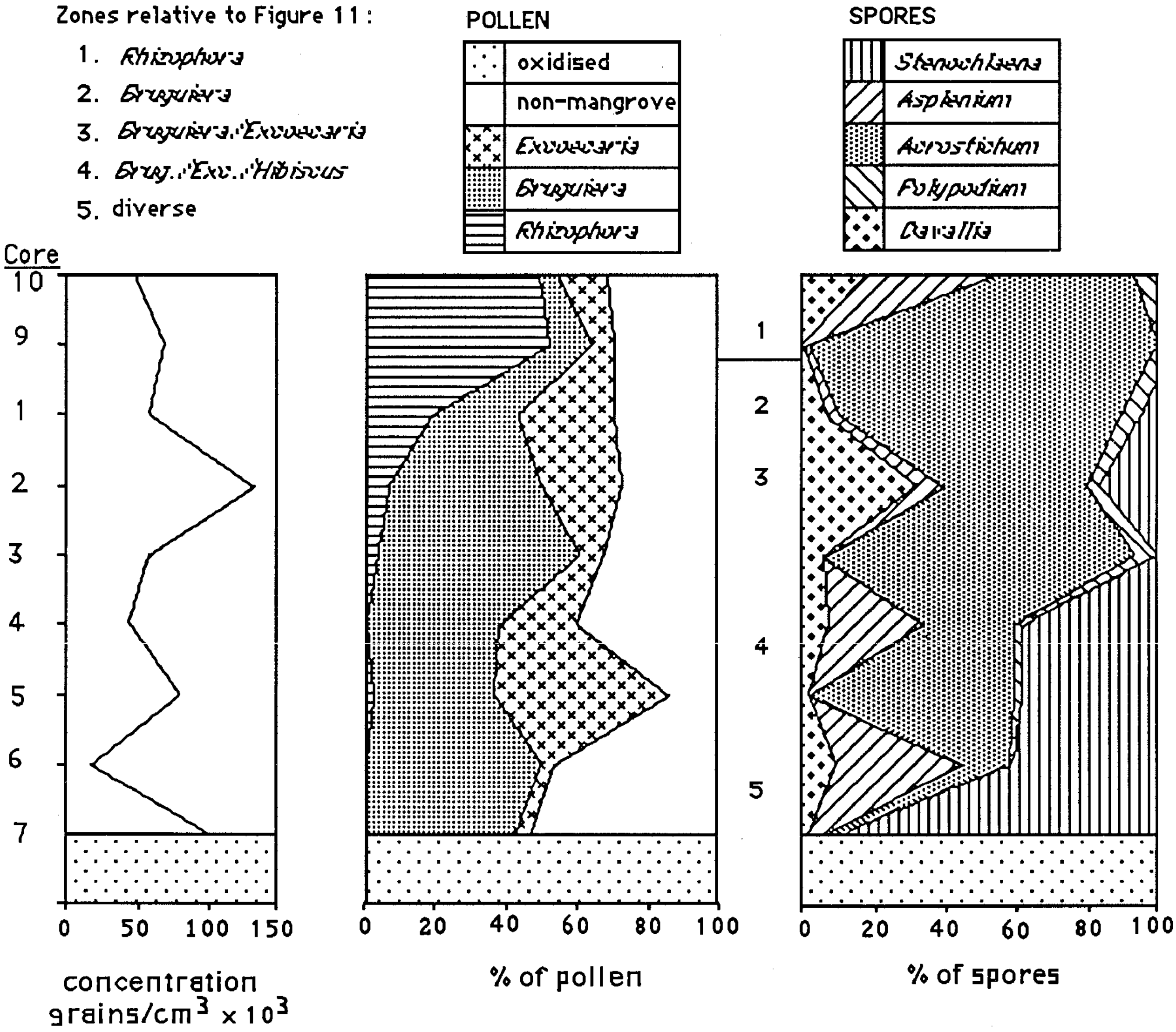


Figure 17: Pollen diagram of surface samples across the Folaha transect.

period were uncommon in the mid-Holocene, aeration of peats in drought events causing the destruction of pollen (Cowgill & Hutchinson 1963).

As sea level rises, mangroves encroach on this marsh. The upper zone mangrove forest shown by pollen assemblages from 1-290 to 1-260 has its modern analogue in the *Hibiscus / Bruguiera / Excoecaria* zone from core 7 to core 4. Upper fringes of the ancient forest are less diverse than the modern analogue, with 54% of pollen from mangrove taxa at 1-290 and 46% at 7-0, indicative of disturbance in the modern forest. The upper diverse fringe in both cases shows greater frequency of *Bruguiera* than lower in this zone. In the ancient forest, *Pandanus sp.* was more common than it is presently in the modern analogue.

Owing to low pollen production, *Hibiscus* and *Excoecaria* do not show the extent of their presence in the ancient forest as do the Rhizophoraceae. However, the occasional pollen of these species by comparison with the modern analogue indicates that they were important constituents of the ecosystem between 1-290 and 1-250. This zone is marked by a *Stenochlaena palustris* spike similar to that of the modern analogue, this epiphyte growing on *Hibiscus* and *Excoecaria*. Increased concentration of the fungal ascospores of *Phoma sp.* at these levels is also indicative of the presence of its host, *Hibiscus tiliaceus* (Kohlmeyer &Kohlmeyer 1979). Through these levels, *Bruguiera* shows high pollen representation, though with a slight reduction at 1-270. This is similar to the lower proportion in the modern analogue at cores 5 and 4, the most productive part of all zonations in terms of above ground biomass, where *Hibiscus* is most dominant. The *Rhizophora* proportion remains low throughout.

*Excoecaria* pollen is less common in the lower peat unit than the upper and surface peats, showing conformity with pollen analyses of mangrove sediments elsewhere. *Excoecaria* pollen usually shows poor representation and localised distribution (Caratini et al. 1973, Tissot 1980, Grindrod 1985). The increased representation of *Excoecaria* pollen in recent peats and surface samples could be caused by increased species abundance, owing to the brackish condition of the lagoon at the present sea level, or increased pollen production. Reference material showed little variation from the detailed description of Tissot (1980), so could not support a minor endemic development of *Excoecaria agallocha* in Tonga suggested by the increased pollen representation.

At 1-240 the *Bruguiera* proportion increases, and *Stenochlaena* and *Phoma* decline in abundance, indicating a zonation change with *Hibiscus* and then *Excoecaria* becoming absent as sea level rises. There is increased representation by the lower mangrove sub-dominant *Polypodium scolopendria.* The *Rhizophora* proportion slightly increases, indicating that this lower zone is closer. *Lumnitzera* pollen shows its most significant presence from 1-250 to 1-240, consistent with its present occurrence in the *Bruguiera* / upper *Rhizophora* zonations.

*Acrostichum aureum* spores show greater presence, indicative of storm related disturbance in lower mangrove zonations. It is thought that mid- Holocene coastal conditions were more subject to storm damage than now, as the growth of protecting reefs lagged behind that of sea level rise (Curray et al. 1970, Hopley 1984).

With continued sea level rise, at 1-230 the *Bruguiera* proportion declines and that of *Rhizophora* increases. The *Rhizophora* zone is shown to be present over core 1 from 1-220 to 1-200, with dominance of *Rhizophora* pollen. Using the modern analogue of *Rhizophora* colonisation of elevations between 0.4 and 0.7 m above MSL, at 1-220 MSL was 2.2 m below present, and at 1-200 it was 1.7 m below present MSL. Ascospores at these levels show significant present of the fungus *Cytospora rhizophorae*, which is host specific to *Rhizophora mangle* and *Rhizophora racemosa* (Kohlmeyer & Kohlmeyer 1979). Occurrence of sponge spicules is very high. At 1-200, the rate of sea level rise is too fast for sedimentation rates within the mangroves to maintain the substrate at an elevation able to be colonised, consequentely mangroves at the core 1 location are drowned out.

Pollen analysis of the lower peat unit showed considerable presence of volcanic ash throughout the unit. Scans of concentrated matter from lower peat units in all other cores showed similar abundance, with particularly heavy falls at certain levels. A period of volcanic activity about 6000 to 5000 BP was responsible for deposits of ash over western and central areas of Tongatapu, including the Folaha location, from which the Vaini soils developed (Gibbs 1976, Orbell 1983). The results from the Folaha core 1 confirm that there was considerable ash fall over this area broadly from 7000 to 5500 radiocarbon years BP.

## UPPER PEAT UNIT.

Stratigraphic sequences show lagoon silt beneath shallow mangrove peat, indicating that the environment of deposition has changed from open lagoon to mangrove. Thus, there has been a fall in lagoon water level, to expose areas of former lagoon bed such that these can be colonised by mangroves. The upper peat is usually only 30 cm thick, except at cores 1 and 2, which seems to have formed in a deeper pool of the former lagoon, giving 70 cm of peat now (see Figure 12). Ponds and ridges in the low tide area are common features in the Fanga 'Uta lagoon, and were present in earlier times (Spennemann 1986).

When this slight fall occurred, areas of lagoon bed at the Folaha transect were exposed. Oxidation of these occurred, at upper areas of the transect, the upper 20 cm of lagoon silt at core 7 being a yellow colour as opposed to the usual grey, and pollen results from the transitional 5-20 level showing oxidation. Mangroves colonised these bare tidal flats, pollen analysis of the upper peat at core 3 and 5 showing that *Bruguiera* forest came into this upper area without being preceded by *Rhizophora.* The lower pond in the area of cores 2 and 1 would have been left dry or impounded by the higher ridge at cores 9 and 10. Pollen analysis of core 1 shows that this was initially colonised by *Rhizophora*, then as peat accumulation raised ground levels, *Bruguiera* forest extended from core 3 down over core 2 and 1.

*Rhizophora* is presently located from midway between core 1 and 9 to core 10, from 0.7 to 0.4 m above MSL respectively, and stratigraphically on the seaward fringes of the infilled former pond, and on the ridge that impounds this. Differences in elevation between the Rhizophora spike at the base of the pond and the present location is 0.4 m, indicating that infill of this degree was necessary before peat levels reached a new stability.

All pollen analyses of upper peat show a high degree of vegetational disturbance, through the proportion of *Acrostichum* spores. In the present forest the disturbance that results in *Acrostichum* cover is due to man, though at the time of these zonation changes *Acrostichum* would also have flourished. Pollen of non-indigenous species, particularly *Psidium guajava*, are present at all levels. The guava arrived in Tonga in the 1830's, and probably became a rampant weed rapidly (Arthur Whistler, pers. comm.). This confirms the recent date of establishment of this mangrove area.

The stratigraphic record at the Folaha mangrove swamp therefore supports the proposal of Zann (1984), that a sudden tectonic uplift of the land of 20 to 40 cm occurred in very recent times, from 40 to 200 years ago. The depth of peats, and infill of the impounded pond show that this sea level fall was 30 to 40 cm. The alien pollen present at all levels in peat indicate that the fall occurred post- 1830.

Early maps of Tongatapu show a significant change to lagoon shorelines between 1852 and 1875. Results from the Folaha transect suggest that Nuku and Nukuhetulu were mid-lagoon islands as recently as two centuries ago, and similar changes to the east of the lagoon peninsula at Kauvai and Longoteme could substantiate the lagoon shape as shown by Wilson (1799), Paris (1833) and Heath (1855). A shoreline change is described during an earthquake in late 1853 (Sawkins 1856), a year after Heath's visit with the *Calliope* in 1852. The earthquake was in association with activity of the Hunga Tonga/ Hunga Ha'apai shoals to the west of Tongatapu, and volcanic ash occurs in peat at the base of the impounded pond. All the evidence therefore indicates that the 1853 event was the cause of a slight raising of the island, resulting in significant shoreline changes within the shallow Fanga 'Uta lagoon, a recession that is recorded by sensitive indicators such as microatoll heads (Zann 1984) and mangrove distributions.

## Assessment of mangrove pollen stratigraphy as a sea level indicator.

Indicators of sea level are of two types (Chappell et al. 1983), those generally suggestive of a sea level stand or change, with modern equivalents forming at varying heights or depths relative to MSL, and those with a specific formative relationship with MSL, which can be used to accurately determine past sea levels from fossil features. Precision required for study of Holocene sea levels develops techniques for use of indicators of the latter type, either organic faunal remains in growth position (Doyle et al. 1979, Taylor et al. 1980), or distributions of mangrove pollen within peat.

Results from the Folaha core 1 lower peat give detailed sea level reconstruction for the period covered, of actual position of MSL at the dated levels, by use of pollen assemblages to identify the plants contributing to formation of that peat; and therefore the elevational position in the ancient swamp at that time. This technique applied to peat formations of other Pacific islands would greatly improve Holocene sea level records available, removing uncertainties regarding calibration to MSL of past sea level data.

The Folaha site has the potential for a sea level construction of far greater detail, if pollen analyses were conducted on several cores, so allowing comparisons between cores, which could identify sudden zonational changes that represent tectonic movements, as shown by results from the upper peat unit.

Use of mangrove zonations as a sea level indicator in this manner assumes that their elevations above the former MSL was the same as that presently. Differences could be caused by change in factors that control zonational elevation, such as amount of fresh water runoff, frequency of storm action, and tidal range. However, the amount of difference caused by change in these factors is small in relation to the vaguaries of other sea level reconstruction techniques in use.

Upper peat and surface pollen and vegetation distributions showed a variation of elevational location that suggests a ±40 cm error margin in the Tongatapu location on use of mangrove zonations to determine former sea levels. The upper peat unit in core 1 at Folaha shows *Rhizophora* colonisation during the recent recession of an area lower than its expected elvational range, this being impounded and therefore available for colonisation by a ridge at core sites 9 and 10 (Figure 12). Elevations within the swamp showed some irregularity, indicating that on the shores of a calm and shallow lagoon, distance from open water had an equal control on soil water salinity, to cause zonation parallel to the shore.

Therefore, while pollen analysis of mangrove peats can show variation in stand composition in response to a changing sea level, direct interpretation of sea level from this evidence assumes that all other factors that control the elevation of mangrove species location are constant. The indications from Tongatapu are that such an assumption cannot be made without substantiation, with patterns of mangrove zonation and succession altering under different strengths of environmental influences. In more exposed locations on the north shore, mangrove colonisation was haphazard, and no peat was able to form beneath the plants, while at calmer locations within the central lagoon, mangroves were organised into zones and were able to accumulate a peat. For a resolution of sea level reconstruction from pollen analysis of mangrove peats, to less than ±10 cm in the microtidal situation, it would be necessary to establish the degree of variation in elevation of mangrove zones, particularly *Rhizophora*, under different strengths of environmental control. The variation of these within short distances on Tongatapu would make this location ideal for such a study.

# CHAPTER 6: CONCLUSIONS.

## 6.1 Conclusions.

Pollen analysis of mangrove peat is shown to refine the sea level record indicated by intertidal stratigraphy, establishing relationships of pollen assemblage indicators with location of parent plants from patterns in the present swamp. The pollen of *Rhizophora* is the most useful indicator, the pollen spike being distinct by its proportional magnitude and narrow elevational range. Patterns of *Rhizophora* pollen distribution indicate that its sedimentation is primarily controlled by tidal processes. The pollen of other mangrove and non-mangrove taxa shows similar adjustment to sea level change, but these are less able to be calibrated owing to poor pollen production or broad elevational range. The distribution of other microfossils across the swamp, such as fungal ascospores and sponge spicules also helps to interpret the sea level record.

While the record of sea level variation throughout the Holocene are available from the Folaha swamp stratigraphy, the clarity of record described is available for two disjunct periods, the late transgressional and historically recent, owing to the occurrence of peat units. Sea level is shown to have stabilised sufficiently for mangrove expansion from 6870±90, and flourished at Folaha until 5650±80, during which time the rate of sea level rise was 12.3 cm/100 years. This early mangrove community has no equivalent elsewhere on Tongatapu, or in the S.W. Pacific, and is indicative of the sheltered nature of the Folaha location. A mid-Holocene highstand during which the western arm of the Fanga 'Uta lagoon was in direct exchange with the ocean is shown from Folaha stratigraphy, but its height cannot be determined from this work. The period of this highstand is estimated between 4500 and 2500 BP. A subsequent fall to stabilise at a level when the lagoon was enclosed from direct oceanic exchange is also stratigraphically shown.

A more recent fall of sea level initiated the present mangrove forest at Folaha. Pollen analysis of modern peats shows that this fall was sudden, and of a magnitude of 30 to 40 cm. Correlation with evidence from non-indigenous pollen and historical records are used to suggest that an earthquake in 1853 was the most likely cause.

## APPENDIX 1.

### Key to the pollen and spores of the Folaha mangrove area.

A dichotomous key to the pollen and spores occurring in the Folaha mangrove area was developed, by building a reference collection from the flowers of species, and using existing descriptions from elsewhere. Where species descriptions are scarce, those for close relatives are referenced. Binomials and taxonomy are taken from Tomlinson (1986) for mangrove species, and other species from where they occur in Yuncker (1959) and Smith (1979-1981).

Dimensions given are the mean and range of five measurements of polar axis x equatorial axis x (for certain pollen shapes only) breadth , measured in silicone oil. The representation of grains in surface assemblages is given, relative to abundance of the source plants, with references to comments in other work.

SPORES.

1: Monolete.

A: Verrucate, verrucae diameter 5.5(5-6)µm, spore 30.8(28-34) x 52.3(40-66) x 40.0µm. Davallia solida (Forst. f.) Swartz.

(Polypodiaceae)

*detailed description*: p. 10, Heusser 1971 (D. valdiviana)

*pollen representation*: medium.

AA: Baculate.

B: Baculae many, 4-5 µm long, spore 33.6(28-38) x 58.8(46-70) x 58.8(46-70)µm (excluding baculae).

Stenochlaena palustris (Burmann)

(Polypodiaceae)

*detailed description*: Photomicrograph in Tissot (1980, plate 16), from India; photomicrographs of S. laurifolia in Caratini & Tissot (1988, p.223).

*pollen representation*: high.

BB: Baculae occasional, 0.5-1.0µm long, spore 34.0(32-36) x 41.4(39-46)µm.

Polypodium scolopendria (Burmann)

(Polypodiaceae)

*detailed description*: Photomicrograph of Polypodium sp. in Hurtado & Riegler-Goihman (1986); photomicrograph of Polypodium pellucidum-type in Ward (1988, p. 254).
*pollen representation*: medium.

2: Trilete.

A: Finely tuberculate, spore 39.0(32-43) x 56.7(46-68) x 55.3(50-62)µm, some reference spores well sculptured but others near psilate, all fossil spores psilate.

Acrostichum aureum (L.)
(Pteridaceae)

*detailed description*: Lloyd (1980, p.101). Van der Hammen (1963, p.139) comments that faint ornamentation may be lost with age.
*pollen representation*: high.

AA: Psilate/ granulate, spore 200 x 200µm, surface broken into large plates 40-50µm diameter.

Asplenium nidus (L.)
(Aspleniaceae)

*detailed description*:
*pollen representation*: medium.

POLLEN.

1: Inaperturate, granular, 29.2(28-30) x 24.6(21-30).

Cyperaceae
(i.e. Cyperus alternifolius flabelliformis, Cyperus javanicus)

*detailed description*: Rao & Ong (1974, p.3), key to the family p. 235 Faegri & Iverson (1975).
*pollen representation*: high. Over-represented (Dodson 1982, p.19), New South Wales; tendency towards high, localised distribution (Grindrod 1983, p.124); efficient pollen production and wind and water dispersal (Grindrod 1988, p.244).

2: 1-porate.

A: Psilate/ scabrate, 54.8(50-62) x 55.4(49-62)μm, exine thin.

Gramineae.
(i.e. Panicum maximum Jacq.)

*detailed description*: Rao & Ong (1974, p.2-3).
*pollen representation*: medium, wind pollinated.

AA: Finely echinate, 18.0x19.0μm

Pandanus tectorius (Parkinson)
(Pandanaceae)

*detailed description*: Leopold (1969, p.1165);Pandanus sp. described by Erdtman (1952, p.307-9); photomicrograph of Pandanus sp. in Ward (1988, p. 260).
*pollen representation*: high. Ash (1987, p.323) described large quantities of pollen blown from male inflorescences, and found deposited on nearby surfaces and in peat, from Fiji. Morley (1981, p.50) described Pandanus helicopus as a very high producer of pollen, from Malaysia. Dodson (1982, p.20) described Pandanus forsteri pollen as well-represented, from New South Wales.

3: 3-porate.

A: Psilate, parasyncolpate, 12.2(11-14) x 19.3(16-22) x 15.0(14-16)μm, oblate.

Syzygium clusiifolium (A. Gray)
(Myrtaceae)

*detailed description*: Pike (1956); photomicrograph of S. stelechanthum in Ward (1988, p. 260), and Syzygium sp. in Burney (1988, p.70).
*pollen representation*: low.

AA: Finely reticulate, 11.0(10-13) x 22.4(20-24) x 19.2(18-22)μm.

Psidium guajava (L.)
(Myrtaceae)

*detailed description*: Rao & Ong (1974, p.18)
*pollen representation*: low.

4: Periporate.

A: Psilate/ perforate, 24.6(22-26) x 29.2(26-33).

Geniostoma insulere
(Loganiaceae)

*detailed description*: Erdtman (1952, p.247) describes G. rupestre from Fiji.
*pollen representation*: low.

AA: Echinate.

B: Grain diameter 29µm (excluding spines), spines 5µm long. — Wollastonia biflora (Compositae)

*detailed description*:
*pollen representation*: low.

BB: Grain diameter 134µm (excluding spines) spines 20µm long. — Hibiscus tiliaceus (L.) (Malvaceae)

*detailed description*: Rao & Lee (1970, p.263); Erdtman (1952, p.261).
*pollen representation*: low. Malvaceae under- represented (Dodson 1982, p.19), New South Wales.

5: 1-colpate, psilate or faintly granulate, irregular outline, 49.2(42-54) x 33.8(29-38).

Cocos nucifera (L.)
(Palmae)

*detailed description*: Nair & Sharma (1963), Mallik & Chaudhuri (1966-7). Photomicrograph in Tissot (1980), plate 14; Erdtman (1952, p.304) quotes Selling's size description of 34 x 53 x 33µm.
*pollen representation*: medium. Low allochthonous representation in mangrove sediments (Caratini et al. 1973, p. 288), from India.

6: 3-colporate.

A: Reticulate.

B: Grain <45μm diameter. Pores have large costae, 37.4(32-41) x 30.8(29-32)μm, elliptical in e.v., sub- circular in p.v., nexine thinner than sexine.

Excoecaria agallocha (L.)
(Euphorbiaceae)

*detailed description*: Tissot (1980, p.179-183). Other Excoecaria species described Punt (1962, p.97-99).
*pollen representation*: low to medium. 2 to 5% of assemblage (Tissot 1980, p.121), from India. Representation of pollen in sediments only one- third of the expected value (Caratini et al. 1973, p. 291) from India; very localised distribution (Grindrod 1985, p.133, 148), occurrence low to sporadic (p. 121), and poor representation (Grindrod 1988, p.243); Insect pollinated (Tomlinson 1986, p.240).
*flowering phenology:* December, N.E. Australia (Bunt et al. 1984)

BB: Grain >45 μm diameter, sexine thicker than nexine.

C: Grain lobed, 60.7(52-76) x 64.7(64-66) Leucaena leucocephala (Lmk.)deWit
(Leguminosae)

*detailed description*: Erdtman (1952, p.226) describes L. glauca.
*pollen representation*: low. Feeble representation of pollen, but the species is less common in the mangrove (Caratini et al. 1973, p. 290), from India.

CC: Grain not obed, pore gapes, 56.0 x 67(62-78) x 74(68-82) μm, nexine same thickness as sexine.

Morinda citrifolia (L.)
(Rubiaceae)

*detailed description*: Johannsson (1987, p.140); Leopold (1969, p.1175); Erdtman (1952, p. 384) describes M. longiflora.
*pollen representation*: low.

AA: Not reticulate.

D: Sculpturing fine (<1.5μm)

E: Pseudocolpi between colpori, psilate/ scabrate, 35.3(34-37) x 34.0(32-38)μm, costae.

Lumnitzera littorea (Jack) Voigt.
(Combretaceae)

*detailed description*: Leopold (1969, p.1172); Rao & Ong (1974, p.18) described L. coccinea; Huang (1972, p. 80) described L. racemosa.
*pollen representation*: low. Pollinated by birds (Tomlinson et al. 1978, p. 347); very localised distribution (Grindrod 1985, p.148; 1988, p.243).
*flowering phenology:* Nov., N.E. Australia (Bunt et al. 1984, p.93)

EE: No pseudocolpi.

F: Apertures costate, grain irregular in outline.

G: Uniformly perforate, 22.8(22-24) x 22.2(22-23)μm, long colpi.

Rhizophora mangle (L.)
(Rhizophoraceae)

*detailed description*: Muller & Caratini (1977); Assemien (1969, p.75); Bertrand (1983, p. 148); Van der Hammen (1963, p. 141-2) commented on variation of grain size with age.
Pollen indistinguishable from R. lamarkii and R. apiculata (Muller & Caratini 1977, p. 379)
*pollen representation*: high. High (Muller 1959), from Venezuela; (Van der Hammen 1963, p.137), from Guyana; (Bertrand 1983, p.151), from Jamaica;
Wind pollinated (Muller 1959, p.12); (Tomlinson et al. 1979, p.273);
*flowering phenology:* May to June, Florida (Gill & Tomlinson 1971)

GG: Not uniformly perforate, psilate, with scattered verrucae, 23.4(22-25) x 23.8(23-25)μm, relatively short colpi.

Rhizophora stylosa (Griff.)
(Rhizophoraceae)

*detailed description*: Muller & Caratini (1977)

Pollen indistinguishable from R. mucronata (Muller & Caratini, p. 378)

*pollen representation*: high. Wind pollinated (Tomlinson et al. 1979, p.273)

*flowering phenology:* Feb. to April, N.E. Australia (Duke et al. 1984, p. 93)

FF: Apertures not costate.

H: Grain finely granular, 23(22-25) x 23.8(22-26)µm, sub- circular in p.v. and e.v., nexine equal thickness to sexine.

Bruguiera gymnorrhiza (L.)Lamk.
(Rhizophoraceae)

*detailed description*: Tissot (1980, p. 156-159); Leopold (1969, p.1170-1); Huang (1972, p.193)

*pollen representation*: high. Explosive release triggered by insects or birds (Davey 1975, Tomlinson et al. 1979); bird pollinated (Kondo et al. 987).

*flowering phenology:* winter season. Winter, N. Queensland (Tomlinson et al. 1979); April to August, N.E. Australia (Duke et al. 1984, p.93)

HH: Grain not finely granulate, perforate, colpori short, sexine same thickness as nexine, 15x14µm.

Lantana camara (L.)
(Verbenaceae)

*detailed description*: not available.

*pollen representation*: low.

*flowering phenology:* flowers round the year (Gupta et al. 1984)

DD: Sculpturing coarse (>1.5µm)

I: Foeveolate, nexine thicker than sexine, 35.0(33-38) x 25.7(22-28)µm.

Rhus taitensis (Guillemin)
(Anacardiaceae)

*detailed description*: Erdtman (1952, p.48) described Rhus sp.

*pollen representation*: medium.

II: Clavate, clavae 0.5-1.5μm long, grain lobed, sexine thicker than nexine, 71.3(68-77) x 71.3(70-72)μm. Clerodendrum inerme (L.) Gaertn. (Verbenaceae)

*detailed description*:

*pollen representation*: low. Pollen not found in sediments (Caratini et al. 1973, p. 291), from India. Insect pollinated (Vishnu-Mittre & Guzder 1973, p. 114); pollinated by hawk- moths, very low pollen production (Primack et al. 1981, p.349); poor representation (Grindrod 1988, p. 243).

7: 4-colporate.

A: Psilate, no reference material available. Xylocarpus granatum (Koen.) (Meliaceae)

*detailed description*: Huang (1972, p. 165) described pollen of the family. Blasco (1984, p.38) stated that it is hazardous distinguishing pollen within this family.

*pollen representation*: low. Low representation (Grindrod 1983, p.124; 1988, p. 243), from Queensland;

*flowering phenology:* Dec. to Jan., N.E. Australia (Duke et al. 1984, p.93)

AA: Sculptured: striate, pores nearer one pole, 31.5(30-34) x 25.0(24-26) x28.0μm. Derris trifoliata (Lour.) (Papilionoideae)

*detailed description*:

*pollen representation*: low. Pollen not found in sediments (Caratini et al. 1973, p. 291), from India; poor representation (Grindrod 1988, p. 243).

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