Mangrove pollen of Indonesia and its suitability as a sea-level indicator

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How to cite:

Engelhart, Simon Edward (2007) Mangrove pollen of Indonesia and its suitability as a sea-level indicator. Masters thesis, Durham University.

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Thesis submitted for the degree of Master of Science

Department of Geography

Durham University

March 2007

For Kate

Declaration

This thesis is the result of my own work. Data from other authors that are referred to in the thesis are acknowledged at the appropriate point in the text.

Acknowledgements

I would like to thank all those people who have helped in the production of this thesis. Firstly, I would like to thank my supervisors Dr Dave Roberts and Dr Ben Horton for their guidance and enthusiasm in the completion of this project. The completion of this thesis would not have been possible without their input and insightful comments. I would also like to extend my thanks to Dr David Smith at Operation Wallacea for his help and support in the organisation of the associated fieldwork for this project. Thanks also go to Dr Matt Wright for his input into the project.

In addition I am indebted to Emily Ashton, Naomi Bird, Nick Steiner, James Coles, James Lees and James Dutton for their help in the field in the summer of 2004. I would also like to thank the members of the Geography department, specifically Neil Tunstall, Alison Clark, Amanda Hayton, Frank Davies and Derek Coates for all their assistance in the laboratory.

Finally I thank my Dad – John, Step Mum – Jacqui, Sisters – Helen and Amanda and Nana – Nell for their love and support, my girlfriend Lucy for all her support in the field and for keeping me sane after months of microscope work. Thanks also go in this regard to Innes McFee, Alex Walton, James Warden and Ben Ferguson.

Abstract

Mangrove pollen of Indonesia and its Suitability as a Sea-level Indicator

Simon Edward Engelhart

I investigated the mangroves of Southeast Sulawesi, Indonesia, to assess their potential as proxies for reconstructing sea-level during the Holocene. Initial investigations confirmed that the mangrove species demonstrate zonations parallel to the shoreline and are dominated by the family Rhizophoraceae with *Avicennia*, *Heritiera* and *Sonneratia* also important constituents of the mangroves.

The vertical distributions of pollen assemblages were investigated at three sites in Southeast Sulawesi, Indonesia. Partial CCA analysis demonstrated that at all three sites, elevation was a significant control on the distribution of pollen assemblages in surface samples. The three contemporary transects were combined to develop a regional transfer function to elucidate the relationship between the surface assemblages and elevations using the Maximum Likelihood (ML) method. The developed transfer function indicated mangrove pollen can be utilised as a precise indicator of past sea-levels with an error of ±0.22m. The transfer function was applied to two fossil cores from the Wakatobi Marine National Park and evaluated using the Modern Analogue Technique. Both cores showed similar patterns in changes of Reference Water Level and had modern analogues in the contemporary training set. I conclude that mangrove pollen is a suitable proxy for reconstructing sea-level in tropical environments.

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1 – Introduction

1.1 Background

Mangroves are an important aspect of the coastal environment in the tropics and provide protection from tidal and wave action as well as acting as important nursery grounds to a number of species of fish and shrimp (Martosubroto and Naamin 1977; Turner 1992; Sasekumar et al. 1992; de Graaf and Xuan 1999). Mangroves are also of prime economic importance with a UNEP report (UNEP-WCMC 2006) valuing mangroves at up to $3.5 million per square km per year through a combination of coastal defences, tourism and farming. Furthermore, the natural ability of the mangroves to trap waterborne sediment and as such reduce the turbidity of ocean waters (Bigelow et al. 1989) is of essential importance to the development of coral reef systems (Kleypas 1996). Research undertaken after the Indian Ocean Tsunami in 2004 shows that areas with well developed mangroves suffered proportionally less damage than those areas where mangroves had been replaced due to farming and other coastal development (Dahdouh-Guebas et al. 2005, Kathiresan and Rajendran 2005, Horton et al. in review, Bird et al. in review). As such, it is of primary importance to study contemporary mangrove systems and also understand their evolution under periods of sea-level rise and fall during the Holocene. Furthermore, sea-level changes in far-field locations (those with a distal position from formerly glaciated areas), are of interest, as they provide the most robust constraints on the eustatic component of the sea-level signal (e.g. Nakada and Lambeck 1989; Fleming et al. 1998; Lambeck 2002; Milne et al. 2002; Peltier 2002) and can be employed to constrain the source geometry of major meltwater pulses (Clark et al. 2002; Bassett et al. 2005). The use of coral reconstructions (Fairbanks 1989; Chappell and Polach 1991; Bard et al. 1996) has proved extremely useful for reconstructions prior to the Holocene but the large error ranges (±2.5m, Fairbanks 1989; ±5m Blanchon 2005) limit their use for Holocene reconstructions where the error is often greater than the magnitude of the change being investigated.

Microfossils are frequently utilised as proxies for sea-level due to their ability to accurately and precisely reconstruct former sea-levels (e.g. Scott & Medioli 1978, 1980; Horton et al. 1999; Gehrels 2000; Shennan et al. 2000; Campeau et al. 2000; van de Plassche 2000; Horton et al. 2003, 2005a,b; Horton and Edwards 2005, Franceschini et al. 2005 and Ruiz et al. 2005). Early sea-level research relied heavily on the use of marsh pollen as a proxy for sea-level, with the first sea-level curve produced by Godwin (1940) in the English fenland. Developments within the last 30 years in the use of the vertical zonations of foraminifera (Scott and Medioli, 1978) and diatoms (Zong 1997) have resulted in a movement away from pollen as a sea-level proxy in the last ten years, partly due to the coarse resolution of pollen assemblages (Freund et al, 2004) and its apparent unsuitability as a quantitative approach to sea-level reconstruction. Work by Horton et al (2005a) and Debenay et al (2004) have shown that Foraminifera are capable of reconstructing sea level in tropical environments, however the fossil record is prone to preservation issues with Debenay et al (2004) stating that foraminifera in mangrove environments are "dramatically affected by taphonomic processes". Woodroffe et al (2005) in Australia also demonstrate that foraminifera preservation within mangrove sediments is problematic. Diatom preservation is also problematic within fossil cores, potentially due to the high salinity and temperature of the mangrove environments that promotes their dissolution (Barker et al. 1994).

Due to these preservation issues, mangrove pollen has the greatest potential of the major microfossil groups for accurately and precisely reconstructing sea-level from mangrove environments. The strong outer exine of the major mangrove species should result in less taphonomic issues than affect foraminifera and diatoms: indeed palaeoenvironmental reconstructions utilising pollen have been produced from Australia (Grindrod 1985, 1988; Kershaw et al. 2002), Tonga (Ellison 1989), Borneo (Anshari et al. 2001) and Irian Jaya (Ellison 2005). The use of mangrove pollen as a proxy is further enhanced by the coastline parallel species zonations demonstrated by mangroves (Grindrod 1985, 1988, Ellison 1989, Kamaludin 1993, Ellison 2005), which suggest that species zonation is controlled primarily be tidal inundation (and thus elevation), which is essential for a proxy of past sea-levels. Previous studies have relied on qualitative or semi-quantitative methods, which potentially limit the accuracy and precision of the sea-level reconstructions. The development and application of quantitative methods such as the transfer functions (Zong and Horton 1999; Horton et al. 1999; Campeau et al. 2000; Sawai et al. 2004; Patterson et al. 2004), potentially allows for the elucidation of past sea-levels with greater precision and accuracy.

1.2 Aims and Objectives

1.2.1 Aims

1. To develop the first mangrove pollen-based transfer function to quantify the relationship between mangrove pollen and elevation relative to a component of the tidal frame.
2. Apply the transfer function to fossil samples and evaluate the use of mangrove pollen as a proxy for relative sea-level.

1.2.2 Objectives

1. Summarise the suite of relative sea-level observations from near-, intermediate- and far-field sites to better understand the context of this study.
2. Identify the different techniques that have been employed in the reconstruction of relative sea-level and to understand their positive and negative aspects.
3. Systematically document both the modern distribution of mangrove species and their pollen assemblages in Southeast Sulawesi, Indonesia.
4. Understand the relationship between pollen assemblages and the environment, testing the hypothesis that mangrove pollen assemblages are controlled by their elevation within the tidal frame.
5. Develop the first mangrove pollen-based transfer function for sea level.
6. Apply the transfer function to a suite of fossil samples to produce the first quantitative reconstruction of palaeo mangrove elevations in Indonesia.
7. Discuss the implications and limitations of utilising mangrove pollen in a transfer function.

1.3 Thesis Structure

This thesis presents the results of a study of three contemporary mangrove environments in Southeast Sulawesi, Indonesia (Laulua, Mantigola and Kakenauwe), the development of a transfer function to quantitatively elucidate the relationship between mangrove pollen assemblages and elevation, and the application of this transfer function in generating an accurate and precise relative sea-level reconstruction.

Chapter 2 of this thesis introduces the mechanisms of sea-level changes and the typical sea-level curves that are identified in near-, intermediate- and far-field sites. The chapter then introduces the varying techniques that are employed in sea-level reconstruction before concentrating on the use of pollen and transfer functions in sea-level research.

Chapter 3 outlines the geological and geomorphological settings of the sites located in the Wakatobi Marine National Park and the site at Kakenauwe on the island of Buton.

Chapter 4 describes sampling strategy employed by this research and the methodologies used to achieve the aims and objectives outlined in this chapter. It goes on to elucidate the relationship between pollen dispersal and deposition in general and then more specifically within mangroves.

Chapter 5 introduces the contemporary results from the three study sites including the analysis of environmental variables and statistically describes the relationships between pollen distribution and the measured environmental variables.

Chapter 6 outlines the development of the pollen transfer function to two fossil cores collected from the Wakatobi Marine National Park and evaluates the use of a pollen transfer function in reconstructing palaeo mangrove elevations compared to traditional qualitative or semi-quantitative methods.

Chapter 7 evaluates the research in relation to the project's initial aims and objectives and finishes by making recommendations on future research in the field of mangrove palynology and specifically in its use as a quantitative proxy indicator of former sea-levels.

2 - Relative Sea-Level Changes during the Holocene

2.1 Introduction

Relative sea-level change can be defined as the variation in the eustatic function of sea-level and its interplay with any local changes in land elevation at a particular site. As such, a change in relative sea-level (RSL) can denote vertical movement of the land, the sea or both. A RSL rise does not necessarily indicate a change in the eustatic component of sea-level as isostatic processes may be active as well as local scale processes such as uplift or depression of the land surface due to tectonics.

As such, RSL can be affected by the changes of ocean volume caused by the expansion and melting of the polar ice-sheets, steric effects due to changes in water volume at different temperatures or through changes in tidal regime over time (Shennan et al 1995). RSL can also be modified without any changes in total ocean volume. The subsidence and uplift of the oceanic crust due to water loading, changes in the shape of the geoid, tectonic processes on land, isostatic uplift and depression due to the melting of ice-sheets and gravitational changes due to the change in size of the polar ice sheets can all have the effect of changing RSL.

Shennan and Horton (2002) express the interplay between eustatic, isostatic and local scale processes on RSL change as a function of:

$$\Delta\xi_{rsl}(\tau,\varphi)=\Delta\xi_{eus}(\tau) + \Delta\xi_{iso}(\tau,\varphi) + \Delta\xi_{tect}(\tau,\varphi) + \Delta\xi_{local}(\tau,\varphi)$$

Where, $\Delta\xi_{rsl}(\tau,\varphi)$ is RSL at a time and location, $\Delta\xi_{eus}(\tau)$ is the time-dependent eustatic function, $\Delta\xi_{iso}(\tau,\varphi)$ is the total isostatic effect of glacial rebound incorporating both glacio-isostatic and hydro-isostatic factors, $\Delta\xi_{tect}(\tau,\varphi)$ is any tectonic effect and $\Delta\xi_{local}(\tau,\varphi)$ is the effect of local factors on the site.

As already highlighted, eustatic sea-level change reflects the volume of water in the earth's oceans. There is a direct link between the size of the ice-sheets and the global ocean volume with a decrease in one resulting in an increase in the other. At the last glacial maximum (LGM), sea-level was reported to be 120m lower in Barbados based on coral terraces (Fairbanks 1989), 135m lower in the Bonaparte Gulf, Australia (Yokoyama et al. 2000) though this figure has been challenged by Shennan and Milne (2003), 117.8m lower through modelled predictions (Peltier 2002) and 105m lower based on tectonic corrections (Peltier 1994) than at the present day. There is however good agreement between the timings of the sea-level minima with Fairbanks and Yokoyama indicating a sea-level of -120m at 19,000 cal yr. BP in Barbados and the Bonaparte Gulf respectively. Yokoyama highlights the difference in the elevation of the sea-level minima as being due to the Barbados record not commencing from the LGM but slightly later and thus missing the LGM sea-level minima.

Steric effects, whilst a small factor compared to the input of meltwater from the ice-sheets, has an effect on RSL nonetheless. As water is heated, its volume increases and as such, an increase in temperature will not only raise sea-level through an increase in the ratio of glacial ice to ocean water but also by increasing the volume of the water. De Wolde et al. (1995) estimated that sea-level over the last 100 years has risen by between 2.2cm and 5.1cm due to the thermal expansion of water. Cazenave (1999) reports data from the Topex-Poseidon satellite, which shows a 2mm yr^{-1} rise in sea-level since 1993 which "mostly results from thermal expansion of the ocean waters".

Clark et al. (1978) presented a global geophysical model (figure 2.1), splitting the globe into 6 regions based on the theoretical response to sea-level rise since the LGM. As the model suggests, the sea-level response to a glacial event can be complex and as such, far-field locations are extremely important in decoding the eustatic function due to their low combined glacio-isostatic effects. These models have continued to be developed with Peltier, Lambeck, Milne and Mitrovica leading the field although debate continues to rage over the application of these models and whether it is correct to adjust the models to fit one specific data set. Work in the British Isles by Peltier et al. (2002) highlights that modifying the model to fit one locality invariably cause the models to incorrectly predict the sea-level history at another locality.

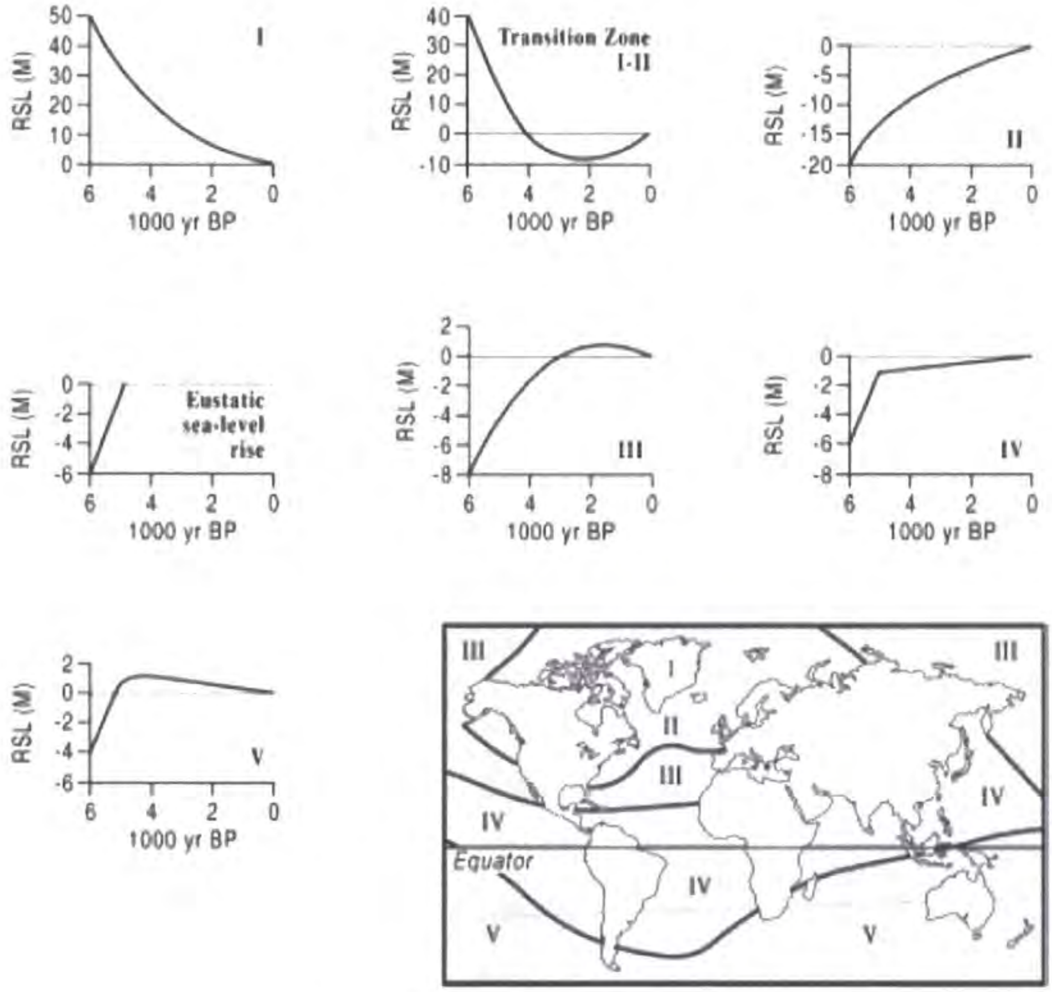


Figure 2.1 – Geophysical Model of Clarke et al. (1978) splitting the globe into six regions based on the theoretical response to sea-level rise since the LGM

2.2 Records of relative sea-level change from near-, intermediate- and far-field sites

2.2.1 Near-field sites

Near-field sites (e.g. Greenland, Norway, Canada, N.W. Scotland) demonstrate a complex response to sea-level rise since the LGM due to the interaction of both isostatic and eustatic processes which have different magnitudes at different times during the Holocene.

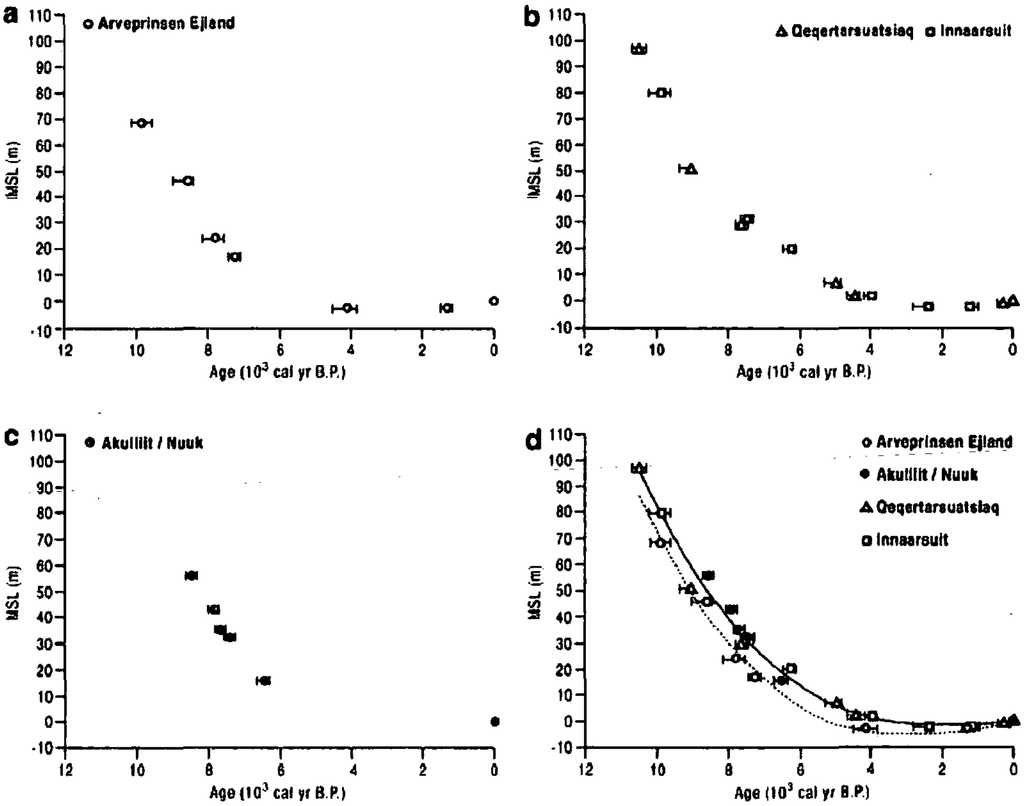


Figure 2.2 – Relative sea-level curves for four sites from Greenland, presented in Long et al. (2003)

Long et al. (2003) demonstrate a rapid sea-level fall (figure 2.2) from the onset of deglaciation due to the rapid isostatic uplift of the land, passing the present sea-level at 3500 cal. yr B.P. Since 2000 cal yr B.P. there has been a 3m rise in relative sea-level due to the further isostatic depression of the land during a 50km advance in the ice-sheets. This has resulted in a spatially variable sea-level curve with late-Holocene sea-level rise being greater in the north at Arveprinsen Ejland than at Qeqertarsuatsiaq.

Data from N.W. Scotland, presented by Shennan and Horton (2002), identifies an initial drop in RSL due to rapid isostatic uplift (figure 2.3). This is in turn replaced by a temporary increase in RSL due to the decrease in the rate of isostatic uplift in the early to mid-Holocene, allowing the eustatic increase to overtake the isostatic uplift. The pattern then reverses again with a decrease in relative sea-level from 6000 yrs BP due to the decreasing nature of the eustatic function, allowing the continuing but reduced isostatic uplift to shape the RSL history.

2.2.2 Intermediate-field sites

Intermediate field sites (England, eastern seaboard USA) generally exhibit a continuous increase in RSL through the Holocene. These sites lies within 2000km of the formerly glaciated areas and so are affected by the peripheral forebulge of the ice sheets. Due to the subsidence of this forebulge, the sites exhibit an increase in relative sea-level rise with the rate of rise decreasing through time as the subsidence of the forebulge slows. Models such as Lambeck (1995) predict this well for southern and middle England, however the model does not predict the late Holocene highstand exhibited by sites in northern Northumberland (figure 2.4) as demonstrated by Shennan et al. (2000). The model of Lambeck did not predict sea-levels above present in this area, however Shennan et al. highlight a highstand of 2.5m due to differential uplift caused by the British ice-sheet.

2.2.3 Far-field sites

Far-field sites are dominated by the eustatic function due to their distance from the polar ice sheets. Therefore, reconstructions from far-field areas are representative of eustatic changes due to the low isostatic effects (Long, 2001), as long as local tectonic influences are accounted for. RSL reconstructions from far-field sites exhibit differing responses to eustatic change due to the principles of equatorial ocean siphoning and continental levering advanced by Mitrovica and Milne (2002). These principles may be responsible for how far-field sites respond to eustatic change with certain sites exhibiting a mid-Holocene highstand (Nunn 2000), a double mid-Holocene highstand (Tija 1996) or no highstand (Kayanne et al. 1993). The unfiltered eustatic signal that far-field sites can provide has resulted in a large number of research projects concentrating on these areas to understand the deglacial chronology of the polar ice sheets.

2.3 Sea-level reconstruction techniques

This section reviews the number of different methods applied to reconstruct RSL in far-field locations. The vast majority of the studies come from cored coral. The sea-level

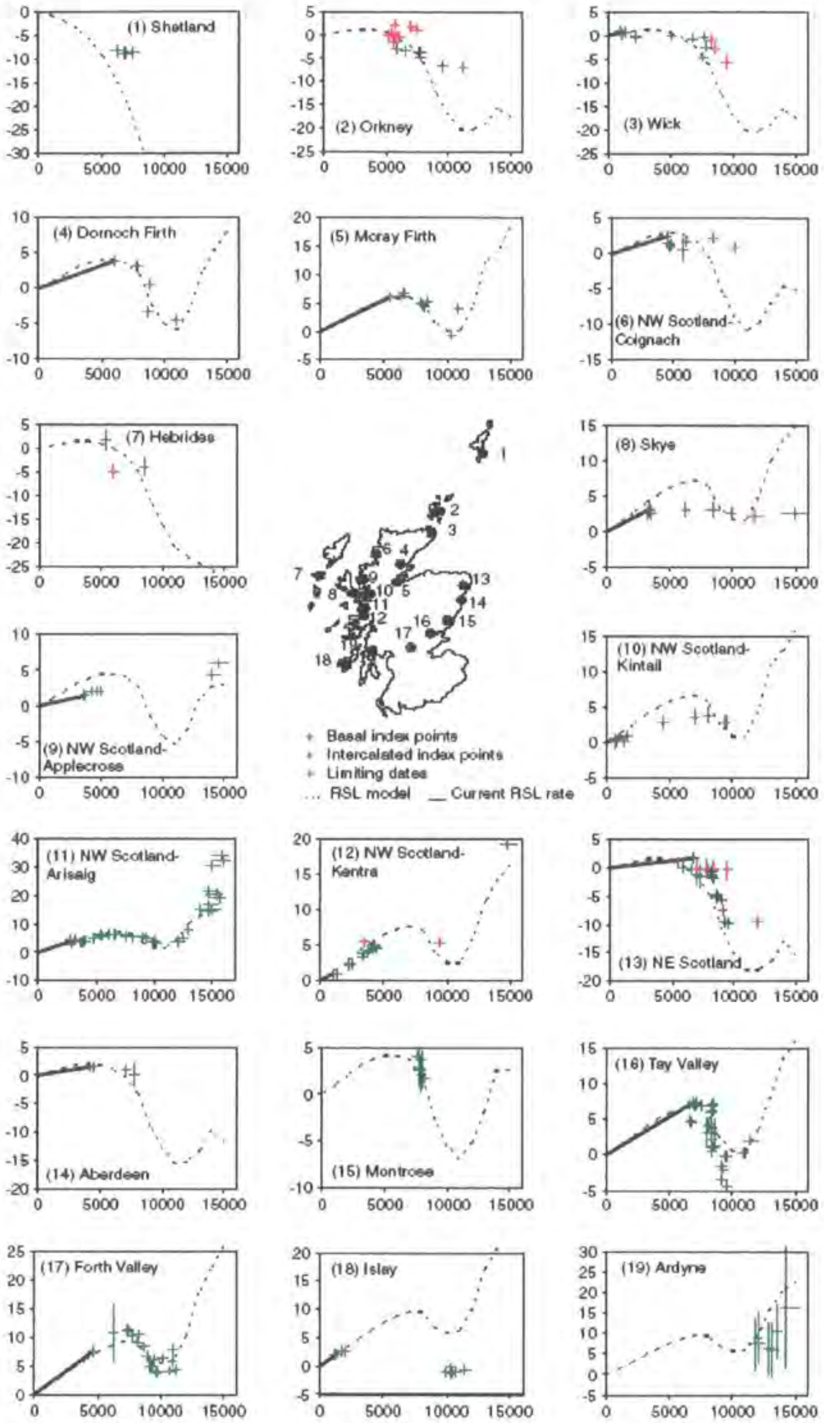


Figure 2.3 – Sea-level data for Northwest Scotland from Shennan and Horton (2002)

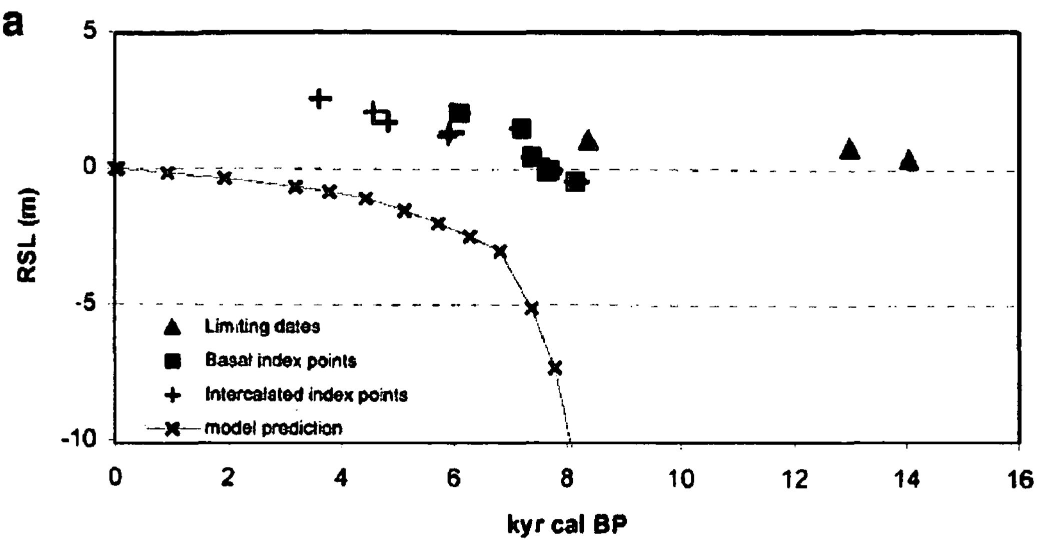


Figure 2.4 – Misfit between the geophysical model of Lambeck (1995) and the data from North Northumberland

curve of Fairbanks (1989) from Barbados gave science its first LGM to present eustatic sea-level curve. However, cored corals have a large indicative range and lack the precision of lithostratigraphical and biostratigraphical reconstructions that are also presented here. Geomorphological features such as wave-cut notches and abrasion platforms have also been used as indicators and whilst they suffer the same issues in terms of indicative ranges as coral based approaches, they have been used by a number of studies into far-field highstands and as such are represented here.

2.3.1 Coral approach

The use of coral records as proxies for sea-level change has dominated the debate over the change in the eustatic function since the LGM. Fairbanks (1989) first proposed a coral based curve dating from 19,000 years BP and giving a LGM sea-level minima of

120m. Fairbanks curve is taken from Barbados and this introduces an error due to the tectonic instability of the Caribbean. Barbados is on an accretionary prism between two oceanic plates and has been undergoing periods of uplift since the LGM. Whilst the Fairbanks reconstruction takes into account a constant rate of uplift, presumed to be 0.34mm yr^{-1}, there is evidence that the uplift is in fact episodic and not continual with Lambeck et al. (2002) attributing a different uplift rate of 0.25mm yr^{-1}. The nature of episodic tectonic events makes it extremely difficult to account for this error and any reconstruction based within the area must be treated with caution. The second issue with Fairbanks reconstruction is that it is taken from three separate coral sequences. This has resulted in gaps in the record with often large differences between the sea-levels at both side of the split. This has been interpreted as meltwater pulses from the polar ice sheets but this is not as reliable as a continuous record demonstrating the rise in eustatic sea-level since the LGM. Meltwater pulse 1a dates to 14.5 ka BP and is notable by a 24m sea-level rise in less than 1000 years. This event is seen to precede the Younger Dryas by 1000 years and is also represented in the delta 18O record (Fairbanks 1989).

Chappell and Polach (1991) present a coral record from raised coral terraces in the Huon peninsula in Papua New Guinea. This record is again fraught with tectonic issues with the study classifying a continuous uplift rate of 1.9mm/yr since the LGM. Again, the Huon Peninsula is prone to episodic large-scale uplift events and not continuous uplift and the presumption that uplift is continuous is flawed and may provide erroneous data.

Bard et al. (1996) presented the first set of coral data not taken from a tectonically uplifting coastline in Tahiti. The record obtained in Tahiti parallels that of Fairbanks in Barbados and confirms the existence of meltwater pulse 1a. Whilst Tahiti is not tectonically active, its creation was linked to tectonic activity in the area and as such is now subsiding at an estimated rate of 0.2mm yr^{-1}. The Tahiti record is interesting, as it does not contain the further meltwater pulses suggested by Fairbanks (1989) from the Barbados record. Due to the global nature of the eustatic function, any large meltwater pulse should be recorded globally even if they are not entirely synchronous or of the same magnitude.

The coral records presented here have allowed us to gauge the eustatic component since the LGM. However, these records are not as accurate or precise as they are often highlighted to be. As already flagged, all three of the cored coral records come from areas with a tectonic component and this is further complicated by the episodic nature of the uplift rates at the Huon peninsula and in Barbados. The non-appearance of meltwater pulse 1b and meltwater pulse 2 in the Tahiti record casts doubt on what should be a global change in eustatic sea-level. Coral reconstructions are further constrained by the accuracy of the species used. The majority of coral reconstructions are based on *Acropora palmata*, a shallow dwelling coral believed to live within 5m of the surface. However, further work on species has found that it has a poorly constrained depth limit and this leaves the species with an indicative range of ±2.5m at best even before complications associated with storm ridges (Blanchon 2005)

Further work has since been developed by Woodroffe et al. (2000) and Smithers and Woodroffe (2001) on using coral microatolls as indicators of past sea-level. Coral microatolls are intertidal corals and their growth range is limited by sub-aerial exposure at low tides. Smithers and Woodroffe (2001) state that the upper growth limit of *Acropora* microatolls varies by as much as 40cm. However, in earlier research by Smithers and Woodroffe (2000), it is noted that the microatolls occupy a constrained, relatively narrow and consistent elevation range, making the species ideally suited to high precision sea-level reconstructions and with error ranges over 10 times smaller than the errors allowed for from cored coral.

Nunn (2000) uses microatolls to investigate the late-Holocene sea-level regression from Fiji. He concludes that sea-level attained a height of 1.6m above LAT between 6000-3000 yr BP. Whilst Nunn takes into account errors in measurement (±10cm) he does not quantify the error caused by the variation in the growth position of *Porites* microatolls, which as highlighted by Smithers and Woodroffe (2000) could be as much as ±20cm. Even so, the errors are still well within the altitudinal range suggested for the highstand and as such this can be interpreted as a reliable late-Holocene reconstruction.

Scoffin and Le Tissier (1998) present data from Phuket, Thailand based on dated fossil massive Porites corals, which commenced growing 6 ka cal BP. They conclude from these data that spring tides in the Phuket region were at least 1m higher than present at this period. Sea-level has since declined from this point at a steady rate over the last 6000 years. Scoffin and Le Tissier (1998) interpret this data as representing either a mid

Holocene higher sea-level from data based on mid-ocean coral reefs or due to the hydroisostatic flexure of the Thai coastline. This conclusion is reached due to the relative tectonic stability of the Phuket area that precludes tectonic based interpretations of falling sea-levels.

2.3.2 Lithostratigraphic approach

Gischler (2003) presents a record of 31 vibra-cores taken from the Belize platform lagoonal areas. The majority of the cores recovered showed a general succession from a basal soil overlying a Pleistocene limestone, which is in turn overlain by mangrove peats and carbonate sediment. Gischler explains the development of the facies as being caused by the Holocene transgression. As sea-level rose, enhanced groundwater was made available which aided soil production. As the sea-level continued to rise, the bedrock rim was breached and allowed for the development of *Rhizophora* and *Avicennia* mangroves. Continued sea-level rise resulted in the diminishment of the mangroves and the development of peripheral reefs on the bedrock rim. Further rise eventually resulted in open marine conditions being established.

Gischler's study differs to that of Mackinnon and Jones (2001) who identified freshwater to brackish peats below the mangrove deposits on Grand Cayman. It is hypothesised that the inundation of the Belize platforms occurred during the early Holocene when eustatic sea-level rise was greater than in the late Holocene when Grand Cayman was inundated. Rates of sea-level rise of 0.7mm yr^{-1}, 0.41mm yr^{-1} and 0.28mm yr^{-1} are reported though no effort is made to quantify any error ranges for this reconstruction. The study is limited in that while the facies are used to identify a trend in sea-level, no attempt is made to quantify the error terms associated with the change in sea-level. Shennan (1982) demonstrated that indicative ranges can be identified for facies in the Fenland, UK, and this should also be possible for Belize. Sediment compaction may also play a part in distorting the reconstruction and placing index points lower than their original point of deposition as highlighted by Long et al. (2006). However, when the index points are plotted against a western Atlantic coral based sea-level curve presented by Lighty et al. (1982), the index points do not plot significantly below the coral based curve. Shennan and Horton (2002) prefer the use of basal soils and peats above Pleistocene substrate as it is less prone to compaction than intercalated sediments and this may explain the good general fit between these points. Gischler also highlights that the rates of sedimentation are not able to keep pace with the Holocene rise in sea-level and thus highlights a large potential error in using cycle thickness as a proxy for eustatic sea-level change.

Bezerra et al. (2003) reconstruct sea-level along the Brazilian coast using beachrock, peats and tidal flat deposits as proxies. This study advances the use of lithostratigraphical features as sea-level indicators as errors are quantified. Beachrock facies A is assigned a precision of ±0.5m and beachrock facies B is assigned a precision of ±1.0m. The peat deposit sampled is taken to represent middle to upper foreshore and assigned an error of ±1.0m. The results point to a rapid rise in sea-level between 7100-5800 cal. yr BP and around 5000 cal. yr BP to a level of 2.5 to 4.0m above present sea-level. A second highstand is identified at between 2100-1100 cal. yr BP.

The field data presented by Bezerra et al. generally fits the model of Peltier (1998) with the prediction of a sea-level above present since 7000 cal. yr BP. However, the second sea-level highstand hypothesised by Bezerra et al. (2003) is not present in the model of Peltier (1998) and deviates by 2-3m. This would suggest that if this second highstand is indeed present in the record, that local factors must also be affecting the coastline at this point in Brazil. This would seem likely, as the error range associated with the second highstand is small, especially when compared with the error range for the entirety of the reconstruction. The large differences exhibited between the reconstruction of Bezerra et al. (2003) and the reconstructions of Bittencourt et al. (1979) and Suguio et al. (1985) highlight that local affects on the Brazilian coast may well be significant in terms of sea-level changes and that sea-level curves along the Brazilian coast only have local or regional validity (Bezerra et al. 2003). However, Baxter and Meadows (1999) present data from Verlorenvlei, South Africa, that also demonstrates a highstand between 6000 and 4000 radiocarbon years BP and a second highstand of small magnitude at around 1500 radiocarbon years BP. The magnitude of the South African second highstand is small compared to the second highstand presented by Bezerra et al. (2003) even when taking errors into account. If this event is due to a global eustatic change then there is a large variation in the response due to either local factors or global factors such as changes in the shape of the geoid.

2.3.3 Biostratigraphic approach

Baker et al. (2001b) compare RSL reconstructions for the east coast of Australia using calcareous remains of inter-tidal fixed biological indicators (FBI). Over a 3000km stretch of coastline, it would be expected that hydro-isostatic processes would result in differing RSL curves along the coastline. What is in fact reported is that there is a near-uniform and synchronous sea-level height along the north-south span of the east Australian coast. At 4990-3070 cal. yr BP, a consistent ~1.7m highstand is present and from 3070-1510 cal. yr BP a consistent ~1.0m highstand can be found along the coastline (figure 2.5). These results are in distinct opposition to the geophysical models of Lambeck and Nakada (1990) who predicted no sea-level above present for the central and southern New South Wales coasts. These results have strong implications for the presumed hydro-isostatic explanation of the Mid Holocene Highstand (MHHS), as the effects of continental loading should result in differential heights and timings of sea-level highstands along this long coastline. Baker et al. (2001b) go on to suggest that a rapid synchronous drop in sea-level of 0.7m occurred along this coastline at 3900 cal. yr BP which could not be explained by the current geophysical models. This fall is presumed to be rapid as a slow and steady decline would result in the erosion of the biological indicators and this is also demonstrated by evidence from the Cook islands, presented by Yonekura et al. (1988) who suggest that the presence of sea-level notches in soft limestone is indicative of a rapid fall in sea-level, as a gradual decline would result in the incremental erosion of these features.

Such evidence would appear to reinforce the suggestion by Baker and Haworth (2000), that sea-level on the Australian coastline oscillated from the MHHS and did not experience a smooth decline as suggested by the geophysical models. This is further expanded by Baker et al. (2001a) who compare the coastline at Port Hacking, New South Wales to the coastline at Laguna-Imbituba, Brazil. Both these coastlines occupy similar

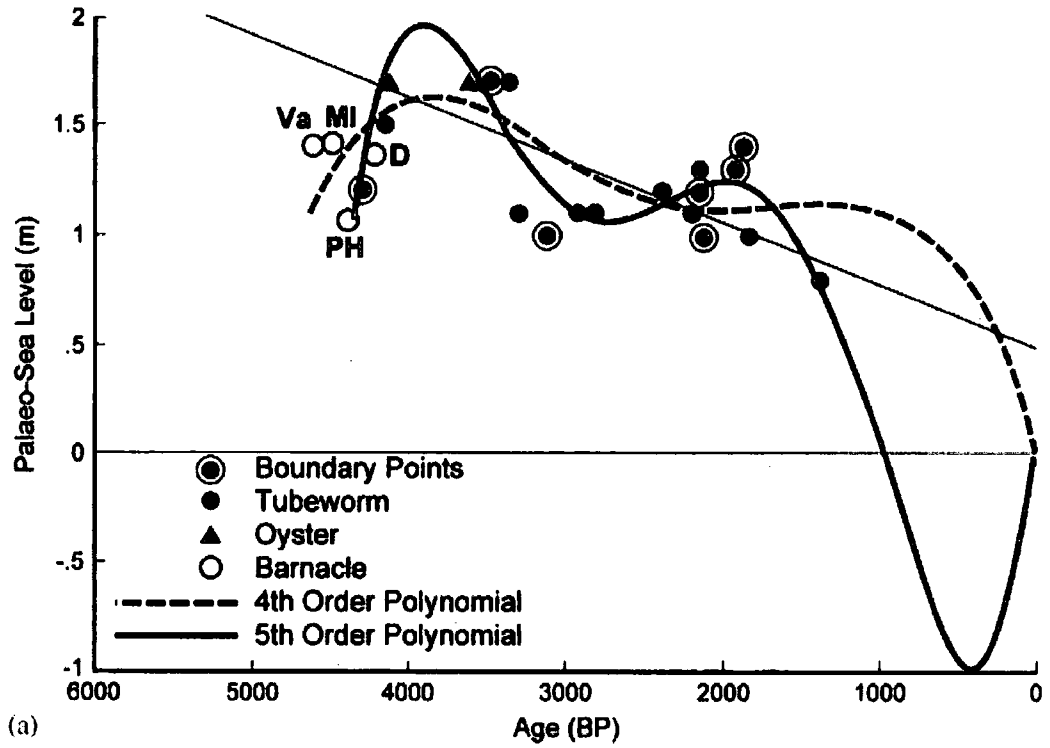


Figure 2.5 – Linear and oscillating regression models taken from Baker et al. (2001b) for the east coast of Australia

latitudinal locations and as such, could potentially be affected in similar ways by global changes. The data presented does indeed highlight a similarity in the timing and changes at ~5200 cal. yr BP and ~3800 cal. yr BP but differential changes after ~2400 cal. yr BP. This would suggest that there was indeed a synchronicity in the southern hemisphere relative sea-level changes in the mid-Holocene but that local changes proceeded to be dominant in the period of smooth decline that occurred during the late Holocene after ~2400 cal. yr BP.

This does not gain reinforcement from the work of Belperio et al. (2002). A consistent drop is identified on the southern coastline of Australia from a highstand of ~2m just before 6000 cal. yr BP. The further splitting of this data into seven geographical regions reveals that the magnitude of the highstand increases with the distance from the shelf margin, supporting the effects of hydro-isostatic loading on the MHHS. Belperio et al acknowledge the number of different methods of fitting sea-level curves to data points and conclude that the curve fitting technique is not the issue. What needs to be addressed is the quality and spread of data. Whilst this explains the differences from interpreting the method of falling sea-level, this does not take into the account the similarity of the magnitudes of the highstands along the eastern Australian coastline. A process must be acting on this coastline that suppresses the effects of hydro-isostatic loading which is shown to be active on the southern Australian coast.

These studies highlight the issue of developing sea-level curves based on very few index points. In this situation, a sea-level envelope is the preferred method of reconstruction as the data points presented by Baker et al. (2001a) could easily be explained by both an oscillating fall from a MHHS and a gradual decline. It is necessary to develop sea-level reconstructions with a greater spread of data and on sub-millennial timescales to interpret the manner of relative sea-level fall in far-field sites. The identification of a 1400 year cycle in oscillations as propounded by Baker et al. (2001a) based on two groups of data points that each cover a spread of 1400 years is misguided and highlights the dangers of an over-reliance on statistical approaches when the quality of the dataset is not appropriate for such statistical analysis. Through the use of a transfer function, it is possible to assess these reconstructions on a sub-millennial scale and provide a dataset that is more suitable to statistical analysis.

Geyh et al. (1979) present a sea-level curve for the Holocene in the Strait of Malacca based on peats, mangrove wood and roots. Rising from over 20m below present MSL at 8000 radiocarbon years BP, a sea-level highstand of +5m is attained between 5000 and 4000 radiocarbon years BP. Whilst the errors associated with determining the elevation of the peat layers found at 5.8m are apparently large (although the exact errors are not quantified in the reconstruction), the scale of the highstand is presumably larger than the associated errors. Whilst the Strait of Malacca lies within the tectonically active Southeast Asian region, comparison of the curve to those generated in Mozambique and Mauritania, supposedly tectonically stable areas, shows the curves are similar and Geyh et al. (1979) suggest that the area was not affected by tectonic subsidence or uplift at least during the Holocene.

2.3.4 Geomorphological approach

Tija (1996) presents a reconstruction based upon geomorphological and biogenic indicators for the Malay-Thai Peninsula. Abrasion platforms and sea-level notches are used to assess the indicative meaning of possible raised shorelines in the region. Tija (1996) draws a sea-level envelope based on 130 radiocarbon dated shoreline indicators that would appear to suggest a sea-level highstand of up to 5m, in agreement with Geyh et al. (1979). The reconstruction also shows two sea-level highstands as demonstrated by Bezerra et al. (2003) and Baxter and Meadows (1999). However, as Tija himself demonstrates the sea-level index points collected can also demonstrate that sea-level showed a progressive descent from the mid-Holocene highstand to present levels or that sea-level followed a stepwise descent with long periods of stillstand. As Baker and Haworth (2000) highlight, no one model of sea-level fall during the Holocene has statistical exclusivity. To accurately answer whether sea-level fall oscillated or was a gradual descent, it is necessary to use more precise indicators with a finer resolution. The reconstruction of Tija, based on points that not only have large vertical errors but are also separated by hundreds of years, makes statistical analysis of the most appropriate model impossible.

Dickinson (2001) presents paleoshoreline data from 51 sites on 11 island groups in the Pacific using paleoreef flats, emergent limestone terraces and incised shoreline notches. Whilst all the sites vary in terms of their local and tectonic components, their proximity to each other should allow for similar effects from a changing eustatic function. Whilst Dickinson does not actually advance the study further by reconstructing sea-level from the paleoshoreline data, he does note that the paleoshoreline indicators are in accordance with the highstands predicted for those areas from the geophysical model of Mitrovica and Peltier (1991).

2.4 Pollen as a proxy indicator of past sea-level

Pollen was the basis of the majority of RSL reconstructions during the 1960s, 70s and 80s. Recent research has concentrated less on its use due to the higher precision offered by other microfossils e.g. diatoms and foraminifera. However, pollen is still extremely useful as it is the only microfossil, which provides climate or chrono-horizon information in addition to an indicative meaning. As Freund et al. (2004) highlight, the use of pollen in sea-level reconstructions in temperate regions is hindered by the rather coarse resolution of the assemblages. One example is *Plantago maritima*, which is indicative of a low marsh environment but due to its ubiquitous pollen dispersal, is found throughout the marsh environment. However, Roe and van de Plassche (2005) conclude that wetland pollen assemblages are suited to identifying the major vegetation zonations within a marsh, although further research is required to improve the precision of these reconstructions. Whilst pollen from temperate inter-tidal marshes shows some complications when employed for sea-level reconstruction, mangrove pollen from the tropics has been shown to have distinct zonations parallel to the shoreline. This would suggest a species zonation controlled by frequency of inundation and therefore elevation. As such, this should make mangrove pollen a suitable proxy for sea-level reconstruction.

Grindrod (1985) undertook a palynological investigation at Princess Charlotte Bay in North Queensland, Australia. Using pollen traps and surface samples, a model was developed for pollen dispersal across the chenier plain. This model was then applied to two fossil cores to reconstruct the vegetation history of Princess Charlotte Bay. As the mangroves are an open system, the potential redistribution of pollen assemblages by tides and the effects of bioturbation are of great concern. Any redistribution of autochthonous assemblages or the introduction of allochthonous assemblages by the tides could render a mangrove pollen based sea-level reconstruction unreliable. However, the study identifies that the major mangrove taxa demonstrate a highly localised pollen dispersal strategy, giving the potential for a precise sea-level reconstruction. In part, this is due to a reliance on insects as vectors of dispersal (with the exception of *Rhizophora*, which is wind pollinated). Whilst Grindrod (1985) states that pollen may be highly effective in reconstructing local sea-level history, he does not attempt to reconstruct relative sea-level change at Princess Charlotte Bay. It is recorded that the vertical zonations exhibited by mangroves are narrow and therefore are suitable for precise sea-level reconstructions.

Ellison (1989) expands on the work of Grindrod and develops a sea-level reconstruction based on mangrove pollen from Tongatapu, Tonga. Ellison (1989) identifies three environmental factors as a requirement in mangrove pollen studies. Firstly, a small species assemblage so as to avoid overly complicated zones. Secondly, sites situated away from the mouths of large rivers to reduce the effects of progradation and thirdly a small tidal range so species do not occupy large elevational ranges. Whilst points two and three are still valid, point one can now be circumvented through the use of transfer functions. Whilst a large species assemblage may make zonations difficult, the transfer function approach should be able to elucidate the relationship between elevation and assemblages. This highlighted drawback can now be employed as an advantage because a large number of zones should reduce the elevation ranges associated with each zone and result in a more precise reconstruction.

Ellison (1989) forms two qualitative zones of mangrove pollen and uses these to interpret a cored mangrove sequence. Using the zonations and the lithostratigraphy of the cores, a trend in sea-level change is established. However, the reconstruction is qualitative in the extreme and no relative sea-level curve is established. A suggested error margin of ±30cm (equal to the tidal range of the area) appears to be optimistic when compared with quantitative methods such as Horton and Edwards (2006), using foraminifera (a sea-level indicator with tightly constrained elevations) that only obtain a precision of ±0.21m. However, Ellison (1989) makes an extremely valid point on the presumption that all other controls on the composition of the mangrove are constant during a period of sea-level change. More research is needed into the effects of differing environmental factors on mangrove composition to avoid the danger of interpreting changes in composition as sea-level induced when they are in fact due to other environmental factors. Through the study of a wide range of mangrove ecosystems, it should be possible to assess the ranges over which specific species occur. If it can be highlighted that a certain species will be found between two altitudes regardless of the other environmental factors, then and only then can these presumptions be justified.

2.5 The use of Transfer Functions in relative sea-level reconstructions

The use of transfer functions in relative sea-level constructions is a relatively recent technique with the first example being that of Guilbault et al. (1996), who used the technique in research into coseismic subsidence in Canada. The technique has since been the subject of a number of studies (e.g. Horton 1997; Gehrels et al. 2001; Zong 2004;

Sawai et al. 2004; Patterson et al. 2004). Transfer functions have been applied using microfossil types such as foraminifera (Horton et al. 2003), diatoms (Zong and Horton 1999) and testate amoebae (Gehrels et al. 2001) but pollen has yet to be incorporated into a transfer function.

Zong and Horton (1999) collected contemporary samples from six sites around the UK for diatom analysis. The sites were chosen due to their adherence to three criteria. Firstly that they exhibited a differential tidal range, secondly that they showed a clear vegetational succession from tidal flat, to low marsh and through to high marsh and thirdly that the environmental conditions at the sites were similar to the conditions found at the fossil sites that were to be reconstructed. The sites came from differing coastal regimes with three estuarine sites, two open coastal sites and one lagoonal site. The elevation at all sites was converted into a Standardised Water Level Index (SWLI, following Horton, 1997) to account for the differing elevations with respect to tidal range.

The Zong and Horton (1999) transfer function was developed using Weighted Averaging (WA) due to the uni-modal response of the diatom assemblages to changes in elevation. More recent studies i.e. Horton et al. (2003) have chosen to use Weighted Averaging – Partial Least Squares (WA-PLS) to obtain the best reconstruction. However, Zong and Horton (1999) justify the use of Weighted Averaging due to its performance when there is a high level of noise associated with the data. The transfer function was further adapted to use tolerance down weighting, giving greater predictive potential to those species that have a limited ecological range. Using both classical and inverse methods, the transfer function was assessed for its predictive potential. The Tol-WA inverse transfer function demonstrated an $\text{RMSEP}_{\text{jack}}$ of 19.45 and an r^2_{jack} of 0.71. The Tol-WA classical transfer function demonstrated an $\text{RMSEP}_{\text{jack}}$ of 21.38 and a r^2_{jack} of 0.72. As such, the classical transfer function gained a slight increase in predictive ability at a cost of an increase in the associated errors. The transfer function is then applied to a fossil core taken from Kentra Moss. Zong and Horton (1999) report that the tide levels calculated using the transfer function are more precise than the qualitative assessments made by Shennan et al. (1995)

Plater et al. (2000) extend the work of Zong and Horton (1999) by using their contemporary diatom data from Cowpen Marsh to establish sediment accretion rates on the marsh during the Holocene. This is established by combining the transfer function reconstructed tidal level data with the equation of the regression line for the present-day relationship between altitude and sediment accumulation rate to output an estimate of the tidal sedimentation rates during the Holocene. The study highlights the issue that the reconstructed tidal sedimentation rates are 3 times larger than the actual Holocene sedimentation rates using dry mass accumulation. If the transfer function approach is to be validated, then the amount of sediment available for tidal deposition during the Holocene must be lower than at present. Plater et al. (2000) highlight that this is a plausible presumption as changes in the tidal regime (as identified by Shennan et al. 2000) and known changes in terrestrial sediment flux due to human interaction with the environment, will have reduced the amount of potential sediment that is available for tidal sedimentation.

Edwards and Horton (2000) further develop the transfer function by integrating the use of the Modern Analogue Technique (MAT) as a tool to assess the performance of the transfer function. Whilst MAT can be used to generate sea-level reconstructions, it is used in this instance to gauge whether the contemporary training set contains good modern analogues for the fossil reconstruction. Without this performance test, it is possible that the transfer function will output a reconstruction for which there is no modern analogue, resulting in an index point that could potentially be erroneous. MAT can be used to highlight instances where there is no good modern analogue due to uneven spatial sampling or as is the case with Edwards and Horton (2000), where the dissolution of calcareous tests in the fossil record causes fossil tidal flat areas to be different to contemporary tidal flat areas.

Edwards and Horton (2000), present a training set compiled from 10 contemporary sites around the UK. All samples were stained using Rose Bengal at the point of collection to determine which tests were living at the time of collection. Following Horton (1997), the death assemblage is used as it is "considered to be most representative of the fossil assemblages and less susceptible to seasonal variation". Transfer function SWLI-99 based on WA shows a good correlation between assemblages and elevation with an r^2_{jack} of 0.75 and an $RMSEP_{jack}$ of 12.47. However, when SWLI-99 was applied to core ARN1-95-90, 10 out of the 26 fossil samples were found to contain no modern analogue in the training set. Edwards and Horton (2000) conclude that the lack of modern analogues is due to the dissolution of calcareous tests as the majority of samples without modern analogues are indicative of low marsh or tidal flat environments.

In an attempt to alleviate this problem of calcareous test dissolution, Edwards and Horton (2000) remove the calcareous tests from the contemporary training set to create an agglutinate-based foraminiferal transfer function (ABFTF). Whilst the ABFTF loses precision, especially in the tidal flat environment, it gains in its predictive power due to the reduced occurrences of samples with no modern analogue (3 from 26). It is interesting to note that both the water level reconstructions presented by Edwards and Horton (2000) are broadly in agreement with each other as well as with the lithostratigraphic interpretation of the fossil record.

Horton et al. (2003) present a transfer function from Cocoa Creek, on the Great Barrier Reef coastline, Australia. Taken from a mesotidal fringing environment, this paper represents the first use of the transfer function approach in sea-level research in Australia. Whilst the study identifies similar species composition to that found around the world and as predicted by Scott and Medioli (1980), the training set shows an extremely strong and highly significant relationship between the assemblages and elevation. The strength of this relationship allows for reconstructions with precisions of ±0.07m, currently the most precise reconstruction through the use of microfossil transfer functions. It is disappointing that this study does not go on to apply the transfer function to a fossil core. As noted in Edwards and Horton (2000), it is not simply enough to develop a highly precise transfer function; it is also necessary to evaluate the performance of the transfer function through its application and the analysis of the modern analogues provided. It is to be hoped that further research is undertaken using this highly promising transfer function including its application to a local fossil core.

Horton and Edwards (2003) examine the temporal effects of foraminifera distribution on the construction of a transfer function training set. Samples were taken on a monthly basis from a 32 sample transect at Cowpen Marsh. The study demonstrates that a transfer function with a high r^2_{jack} can be produced throughout the year, although the precision of the transfer function varies between 0.29m in the winter to 0.35m in the summer. Taking a sample in each season reduces the error to 0.21m. Whilst further temporal sampling reduces the error, taking a sample every month only increases the precision to 0.18m, a negligible increase in precision for the extra amount of time necessary in preparation. Horton and Edwards (2003) demonstrate the great effect that temporal variations may have on a transfer function and it is extremely important to take these into account. It is one of the transfer functions greatest strengths that temporal assemblage information can be easily incorporated and assist in increasing the precision of the reconstruction.

Horton and Edwards (2005) develop both a regional and local transfer function to reconstruct relative sea-level change from Holkham, North Norfolk. A local transfer function is developed using the two nearby marsh sites of Brancaster and Thornham. The regional transfer function is constructed using the Brancaster and Thornham data and adding it to an existing dataset of 11 transects from around the UK. Whilst the vertical error of the local transfer function is 0.09m less than the regional transfer function, it achieves this at a great loss of predictive power due to the number of samples that do not contain a modern analogue in the training set. The local training set records 14 no close analogue situation in 23 samples, whilst the regional training set contains good modern analogues for all 23 samples.

This conclusion is in contradiction to the work of Gehrels (1994) and Allen and Haslett (2002) who all advocate the use of training sets from within the local area due to the danger of opening the reconstruction to increased errors. It is preferable to use a local transfer function when MAT can confirm that the training set provides a good modern analogue for fossil conditions. However, when a number of no modern analogue situations occur within a training set, then the loss of precision is of small concern compared to the greater predictive power that the regional transfer function allows. It is not surprising that the closest modern analogues are not found within the local area as the North Sea underwent considerable adaptation during the sea-level transgression through the Holocene with changes in tidal range as highlighted by Shennan et al (1995). It is more likely that coastal areas which have not seen large changes in tidal regime, sedimentation regime and human impact throughout the Holocene will provide close modern analogues within the local area, whilst those that have undergone considerable change will require a regional approach to find modern analogues.

Edwards et al. (2004) construct a regional training set from the eastern seaboard of the USA, in Connecticut with four marshes being chosen over a 60km stretch of coastline.

The transfer function developed CTTF03 is used to reconstruct palaeomarsh elevation with the entire dataset possessing good modern analogues. To test the reliability of the reconstruction, the same core is also reconstructed using a transfer function derived from transects in the neighbouring state of Maine. The two reconstructions are comparable with 80% of the two constructions within the error terms associated with them. However, the Maine training set identified 11 fossil samples with no modern analogue. Edwards et al. (2004) note that the species *A. mexicana* is found in only two samples in the Maine training set compared to 33 samples in the Connecticut training set, resulting in an over-estimation of the surface elevation by the Maine training set. However, the transfer function still recorded the *A. mexicana* zone as containing good modern analogues. Edwards et al. (2004) are quick to note that transfer functions are not 'black boxes'. Referring to foraminifera specifically but just as applicable to other microfossils "a firm understanding of the behaviour of foraminifera constituting the training sets underpins interpretation of the reconstructions".

Further performance testing of the transfer function is achieved by analysing a second core taken 6.5m away from the initial core used for reconstruction. The principal changes in paleomarsh elevation are noted in both cores, identifying a lateral change in palaeomarsh elevation across the marsh. The regional transfer function presented here demonstrates strong performance with a precision of ±0.09m, far lower than the regional transfer functions presented by Zong and Horton (1999) and Horton and Edwards (2005).

As Edwards et al. (2004) note, the transfer function has the added benefit of providing a clear and transparent reproducible methodology that allows for the quantification of errors. Development of the methodology since its first application has seen a reduction in errors associated with both local and regional transfer functions. The scientific community working with this technique have proved quite adept at responding to methodological issues as shown through the treatment of regional and local transfer functions and through the quantification of spatial and temporal issues related to microfossil incorporation into sediments. Whilst some work has been undertaken on taphonomic issues i.e. Patterson et al. (2004), this is the next methodological challenge. It is also necessary to work on the uneven spatial sampling that may be responsible for the lack of modern analogues in reconstructions. Research such as that of Hardbattle (2004) on sub-tidal transfer functions is moving some way in redressing this imbalance.

2.6 Conclusions

This chapter has highlighted the current knowledge on sea-level change since the LGM in near-, intermediate- and far-field sites and demonstrated the techniques that have commonly been used in these reconstructions. Near-field sites typically show falling relative sea-levels due to isostatic rebound with some evidence for increasing sea-levels of around 3m over the last 4000 thousand years as eustatic sea-level rise overtook isostatic rebound. Intermediate-field sites such as northern England show a pattern of RSL changes moving from north to south with sea-level highstands between 6000 and 4000 cal. Yr. BP associated with isostatic rebound in the north and continuous RSL rise in the south due to the combination of the eustatic increase and the isostatic depression due to the removal of the ice-sheets. RSL reconstructions from the far-field show a complicated distribution with many sites exhibiting a sea-level highstand, possibly due to the principals of equatorial ocean siphoning and continental levering. There are variations in both the timing of and the magnitude of the sea-level highstand, which have yet to be fully explained by other mechanisms or local factors.

It is clear that further research is required in far-field sites involving the use of more precise sea-level indicators as the large error ranges of coral reconstructions and the associated tectonic corrections render these reconstructions unreliable on the century time scale. Microatolls provide a new method of coral reconstruction with a good level of precision but this technique has yet to be applied to a long term reconstruction and it remains to be seen whether this technique is suitable for such reconstructions. Whilst lithostratigraphical indicators have potential to deliver sea-level reconstructions, these reconstructions are hindered by the large vertical error range associated with the reconstruction and issues of sediment compaction that can cause the index points to be lower in tidal frame than when they were deposited. With continued debate over the nature of the deglaciation from the LGM, including whether sea-levels have oscillated or seen a continued sea-level rise or fall, it is necessary to develop more precise RSL reconstructions from far-field locations.

The application of a mangrove pollen based transfer function has the potential to develop the first precise, quantitative RSL reconstruction from Indonesia as well as being the first mangrove pollen transfer function. The transfer functions developed by Horton (1997), Zong and Horton (1999), Edwards and Horton (2000), Horton et al. (2003), Edwards and Horton (2003), Edwards et al. (2004) and Horton and Edwards (2005) show the ability of the transfer function to develop precise sea-level reconstructions. Through the application of this technique to the mangroves of S.E. Sulawesi, Indonesia, it should be possible to identify whether the region experienced the sea-level highstand predicted by Clarke (1978) and to understand the late deglacial chronology from a tectonically stable, far-field site.

3 - Descriptions of sites in the Wakatobi Marine National Park and Buton Island, S.E. Sulawesi

3.1 Introduction

Sulawesi is considered to lie at the triple junction of the Asian, Australian and Pacific convergent plates (Villeneuve et al. 2002). The island has seen at least four major tectonic events during the Mid-Cretaceous, Oligo-Miocene, Middle Miocene and Early Pliocene (Villeneuve et al. 2002). Many parts of the island still show signs of active tectonic processes with recent earthquakes of 6.5 (Bau Bau, February 2005), 6.5 (Peleng, May 2000) 6.2 (Palu, January 2005) and 5.5 (Donggala, October 1998). Volcanoes are also present on the northern arm of the island with the recent notable eruption of Soputan (2005) and Karangetang (2005). As figure 3.1 highlights, the study sites in the Wakatobi Marine National Park and Buton Island are on separate blocks and may therefore have experienced different tectonic movements and processes over both long term and short term (i.e. Holocene) timescales. Beaudouini et al. (2003) highlight that seismic activity is lower in south and central Sulawesi compared to the northern section of the island. Both locations described in this chapter share the same micro-tidal regime due to similar physiographic conditions, which is semi-diurnal with a range of 1.5m. This was confirmed following Horton et al. (2005) and levelling the tide for a 24 hour period to compare to predictions.

This chapter aims to do the following:

1. Highlight the geological and geophysical features and processes at all three study sites.

2. Identify the mangrove species zonations at the three study sites and to place them within the context of the local environment.

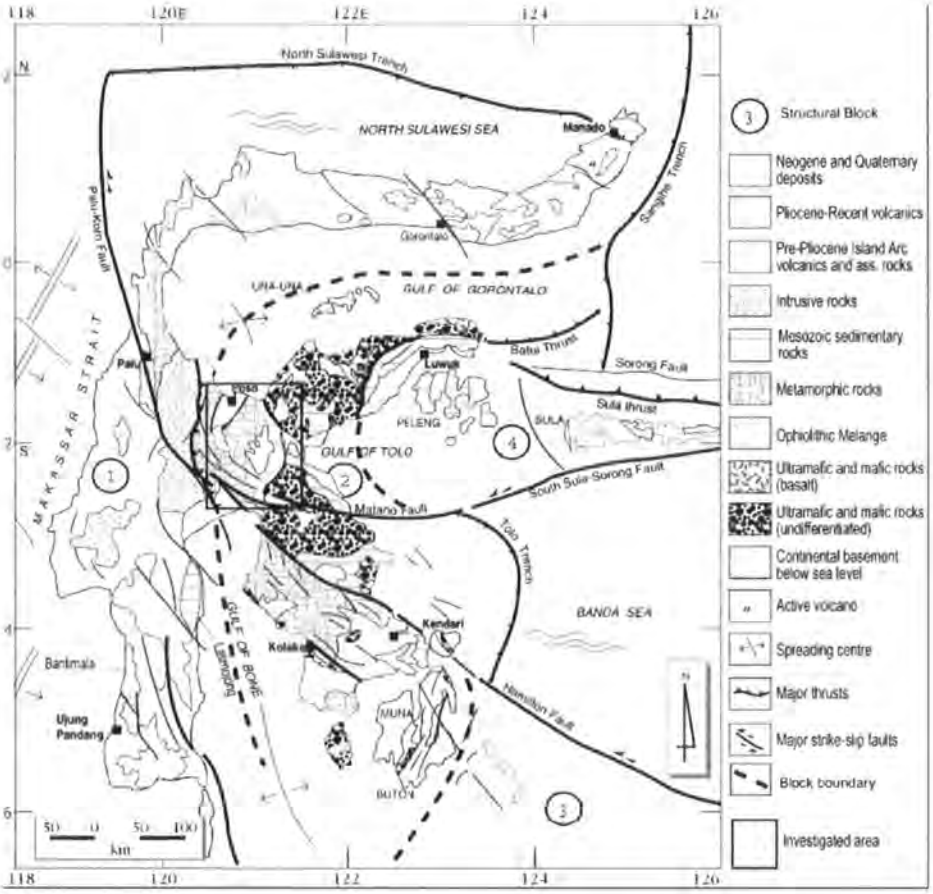


Figure 3.1 - Simplified Geological Sketch Map of Sulawesi (Villeneuve et al. 2002)

3.2 Wakatobi Marine National Park, Tukangbesi Archipelago, S.E. Sulawesi

The Wakatobi Marine National Park occupies an area of 1.39 million hectares, making it the second largest marine protected area in Indonesia (Figure 3.2). The national park is made up of the four principal Islands of Wangi, Kaledupa, Tomea and Binongko, which together form the Tukangbesi archipelago.

Villeneuve et al. (2002) highlight the Tukang Besi block as being a submerged continental basement (Figure 3.1). Smith and Silver (1991) identify a Miocene collision of microcontinents that resulted in the Tukang Besi platform being emplaced against the Buton and Sula platform. Smith and Silver (1991) also suggest that the Tukang Besi block may be a continental fragment that was removed from the northern margin of New Guinea or Irian Jaya. The reef limestones found in the Wakatobi Marine National Park are identified by Smith and Silver (1991) as being upper Neogene and Quaternary in age. Silver et al. (1983) report that seismic profiles of the block show no major thrusting or convergence episodes. However, Milsom et al. (1999) suggest that the relationship between Buton and the Tukang Besi block is still highly controversial in nature and that they may be geologically related. The uplifted reefs attain heights of 250m on the northern island of Wangi Wangi and over 200m on the other three large islands of Kaledupa, Tomea and Binongko.

Study sites for this research were concentrated on the island of Kaledupa (Figure 3.2), which exhibits an array of mangrove ecosystems with differing zonations of mangrove species. Unlike Horton et al. (2005a), this study did not find that the majority of the mangroves on the island of Kaledupa obeyed a zonation of a landward *Rhizophora* zone, mixed *Rhizophora* and *Sonneratia* zone with a landwards *Avicennia* zone. This zonation was noted at only two prospective sites, one of which showed heavy evidence of wood farming by the local population and, as such, was discounted due to the potential of disrupted modern analogues.

The mangroves studied in this research show similar zonations to those described by Grindrod (1985) and Grindrod (1988) in Northern Australia. Tides at all sites studied are semi-diurnal and micro-tidal with an average spring tidal range of 1.57m.

3.2.1 Mantigola mangrove

This study site is the only site on Kaledupa located on the western side of the island and is shown in figure 3.2. The transects are located on a tidal creek mangrove system, protected by a low lying sand bar upon which the Bajao stilt village of Mantigola is built. The mangroves reach a width of 200m at this point. Vegetation grows up to 10m in height, although most species are only around 5m in height. The site exhibits an exposed tidal flat, moving into a zone of fringing *Rhizophora*, followed by a zone of *Rhizophora* with the occasional presence of *Bruguiera*. This is in turn followed by a *Rhizophora, Ceriops and Avicennia* zone. This zone then moves landward into a zone of *Ceriops* and *Avicennia*. The landward section of the mangrove is characterised by a zone of *Avicennia* with occasional *Ceriops* species, with a greater proportion of *Avicennia* than in the previous zone. The final zone is also marked by the presences of palms, isolated *Xylocarpus* species and the presence of *Acanthus* species.

3.2.2 Laulua mangrove

This study site is located on the eastern side of the island of Kaledupa. The transect is located on a tidal mangrove system, protected by a coral reef flat and is shown in figure 3.2. The mangroves at the study site attain a width of 125m. The site exhibits no tidal mud flat and is characterised by an initial zone of *Bruguiera* and *Rhizophora* species. Moving landwards, this advances rapidly into zone of predominantly *Rhizophora*, followed by a zone of *Rhizophora* and *Avicennia* species. This is backed by a zone of *Ceriops* and then a zone of *Avicennia* before the final landward zone of predominantly mixed *Avicennia* and *Ceriops* species with some palm species present. Vegetation at this site reaches heights of up to 8m.

3.3 Buton Island, S.E. Sulawesi

Buton Island is located off the south-eastern tip of the Sulawesi coast. The island is 130km long and 50km wide at its broadest section and attains a maximum height of 1100m ASL (Figure 3.2). The recent geological history of Buton has seen the uplifting of coral reef terraces, resulting in a stepped formation due to infrequent but rapid uplift events (Milsom, Pers. Comms.). Buton has an abundance of mangroves, though the vast majority now show effects of farming or replanting schemes.

3.3.1 Kakenauwe mangrove

The study site at Kakenauwe is located on the eastern side of Buton Island and is shown in figure 3.2. Freshwater input to the mangrove is limited to a number of small rivers. The mangrove system is 100m wide in places and is generally based on uplifted coral. The transect is located on an area of mangrove 20m thick, with a large tidal mud flat in front of it. The tidal mud flat and mangrove at this point only exhibit a sediment depth of 30cm to impenetrable substrate, which is presumed to be uplifted coral. The mangrove is composed of the mud flat zone, bordered by a fringing zone of *Sonneratia* and *Rhizophora*, which is in turn backed by a *Rhizophora* zone. The species present at this site were mature with vegetation reaching heights of up to 12m.

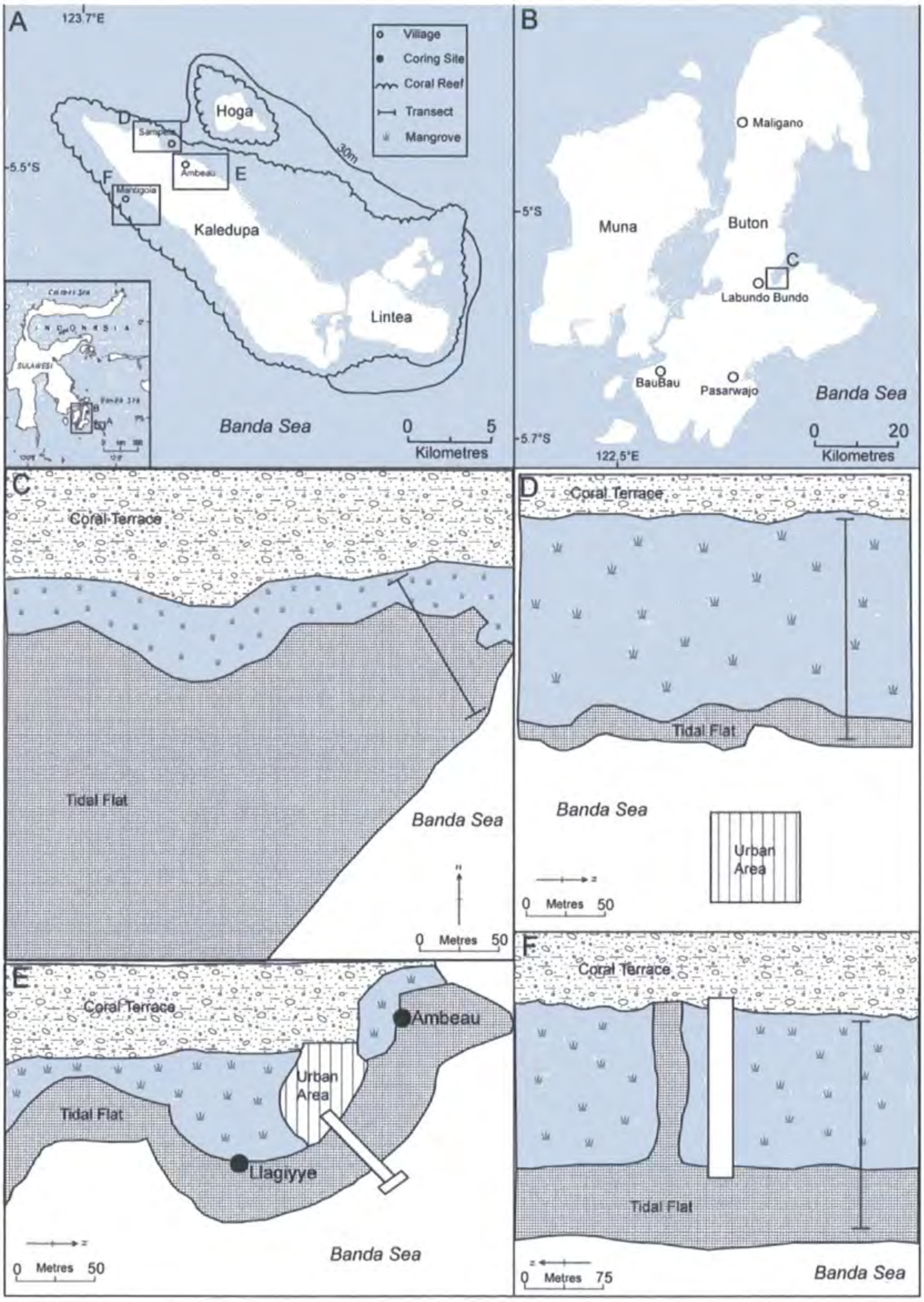


Figure 3.2 - Study Site Locations in Southeast Sulawesi, Indonesia

4 – Methodology

4.1 Introduction

This chapter introduces sampling strategy, the manner of pollen dispersal and deposition within the mangrove ecosystem, the fieldwork undertaken and the laboratory and statistical analysis undertaken.

The methodology of the study follows the standard methodology for sea-level research as outlined by the IGCP. All elevations in this study are quoted as metres Indonesian Height Datum (IHD) which equates to lowest astronomical tide at the study sites.

4.2 Sampling Strategy

Contemporary samples have been collected from three modern mangrove environments to provide modern analogues for sea-level reconstructions using fossil cores. Each site was chosen due to its representative nature of the mangrove flora of S.E. Sulawesi at the present time and to maximise the number of modern analogues for sea-level reconstruction with each site showing differing species content and zonations. Samples were collected from 25 sampling stations along each transect at equal horizontal distances, encompassing major changes in elevations across the transect. The sampling strategy differs from the one used by Horton et al. (2005a) for foraminifera in the WMNP. Ellison (1989) highlights that distance from open water is an important control on mangrove zonation and as such, samples may occupy similar elevations but have different species compositions due to their distance along the transect. The common sampling strategy of sampling at major changes in elevation would miss this diversity due to only one sample being taken for an elevation that may encompass many differing modern analogues.

The three sites were chosen after a reconnaissance survey of the islands of the Wakatobi Marine National Park and the mangroves of Buton, S.E. Sulawesi. The three sites were chosen due to their differences in mangrove species composition to allow for the generation of as many good modern analogues as possible. The sites were also chosen due to their pristine nature, indicative of little human disturbance and as such, composition and zonation at the sites is naturally occurring.

4.2.1 Pollen Dispersal

The study of pollen requires an in-depth knowledge of the production and dispersal of pollen grains. Unlike other microfossils such as foraminifera and diatoms, the presence of a pollen type in a fossil sample does not necessarily indicate that the species was in close proximity to the area at that time. Pollen has many dispersal methods, including wind, water and animal vectors, all of which have the capability to transport pollen outside of the local area. Tauber (1965, in Moore et al. 1991) presents a model for the distribution of pollen containing 5 components, the Trunk space component, the Canopy component, the Rain component, the Local component and the inwashed component. Jacobson and Bradshaw (1981) demonstrate a relationship between the size of site and the various sources of pollen entering it (Figure 4.1). With a site up to 100m in diameter, the local component is dominant. Between 100-300m the extra-local component is dominant and over 300m to 1000m, highlights the increased presence of the regional component. Even so, work by Turner (1964) demonstrated that surface samples near to pine trees, demonstrated high values of *Pinus* with a quick decrease to lower values over a short distance of only 400m. Although it must be noted that this study is not in an inter-tidal site.

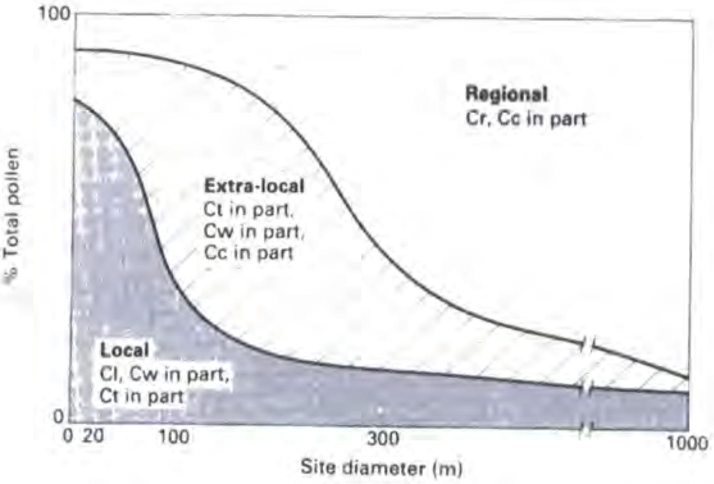


Figure 4.1 – Sources of Potential Total Pollen from Jacobson and Bradshaw (1981)

Pollen analysis of surface sediments has also shown that some pollen types may be over- or under-represented in the pollen record. This is due to differences in the amount of pollen produced and the methods in which the pollen is dispersed. Many tree species produce prolific amounts of pollen, whereas other species produce very little. This is further enhanced by differences in distribution. Those species that use wind as the pollinating vector are generally more likely to be over-represented in the pollen record than those species that use animal vectors for pollination.

4.2.2 Pollen Deposition in Mangroves

The assumption that a pollen species identified in a fossil sample is evidence of that species being in close proximity to the site at the time of deposition is an extremely important one to this study. As such, we must be aware of the pollinating vectors and pollen distribution of mangrove plants.

Grindrod (1985) describes mangrove taxa as having "highly localised pollen dispersal, despite the potential for tidal redistribution". Grindrod also demonstrates that *Rhizophora* pollen is very abundant within the surface samples collected underneath *Rhizophora*-dominated mangrove. It is also reported that *Rhizophora* pollen grains were recorded nearly "2km upwind" from the parent source. Such distribution of grains would suggest that *Rhizophora* pollination is via wind with large amounts of pollen being produced. This is also suggested in Tomlinson (1986) and also by Muller (1959) in the Orinoco Delta, Venezuela. Other species within Princess Charlotte Bay (*Ceriops/Bruguiera* and *Avicennia*) appear to show highly localised distributions due to their inefficient wind dispersal methods and thus reliance on animal vectors for dispersal.

The potential issues with mangrove pollen deposition are not limited to production and dispersal. Due to the open system nature of the mangrove environment, there is considerable potential for the transport and distortion of pollen records by the tides.

Tides may have the effect of washing in regional pollen types as well as reworking sediments. However, Grindrod (1985) states that "it is interesting that the pollen grains of the mangrove taxa maintain limited distributions once deposited in sediments, indicating a low degree of redistribution by either tidal or seasonal flooding".

Whilst Grindrod (1985) has investigated the temporal production of pollen grains through pollen traps over two 6 month periods, he did not translate this into a temporal study of the pollen found in surface samples. Similarly, there has not been any research investigating the effects of spatial variations due to transect location or taphonomic changes to pollen assemblages after deposition, a situation that this study aims to rectify.

4.3 Methodology

Each sampling station was levelled to sea-level, noting the time and date of measurement, to allow for the calculation of elevations in Indonesian Height Datum (IHD) using the time-shifted (1 hour later) tidal curve from Buton Island, S.E. Sulawesi. At each station, a sample of approximately 10cm^3 (10cm^2 surface sample by 1cm thick) was taken for environmental variables analysis and a sample of approximately 5cm^3 (5cm^2 surface sample by 1cm thick) was taken for pollen analysis. Care was taken to extensively clean all apparatus between sampling sites to minimise the potential for cross contamination. Samples were stored in ziplock bags and refrigerated before being shipped to the UK. Care was taken to note the flora surrounding the sampling stations. 3 mangrove sites were chosen for this study, 2 on the island of Kaledupa, Wakatobi Marine National Park

(Mantigola and Laulua) and 1 site on Buton Island, S.E. Sulawesi (Kakenauwe). All three sites exhibit the same tidal conditions.

4.3.1 Mantigola mangrove

The transects at Mantigola extend from 0.88m IHD to 2.37m IHD from lower tidal flat through to a high mangrove environment bordered by a coral terrace. The transect contained 25 sample stations spaced 10m apart and is approximately 250m in width. The transect forms part of an extensive mangrove running north and south of the study site.

4.3.2 Laulua mangrove

The transect at Laulua extends from 0.97m IHD to 2.125m IHD from a fringing *Rhizophora/Bruguiera* mangrove environment to a back mangrove environment with some palm trees. 25 samples were collected along this transect, spaced at intervals of 8m and is approximately 200m in width

4.3.3 Kakenauwe mangrove

The transect at Kakenauwe extends from 0.83m IHD to 1.82m IHD from a large, coral based tidal mudflat to a forest backed *Rhizophora* mangrove environment with 25 samples being collected for analysis, spaced at 5m intervals and is approximately 120m in width.

4.4 Laboratory and Statistical Analysis

4.4.1 Pollen analysis

Preparation of the samples for pollen analysis follows the standard method of Faegri and Iversen (1989). 0.5g of sediment is initially subjected to treatment with 10% KOH to remove alkali soluble organic compounds and also to act as a deflocculent. The sample is then washed through 180um sieves to remove coarse sediments. This process is repeated until the supernatant liquid is clear after centrifuging. Siliceous material is then removed with treatment by HF and HCL before the removal of unaltered lignin and cellulose through acetylosis (9:1 acetic anhydride to conc. Sulphuric acid). The sample is then stained with two drops of safranin before the addition of silicone oil and mounted onto slides with 22x40mm cover slips. Cover slips are affixed at two corners to facilitate the rotation of the pollen grains to aid identification. On samples where the calculation of pollen concentrations is necessary, two lycopodium tablets of known concentration are added to the sample. Slides were counted using a Nikon YS2-H microscope at 400x magnification for counting and 600x-1000x magnification using oil immersion for particularly hard to identify pollen grains. All slides were made anonymous during the counting process so as to eliminate potential bias from the results. All samples were counted to 150 grains following Ellison (1989). A pilot study was conducted to evaluate the use of 150 counts. Significant differences were noted between relative species proportions at 50, 100 and 150 counts. However, 150 and 200 counts both showed similar relative proportions. Whilst 150 counts could be gained for some samples from one slide, as many as 4 slides were counted to achieve the 150 grain quota on samples with low concentrations. Taxonomic keys and identification material come from Huang (1972) and Thanikaimoni (1987). The species *Bruguiera* and *Ceriops* had to be grouped together due to them being undistinguishable under light microscope (Grindrod, 1985)

4.4.2 Environmental variables

Four environmental variables were analysed in the laboratory. Salinity and pH were analysed using 10g of sample and 25ml of distilled water for all samples. Samples were stirred, left to rest for one hour before analysis. Salinity was worked out from conductivity using a standard conversion factor. pH values are quoted to 1 decimal place. Particle size was undertaken using a Coulter counter laser granulometer with between 0.5g to 2g of sample used to achieve optimal obscuration rates. Samples were treated with Hydrogen peroxide (H_2O_2) to remove organic content before being analysed. These results are then split into clay, silt and sand fractions. Loss on ignition (LOI) is used as a proxy for total organic content and follows the methods of Ball (1964). Samples were weighed, place in an oven at 105 degrees Celsius for 24 hours, weighed again and then placed in a furnace at 550 degrees Celsius for 4 hours to facilitate the removal of organic carbon.

These environmental variables were chosen due both to their common use in sea-level research and observations in the field. Species composition changes were often noted with changes in substrate in both apparent grain size and organic content when in the field, justifying the application of grain size and LOI. Changes in canopy cover were also often noted which could increase salinity through evaporation and pH through changes in microbial activity at the surface. It was therefore important to measure these environmental variables to ensure that elevation and not one or more of these variables is controlling species distribution.

4.4.3 Statistical Analysis

Cluster analysis is a method that allows for the classification of species into homogenous zones using the CONISS program. Within this study, cluster analysis has been employed to group sampling sites with similar pollen assemblages. Following Horton et al. (2003), the form of cluster analysis used is unconstrained, based on unweighted Euclidean distance and using no transformation or standardisation of the data. This classifies the data into more or less homogenous zones (Horton and Edwards, 2006). This information can then be used to ascertain an elevational range for each zone. Hill and Gauch (1980) developed Detrended Correspondence Analysis (DCA) as an improved ordination technique, primarily to remove the 'arch' effect associated with standard correspondence analysis. DCA represents samples as points in a multi-dimensional space with similar samples located together and dissimilar samples located further apart. Birks (1992) highlights the complimentary nature of the two techniques with cluster analysis splitting the samples into zones based on the pollen assemblages and DCA providing further information on the patterns and variation within and between groups (Horton and Edwards, 2006).

Canonical Correspondence Analysis (CCA) is a multivariate method of ordination to explain the relationships between biological assemblages and environmental variables.

CCA is derived from Correspondence Analysis (CA), a technique that clusters sites based on the similarity of their species composition. Sites close together can be inferred to be similar in species composition and those apart from each other can be inferred to be dissimilar in species composition. CCA can be "used to extract synthetic environmental gradients" (Horton et al., 2003). These gradients can then be used to explain the environmental preferences of species and to explain the variance in the microfossil data. Partial CCAs were also run on the datasets to assess the individual influence of each environmental variable, any covariance between variables and to highlight the unexplained variance in the dataset (Horton and Edwards, 2006). The significance of the Partial CCAs were determined using a Monte Carlo permutation test under the reduced model (p=0.05, 499 runs)

CCA and DCA analysis was carried out using CANOCO release 4.51 (Ter Braak and Smilauer 1997-2003).

4.5 The Transfer Function Approach

The role of the transfer function is to systematically analyse the relationship between the distributions of microfossil assemblages compared to a present day environmental variable. The transfer function quantifies the relationship between elevation and pollen so that elevations may be expressed as a function of the pollen assemblages. The dataset used to construct a transfer function should ideally be as large as possible so as to cover an extensive range of modern analogues and to control for any random components in the distribution of the assemblages due to sampling variability. The second aspect of the transfer function approach involves the empirical modelling of the relationship between the elevation of a sample and the assemblage constituents of that sample. Regression analysis can be achieved by either the classical approach (where pollen assemblages are expressed as a function of elevation) or the inverse approach (where elevation is expressed as a function of the pollen assemblages). Horton and Edwards (2006) note that inverse approaches tend to work best with samples from the middle of the environmental gradients whilst classical approaches may work best when samples are at the extreme of the environmental gradient and may require a level of extrapolation.

If Partial CCAs demonstrate that tidal inundation is a significant control on assemblage distribution, then the transfer function approach can be justified to quantify the relationship between assemblages and elevation. If this is shown to be the case, then using the program C2 (version 1.4, Juggins 2004), a transfer function will be developed. The method of calibration and regression will be chosen after using Detrended Cananonial Correspondence Analysis (DCCA) to ascertain the length of the environmental gradient. Birks (1995) states that if the environmental gradient is less than 2 SD units, then the assemblages are behaving monotonically along the gradient and linear calibration and regression techniques are applicable. If the length of the environmental gradient is more than 2 SD units, then the assemblages are considered to be showing their optima within the measured gradient, and as such unimodal methods of calibration and regression are used.

The transfer function technique allows for the evaluation of the reconstruction through the Root Mean Square Error (RMSE), the maximum bias and the correlation coefficient r^2. The RMSE and maximum bias indicate the systematic differences in prediction errors whereas the r^2 value measures the strength of the relationship between the observed and the predicted values (Horton et al., 2003). The dataset was also jack-knifed. This 'leave one out' method tests the overall predictive ability of the dataset by removing one modern sample and using the remaining modern samples to predict its value. The Modern Analogue Technique (MAT) was also used to compare the modern and fossil samples using the appropriate dissimilarity or similarity coefficient and thus provide an assessment of the reliability of the reconstruction (Horton and Edwards, 2006). This method allows the identification of fossil samples that are without a modern analogue in the training set. Birks et al. (1990) highlight the 10th percentile of the dissimilarity range of the modern samples as the threshold to indicate a good analogue. As such, fossil samples that do not possess a modern analogue should be treated with extreme caution.

There has been debate over the use of local or regional transfer functions as the most suitable tools for reconstructing former sea-levels. Gehrels (1994) highlights the issues of inter- and intra-site variability and thus recommends the use of a locally based vertical zonations to ensure errors are kept to a minimum. However, Horton and Edwards (2006) developed both local and regional transfer functions for a fossil core from North Norfolk. Whilst the local transfer function did have improved precision over the regional transfer function, Horton and Edwards report that this precision was gained at the expense of predictive ability due to the proliferation of no modern analogue situations. As mangrove environments contain a large number of species, some of which are not always present even in sites that appear similar, the regional transfer function approach was chosen due to the increased likelihood of good modern analogue situations in the reconstruction. Edwards et al. (2004), used a regional transfer function to reconstruct sea-levels in Connecticut, USA, and achieved errors as low as ±0.09m, indicating that precise reconstructions can be gained from regional datasets.

5 – Pollen Distribution in a Mangrove Environment, S.E. Sulawesi, Indonesia

5.1 Introduction

South-East Sulawesi demonstrates a range of mangrove environments, differing in both substrate, geological setting and associated flora (Whitten et al. 2001). Two sites were chosen from the Wakatobi Marine National Park and one site was chosen from the island of Buton. Each site was chosen based on its differing floristic components and species zonations to maximise the number of potential modern analogue situations when considering a reconstruction.

A total of 75 contemporary samples were analysed palynologically from three transects. Pollen and spores were present in moderate number in the majority of samples. Counts were generally achieved with one slide although a number of samples required up to 4 slides to achieve the count. A summary of the samples analysed can be found in Table 5.1. The 150 grain counts are solely of mangrove species as terrestrial species landward of the mangrove do not show a relation to elevation. Samples 1-9 (0-24m) at Kakenauwe were analysed but not included due to the lack of mangrove species within these samples.

Table 5.1 - Contemporary Samples Analysed

Transect	Samples Taken	Samples Analysed	Samples with 150 Grains
Kakenauwe	25	16	14
Laulua	25	25	24
Mantigola	25	25	25
Totals	**75**	**66**	**63**

A total of 41 pollen types are differentiated, which consists of 16 mangrove pollen species differentiated by species name with a further 10 pollen types identified consistently in the mangroves of the Wakatobi Marine National Park but which could not be named due to their non-presence in the identification literature (Huang 1972 and Thanikaimoni 1987). A further 15 terrestrial species are identified but not differentiated to species from Kakenauwe mangrove. A further category of unidentified pollen species is included to take into account those grains which may be broken, corroded or hidden. This category never exceeds 10% of the total pollen sum. When applying statistical techniques within CONISS and Canoco, those species that failed to achieve 2% of the total sum in any samples are excluded following Horton and Edwards (2006).

This chapter aims to:

1. Highlight the contemporary distributions of pollen in three mangrove environments from S.E. Sulawesi.
2. Use statistical analysis to demonstrate that these distributions are controlled by the measured environmental variables and specifically elevation.

3. To compare the contemporary distributions to other palynological studies from South-East Asia and northern Australia and thus demonstrating that the contemporary transects are representative of the mangroves of this region.
4. Show that mangrove pollen can be harnessed as a precise and accurate indicator of former sea-levels.

5.2 Contemporary Characteristics of Mantigola Transect MA200401

5.2.1 Contemporary Pollen Distribution

22 species were identified from 25 sampling stations at Mantigola (Figure 5.1). *Rhizophora*, *Bruguiera/Ceriops*, *Heritiera* and *Avicennia* are the dominant species within the mangrove with each accounting for 80% of the total pollen sum in one or more samples. *Rhizophora* is dominant throughout the mangrove, never contributing less than 40% of the total pollen sum in any sample. This can be explained by the dominance of the species from 0m to 96m and its reliance on wind distribution as the major pollen vector (Grindrod, 1985).

Rhizophora counts are steady at the seaward edge of the mangrove ranging between a minimum and maximum of 92 and 115 between 0m (the front) and 84m along the transect. In the landward portion of the mangrove, between 90m and 144m, *Rhizophora* counts range between a minimum and maximum of 59 and 95. *Bruguiera/Ceriops* counts show no general pattern across the front and middle of the mangrove (0m to 114m) with fluctuations between 9 and 24 grains. At the landward edge of the mangrove between 120m and 144m, they show counts of above 20 consistently in line with the stand of *Ceriops* seen at this location. *Heritiera* attains a minimum count of 3 at 30m along the transect and a maximum count of 36 at 114m.

The *Heritiera* distribution shows a unimodal nature with low counts of between 3 and 16 from 0m to 72m with an increase to the maximum count of 36 at 114m. Counts then drop to between 12 and 21 in the landward section of the mangrove (120m to 144m). *Avicennia* pollen is found across the transect and falls into three distinct zones of appearance. From 0m to 48m, counts are low, ranging between 1 and 6 grains per sample. There is then a hiatus with no grains between 54m and 60m. The second zone of *Avicennia* occurs between 66m and 102m and is characterised by minimum and maximum counts of 1 and 8 respectively. *Avicennia* is again absent at 108m before a third zone characterised by higher count with a maximum of 31 grains at 126m and a minimum of 4 grains at 114m. *Excoecaria* shows intermittent counts across the seaward edge of the transect from 0m to 102m with counts ranging between 0 and 4. The landward portion of the mangrove shows elevated counts at 108m and 114m of 10 before a gradual fall to 4 counts at 144m. *Species C* is also present intermittently but does show a zonation restricted primarily to the middle and landward portion of the mangrove between 66m and 144m. *Species C* counts are low though and the maximum achieved is 8 at 108m. All other species show no general pattern in counts.

Figure 5.2 identifies the patterns of distribution for the four major species at Mantigola.

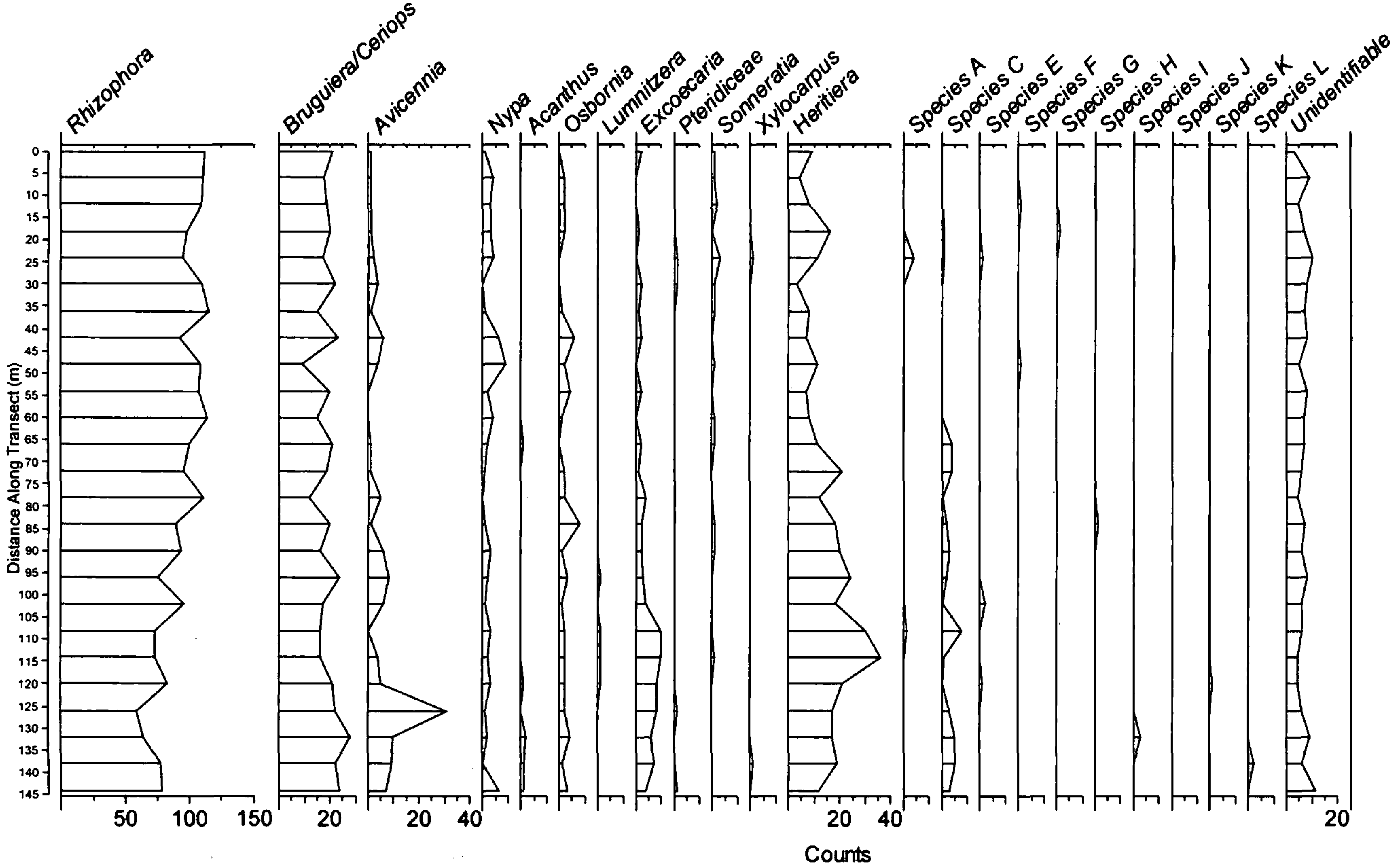


Figure 5.1 - Contemporary Distribution of Pollen at Mantigola MA200401

5.2.2 Cluster Analysis and Detrended Correspondence Analysis

Following the outlined methodology, the number of species in the dataset is reduced from 24 to 11 for statistical analysis. The transect demonstrates 2 clusters which are supported by both cluster analysis (CONISS, unconstrained using Unweighted Euclidean Distance, Figure 5.3) and Detrended Correspondence Analysis ('DCA', Figure 5.3). The use of two different approaches to clustering the dataset demonstrates that the clusters are significant and not a product of a specific statistical method of clustering.

Zone MA1 encompasses 17 sample sites, representing the front of the mangrove. The zone is dominated by *Rhizophora* pollen, constituting at least 60% of the total pollen sum in all samples. *Heritiera* and *Bruguiera/Ceriops* are also ever present throughout this zone. Zone MA2 encompasses 8 sites, representing the rear of the mangrove. Zone MA2 shows a marked change from Zone MA1, with a drop in *Rhizophora* pollen to below 60% in all samples. *Bruguiera/Ceriops* and *Heritiera* both show increases in Zone MA2 compared to Zone MA1 with *Excoecaria* also achieving prominence in this back zone.

Zone MA1 has an elevational range of 0.88 to 2.18m above IHD, whilst Zone MA2 ranges from 2.08 to 2.37m above IHD (Figure 5.3). The crossover in elevational ranges can be explained by the transition zone between the *Rhizophora* dominated mangrove and the more diverse back mangrove between the sample sites at 96m and 102m.

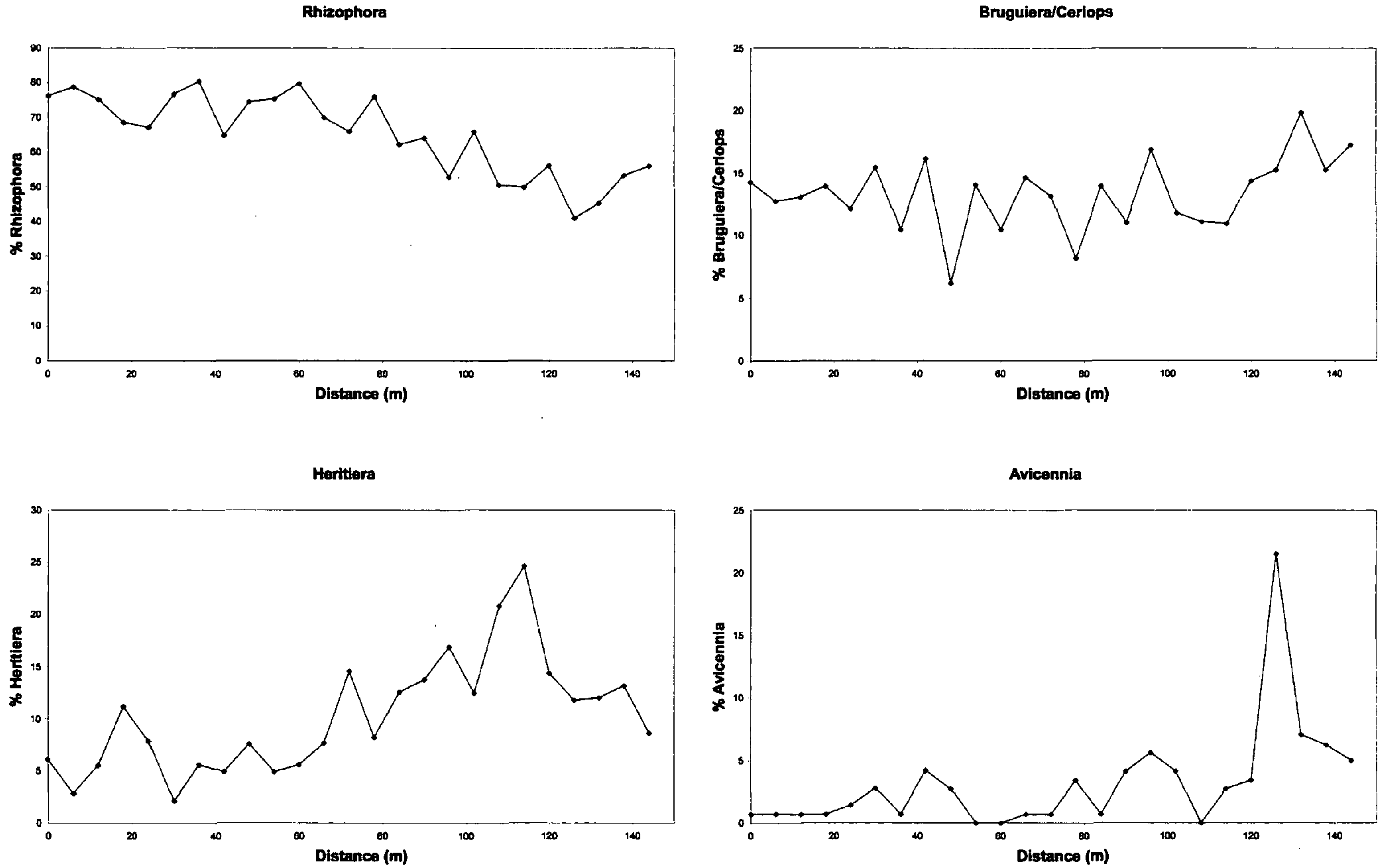


Figure 5.2 - Distributions of Four Major Species at Mantigola

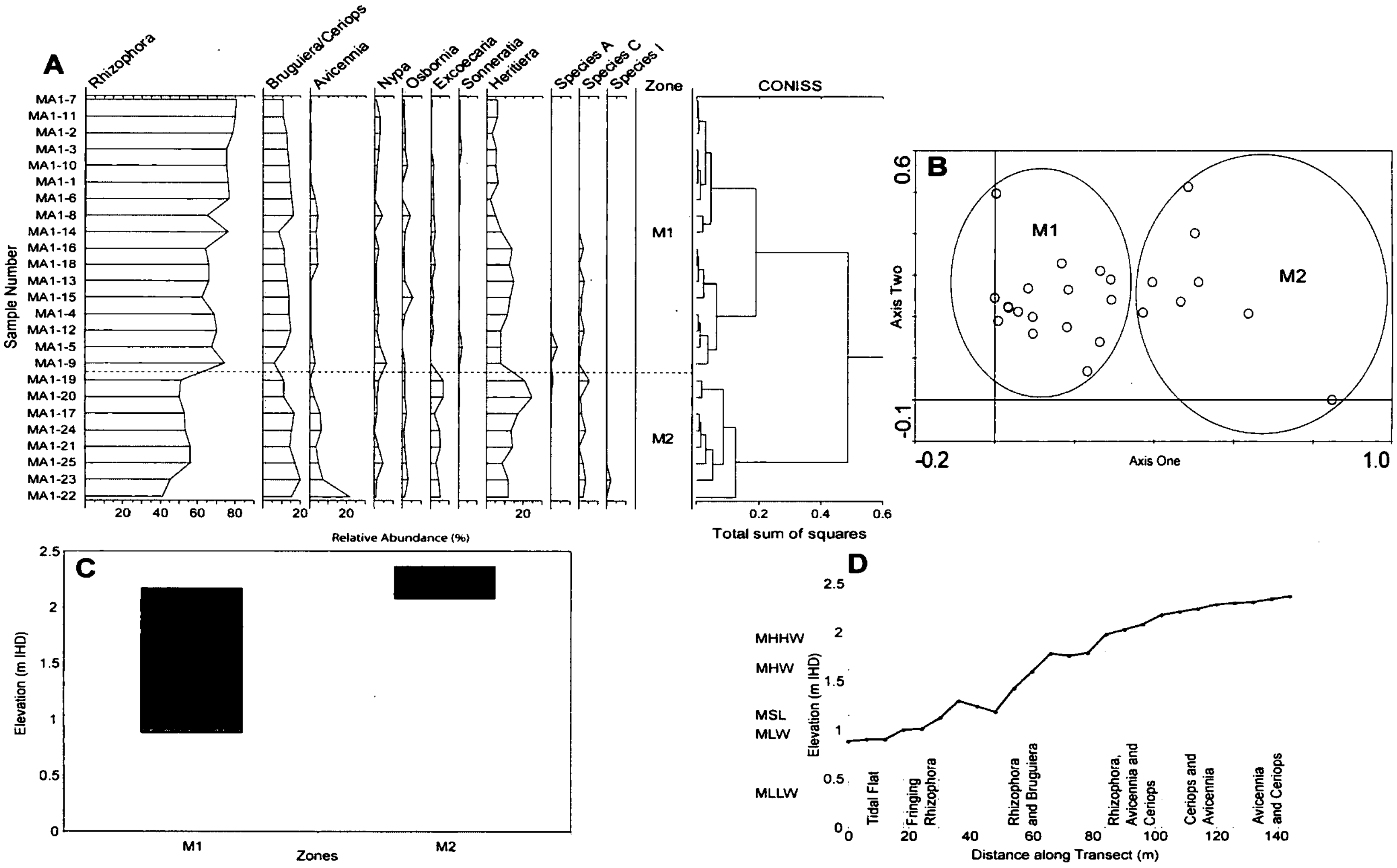


Figure 5.3 - CONISS Cluster Analysis, DCA Analysis, Zone Elevation Ranges and Vegetation for Mantigola

5.2.3 Environmental Variables

Silt shows the most variability in grain size change across the transect, reaching a maximum of 70.6% at 24m and a minimum of 24.06% at 0m (Figure 5.4). Clay is generally consistent below 20% across the transect, however peaks of between 29.4% and 42.7% are recorded at sample sites where the sand fraction is 0%. The sand fraction reaches a peak of 67.5% at sample 0m. Where a sand fraction is present, it generally falls between 35% and 50%, however the sand fraction is present intermittently in the mid-section of the mangrove. Silt in particular shows little variation across the mangrove with the majority of co-variance in the grain size between the sand and clay fractions i.e. in areas with a high percentage of clay there is an associated low percentage of sand with little variation in the silt content. The loss on ignition results shows a general trend of increase across the mangrove with a minimum value of 10.9% at 0m and a maximum of 49.5% at 126m. Salinity levels rise from 6.3 at 0m (front mangrove) to a peak of 42.1 at 120m before declining to 0 at 144m. It is interesting to note that at the rear of the mangrove and specifically at 120m, that pH and salinity show an inverse pattern with a particularly low pH and high salinities. This can be explained by the frequency of inundation resulting in high salinities for areas with low inundation and high evaporation. The reduction at the rear of the transect is due to the area being above the limit of the high tide.

5.2.4 The Relationship between Pollen and the Environmental Variables of Mantigola

In accordance with the methodology outlined, Canonical Correspondence Analysis (CCA) was applied to relate community composition to the recorded environmental variables. CCA was applied using version 4.51 of Canoco (ter Braak and Smilauer, 1997-2003).

CCA Axes One (eigenvalue=0.079) and Two (eigenvalue=0.018) explain 42.8% of the total variance in the pollen data and 84.4% of the species environment relationship (Table 5.2).

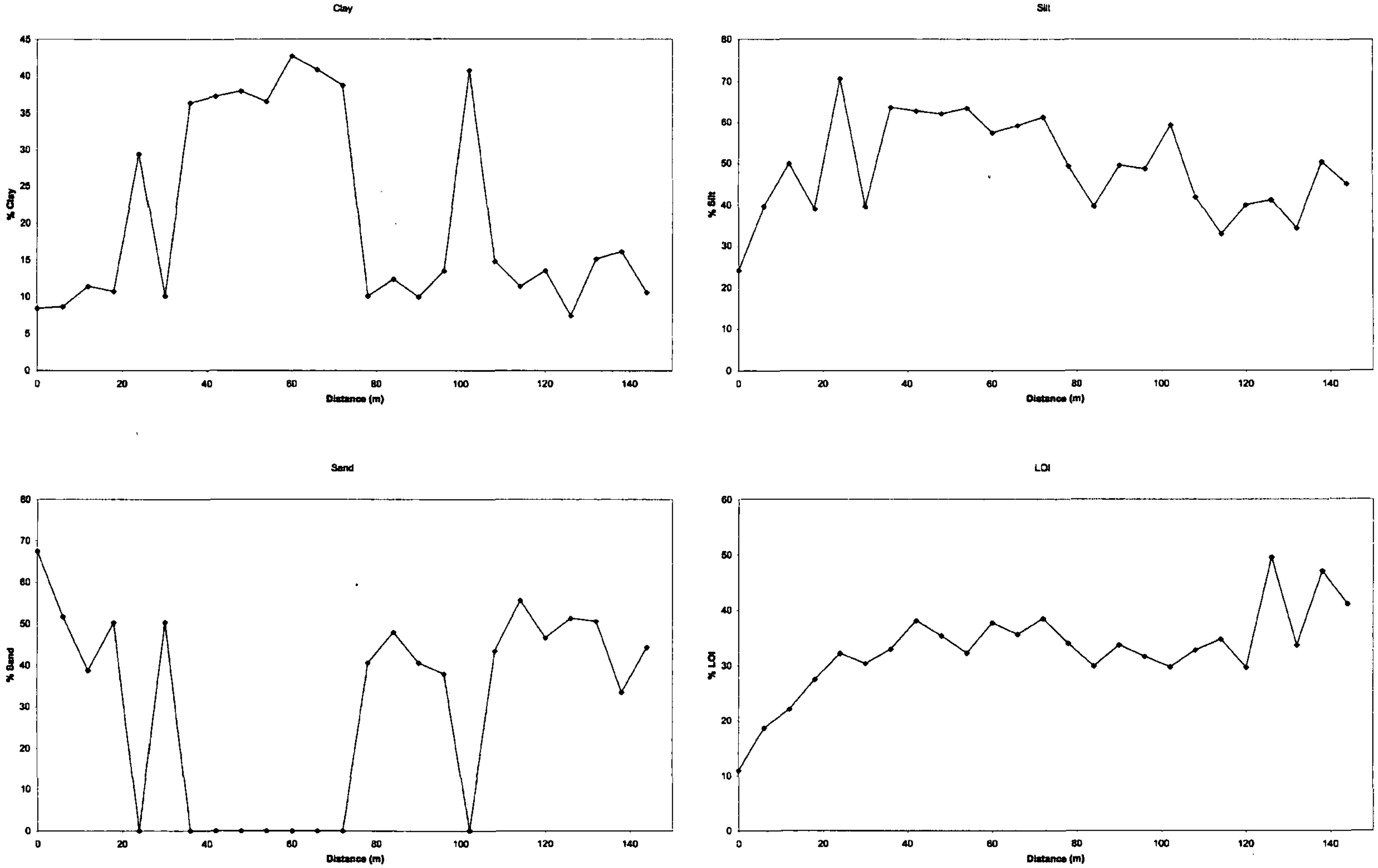


Figure 5.4 - Environmental Variables for Mantigola

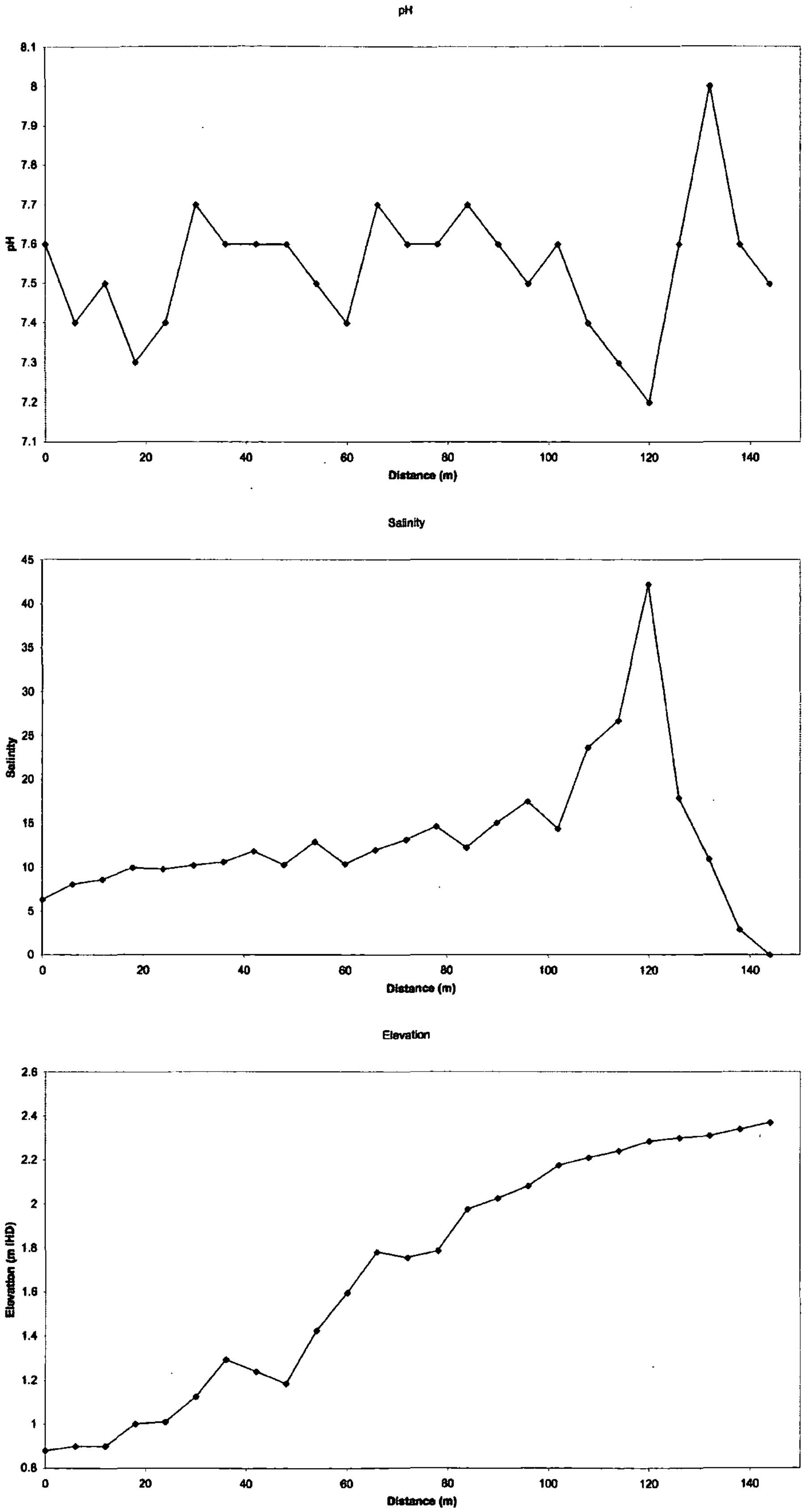


Figure 5.4 - Environmental Variables for Mantigola (Continued)

Table 5.2 Mantigola CCA Summary Statistics

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.079	0.018	0.012	0.003	0.225
Species-environment correlations:	0.919	0.738	0.689	0.349	
Cumulative percentage variance					
of species data :	34.8	42.8	48.3	49.5	
of species-environment relation:	68.8	84.4	95.3	97.6	
Sum of all eigenvalues					0.225
Sum of all canonical eigenvalues					0.114

Intra-set correlations of environmental variables with Axes One and Two shows that sand, silt, clay, elevation and LOI are highly correlated with Axis One, with salinity and pH showing a joint correlation between Axes One and Two (Figure 5.5). Axis One therefore represents the environmental gradient with the low elevation, high silt and clay fraction on the left (tidal flat) through to the high elevation, high LOI values and increased sand values on the right (back mangrove). The species-environment bi plot (Figure 5.6) shows the front mangrove species of *Rhizophora*, *Species A* and *Sonneratia* plotting on the left (high clay and silt fractions, low elevation, sand and

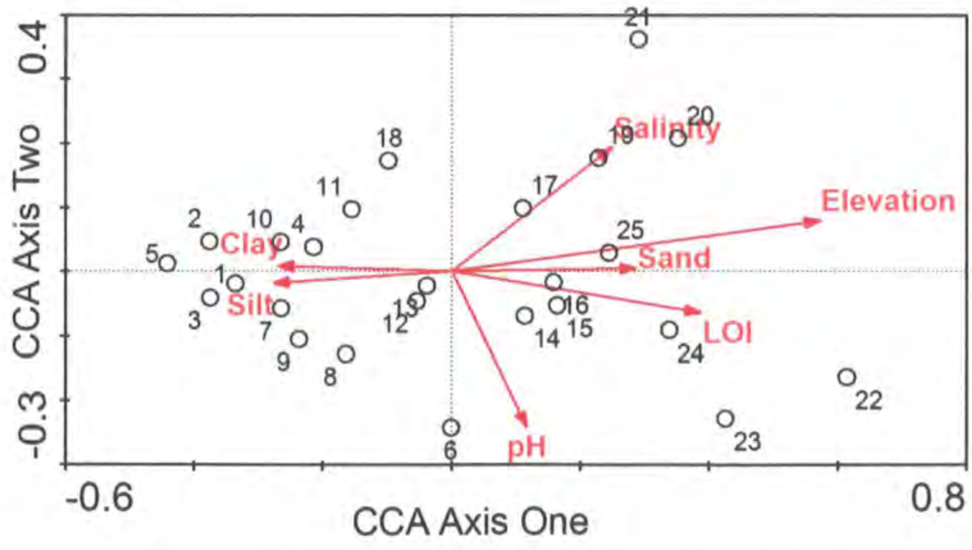


Figure 5.5 – Sample-Environment Bi-plot for Mantigola

LOI) and the back mangrove species *Excoecaria*, *Species C* and *Avicennia* (high sand fraction, elevation and LOI, low clay and silt fractions) plotting to the right.

The seven environmental variables account for 23.8% of the explained variance in the pollen data. Partial CCAs were carried out and show that the total explained variance is composed of 28.2% (elevation), 14.5% (LOI), 8.7% (salinity), 7.8% (silt), 7.4% (sand), 7.4% (pH) and 6.5% (clay). The associated Monte Carlo permutation tests (p=0.05, 499 permutations under reduced model) indicated that the only two variables that are highly significant are elevation and LOI.

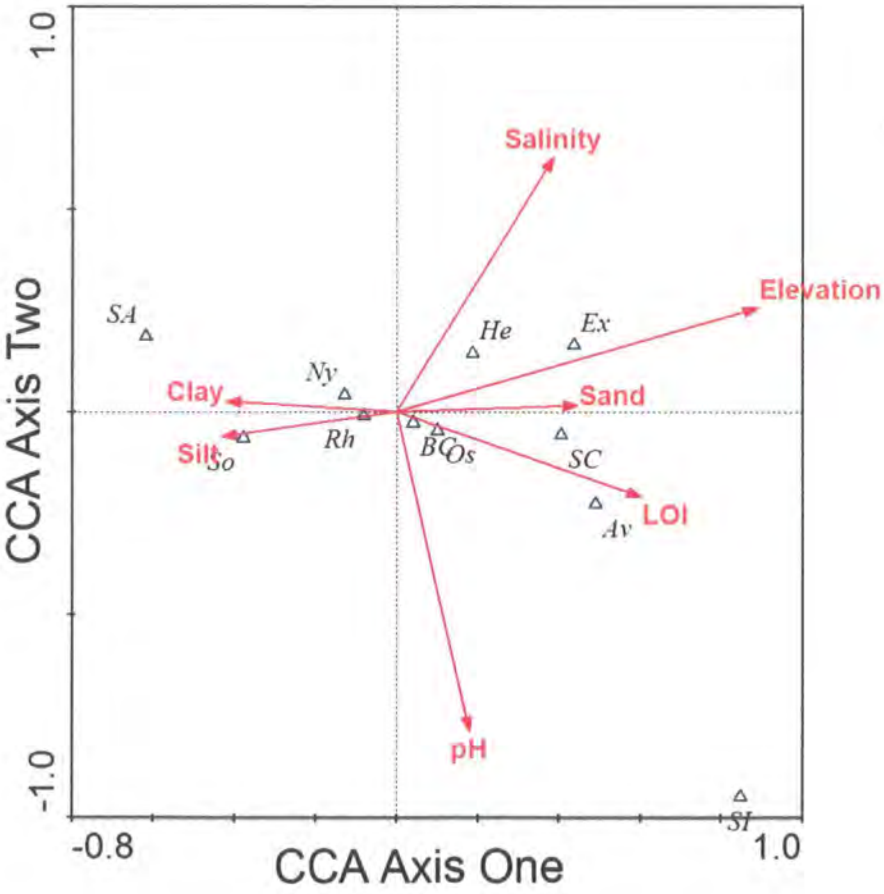


Figure 5.6 – Species-Environment Bi-plot for Mantigola

5.3 Contemporary Characteristics of Laulua Transect LL200401

5.3.1 Contemporary Pollen Distribution

18 species were identified from 24 sampling stations at Laulua (Figure 5.7). *Rhizophora*, *Bruguiera/Ceriops* and *Avicennia* are the dominant pollen species on the transect. *Rhizophora* routinely accounted for over 80% of the pollen sum in a sample with a minimum abundance of 20% at the rear of the mangrove. *Bruguiera/Ceriops* is present in all samples but varies from ~20% at the front of the mangrove to over 60% at the rear of the mangrove. *Avicennia* is present from the mid-mangrove to the rear of the mangrove. The pollen distributions are comparable to the species distribution along the transect, which showed a transition from front to rear of *Rhizophora*, to *Avicennia* and then to *Ceriops*. Whilst not abundant, *Lumnitzera*, *Heritiera*, *Excoecaria* and *Species C* are all present consistently in the mid and back mangrove zones (L2 and L3 respectively).

Rhizophora and *Bruguiera/Ceriops* show interplay along this transect with high counts of one species being mirrored with low counts in the other. *Rhizophora* shows high counts of over 100 between 0m (front) and 44m with the highest count of 118 at 12m along the transect. The rear of the mangrove from 48m to 92m is characterised by *Rhizophora* counts below 100 with the lowest counts of 32 at 84m and 88m at the rear of the transect. *Bruguiera/Ceriops* shows three peaks of counts along the transect which can be ascribed to their presence in the mangrove. The first peak is at the front of the *Rhizophora* zone (0m to 8m) at the front of the mangrove and relates to a stand of *Bruguiera*. Minimum and maximum counts of 23 and 27 mark this zone. Lower counts of 17 and 15 at 16m and 20m respectively indicate the mid-*Rhizophora* zone with no trees of this species in the immediate vicinity. From 24m, counts increase to

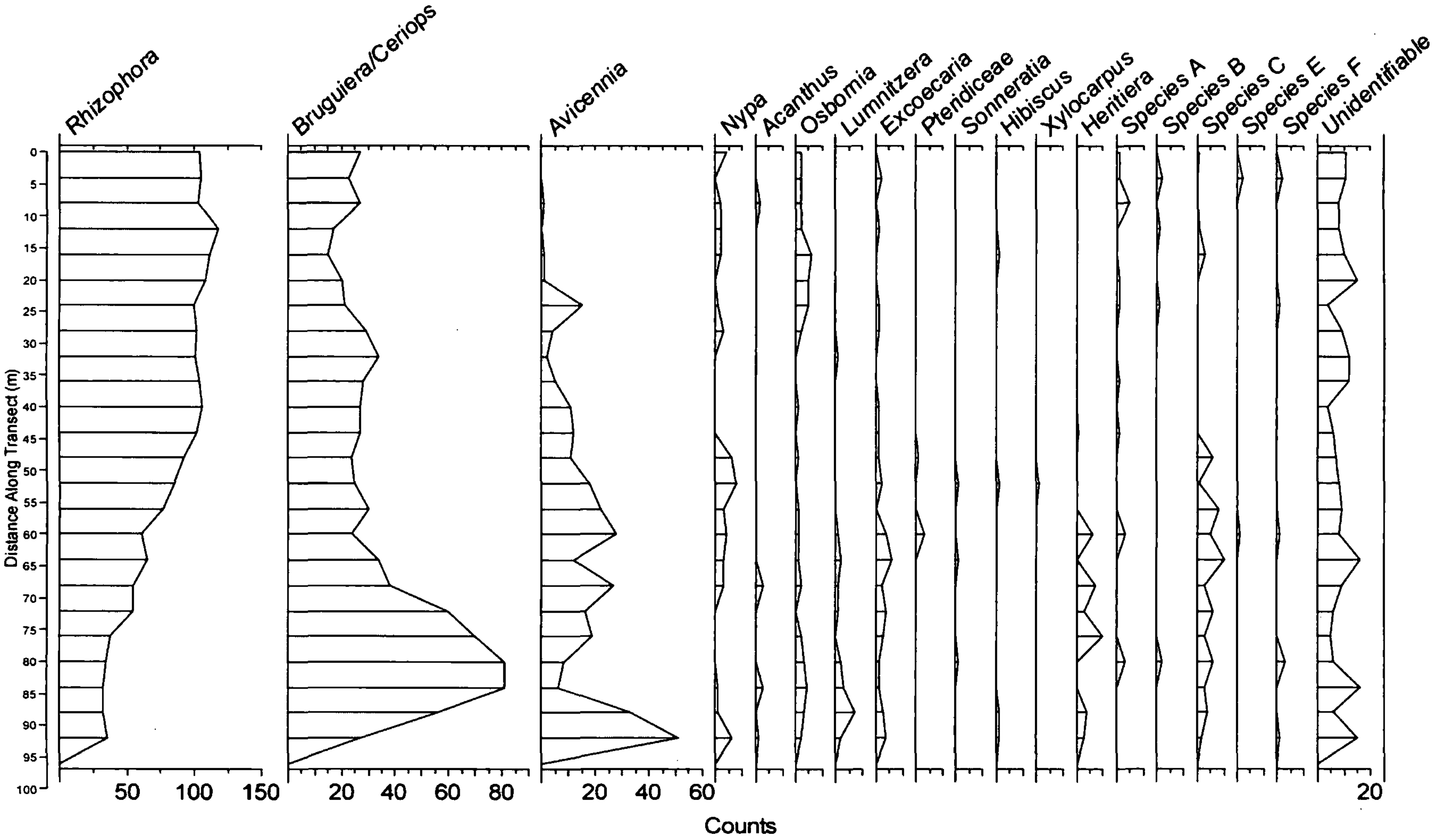


Figure 5.7 - Contemporary Distribution of Pollen at Laulua LL200401

a maximum 34 at 36m, which relates to the first stand of *Ceriops* behind the *Rhizophora* zone. Counts again decrease from 36m to 24 at 52m relating to a movement away from the small *Ceriops* zone. From 56m counts again increase from a minimum of 24 to the highest counts achieved on the transect of 81 at 80m and 84m, which relates to the large *Ceriops* stand at the rear of the mangrove.

Avicennia pollen is generally not present in the front *Rhizophora* zone of the mangrove (0m to 20m) or with only low counts of 1. *Avicennia* counts show a general increase from this point to a peak of 28 grains at 60m in line with the mid-mangrove presence of the species. Counts then fall to the rear of the mangrove reaching a low of 6 grains at 84m before a rapid increase at the extreme rear of the mangrove (88m to 92m) to the highest count on the transect of 51 at 92m. *Lumnitzera* shows a maximum count of 7 at 88m with counts of 3 and 2 at surrounding stations (84m and 92m). *Excoecaria* attains a maximum count of 6 at 64m and its presence as counts of above 2 is limited to the rear mangrove from 60m rearwards. *Heritiera* is present intermittently but attains a maximum count of 10 at 76m and high counts of the species are again limited to the rear mangrove from 60m rearwards. *Species C*, like *Excoecaria* and *Heritiera* is again limited to the rear mangrove for counts of over 3. The maximum count of 10 is attained at 64m with counts of over 3 indicative of the mangrove from 48m rearwards. Other species showed intermittent presence and limited or no patterns in distribution.

The major patterns in distribution of the three major species at Laulua are shown in Figure 5.9

5.3.2 Cluster Analysis and Detrended Correspondence Analysis

Following the outlined methodology, the number of species used for statistical analysis is 13. The transect is subdivided into three zones, on the basis of Cluster Analysis (CONISS, unconstrained and Unweighted Euclidian Distance, Figure 5.8) and DCA (Figure 5.8).

Zone L1 encompasses 14 samples and represents the front of the mangrove system. The zone is defined by high abundances of *Rhizophora* pollen which never fall below 60% of the total pollen sum. *Bruguiera/Ceriops* is present throughout the zone but rarely attains more than 20% abundance. *Avicennia* is present in the zone from the sample site at 24m backwards. Zone L3 represents the rear of the mangrove and is defined by an increase in the abundance of *Bruguiera/Ceriops* pollen to between 40% and 60% of total pollen sum with an associated decrease in *Rhizophora* pollen, which never attains greater than 40% of the total pollen sum. *Avicennia* levels remain similar to those at the rear of Zone L1 but do show an increase towards the rear of Zone L3. *Lumnitzera, Heritiera, Excoecaria* and *Species C* are all present in greater abundances than in Zone L1. Zone L2 represents the mid-mangrove and is defined by a decrease in *Rhizophora* from ~60% abundance at the front of the zone to ~25% at the rear of the zone. *Bruguiera/Ceriops* levels are elevated compared to Zone L1 but lower than in Zone L3. *Avicennia* abundances range from 10% to 40% with an increase moving towards the rear of the zone.

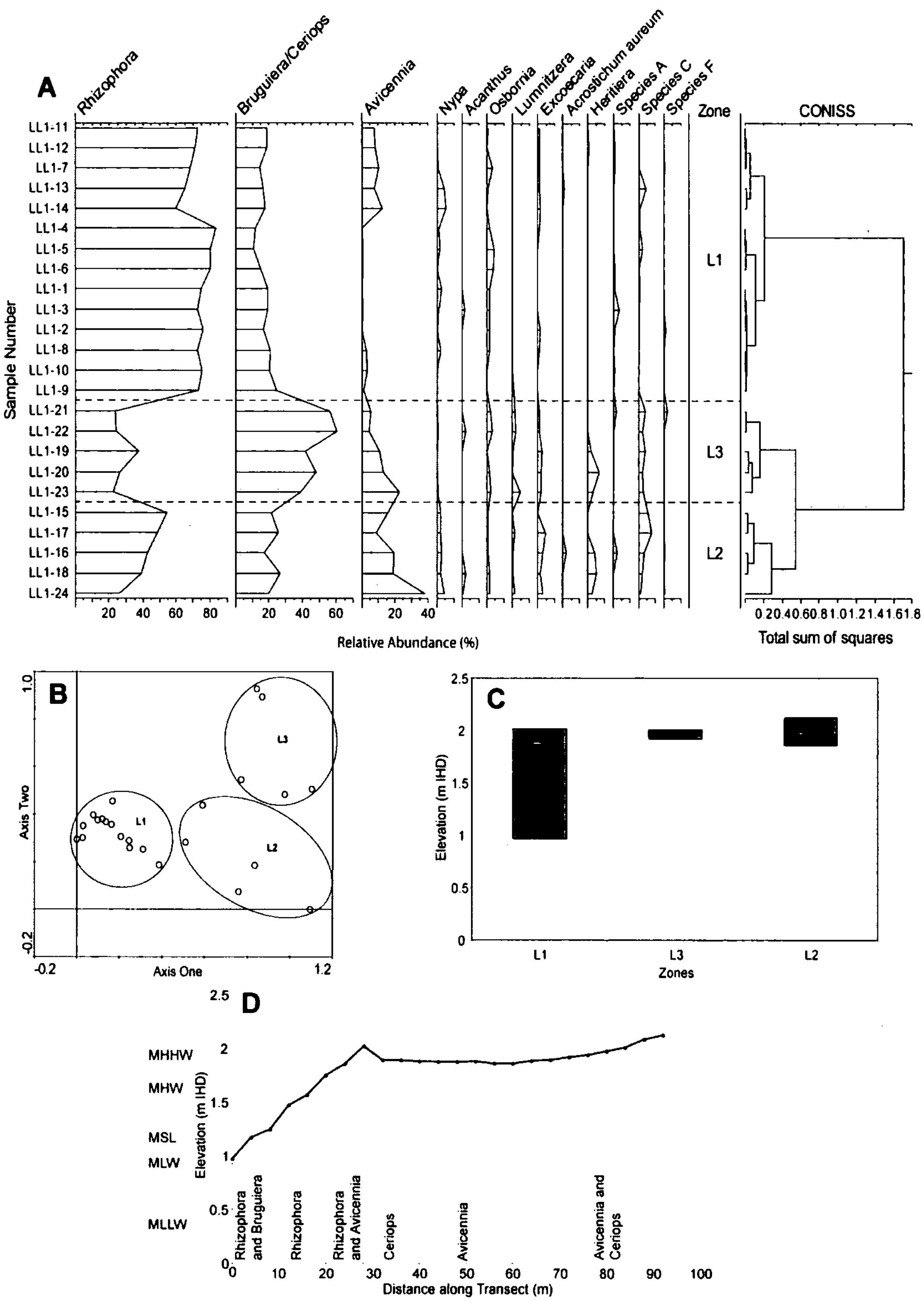
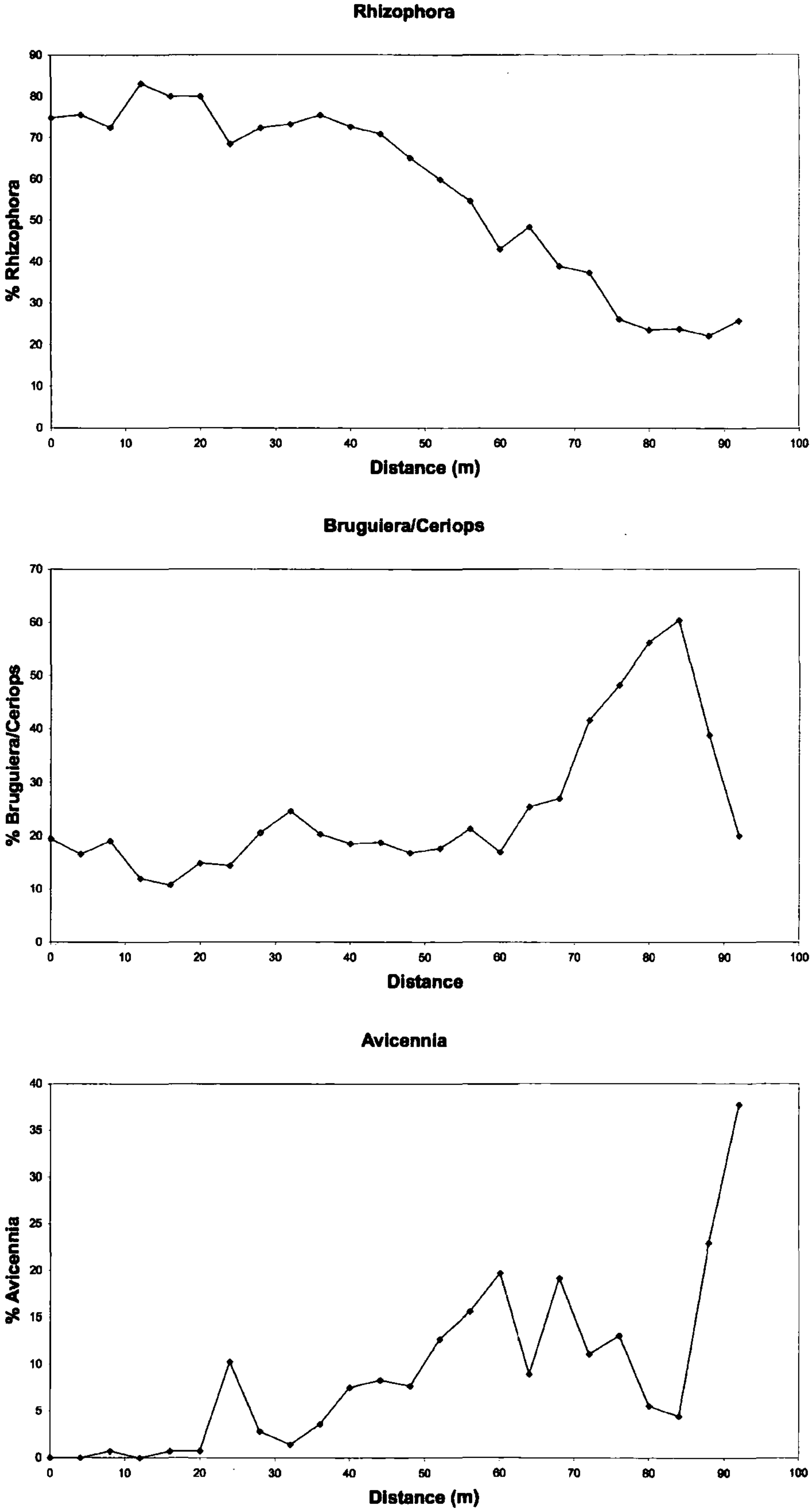


Figure 5.8 - CONISS Cluster Analysis, DCA Analysis, Zone Elevational Ranges and Vegetation for Laulua


Rhizophora

Bruguiera/Ceriops

Avicennia

Figure 5.9 - Distributions of Three Major Species at Laulua

Zone L1 has an elevational range of 0.97m to 2.02m above IHD, Zone L3 has an elevational range of 1.92m to 2.01m above IHD and Zone L2 has an elevational range of 1.86 to 2.13m above IHD (Figure 5.8). The zones show a great deal of elevational overlap. This is due to the elevation of the mangrove showing little change between sites 24m and 92m. This indicates that other environmental variables as well as elevation are controlling the distribution of pollen in the samples.

5.3.3 Environmental Variables

Silt is the dominant fraction at Laulua, showing a general increasing trend from the front to the rear of the mangrove, achieving a maximum of 69.7% at 88m (Figure 5.10). Sand is dominant at the front of the mangrove, declining from 55.5% at 0m to a minimum of 19.3% at 88m following a trend of general decline. At site 28m the sand fraction is not present and is associated with an increase in the clay fraction from 5.87% at 24m to 37.8% at 28m, before returning to a low clay fraction of 8.52% at 32m. Discounting the anomaly at 28m, the clay fraction shows a general rising trend to 24.9% at 64m, followed by a reduction in the clay fraction towards the rear of the mangrove. As at Mantigola, silt shows the least variation with the major changes involving the sand and clay fractions. LOI reaches a maximum at 28m of 49.1%, which correlates with the lowest sand and highest clay fractions and a minimum of 4.3% at 92m. pH shows similar levels at the front and rear of the mangrove of between 7 and 8, with an area of lower pH in the mid mangrove of between 5 and 7. Salinity rises from the front to the middle of the mangrove, with the highest value of 39.6 at 44m. Salinity then falls towards the back of the mangrove. This pattern is once again explained by the frequency and height of inundation.

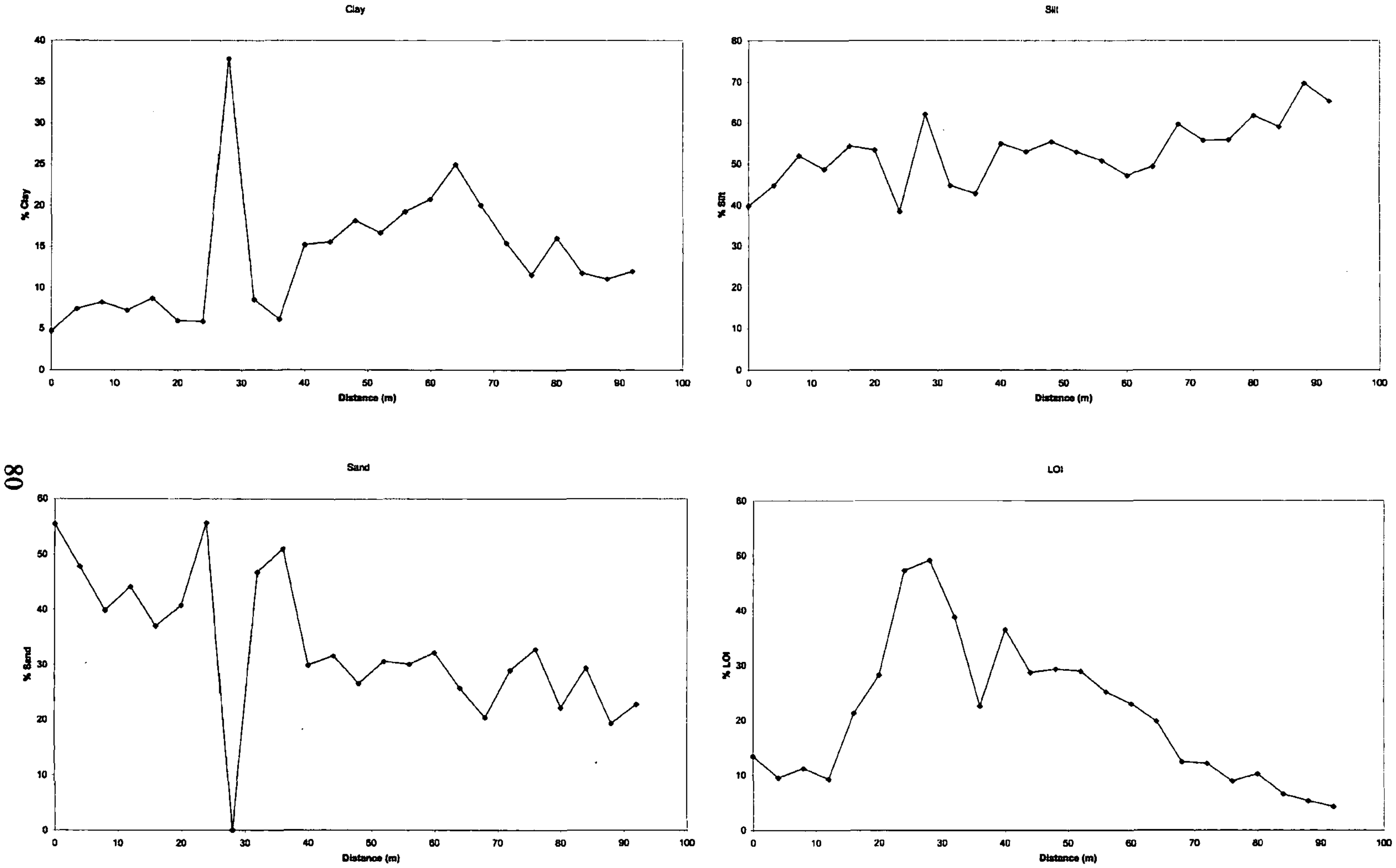
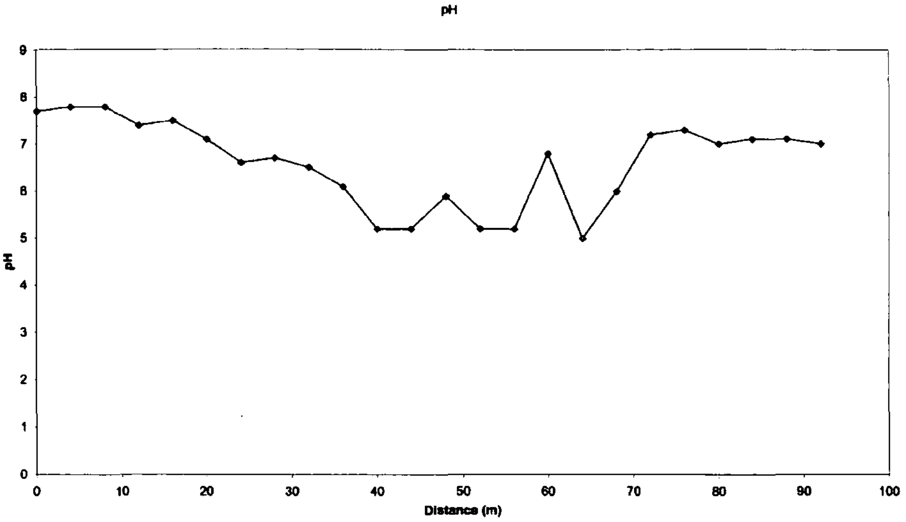
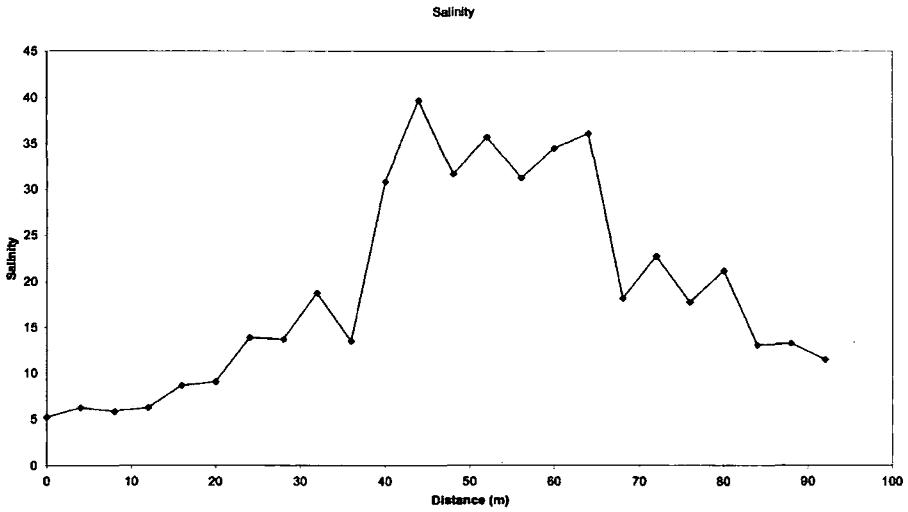


Figure 5.10 - Environmental Variables for Laulua





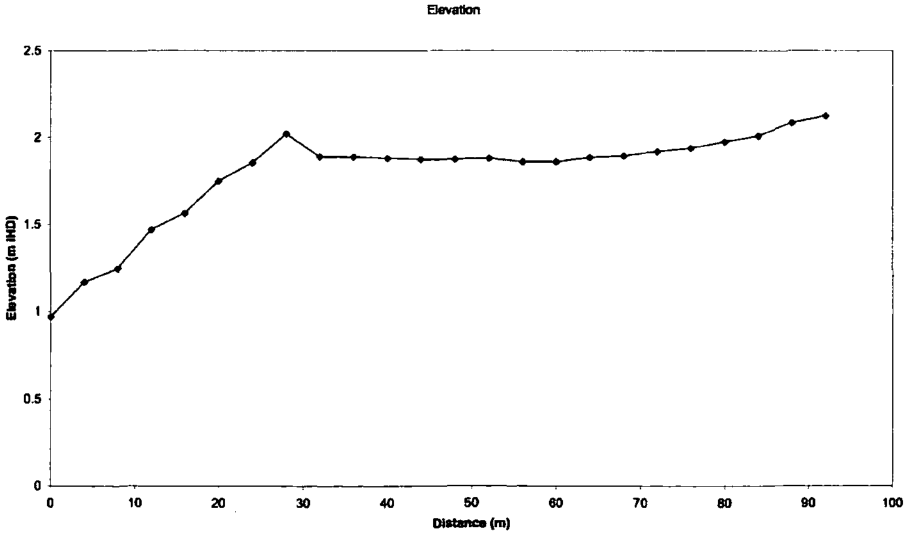


Figure 5.10 - Environmental Variables for Laulua (Continued)

5.3.4 The Relationship between Pollen and the Environmental Variables of Laulua

CCA Axes One (eigenvalue=0.17) and Two (eigenvalue=0.02) explain 45.8% of the total variance in the pollen data and 89.2% of the species environment relationship (Table 5.3).

Table 5.3 - Laulua CCA Summary Statistics

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.170	0.020	0.016	0.005	0.417
Species-environment correlations:	0.918	0.852	0.580	0.543	
Cumulative percentage variance					
of species data :	40.9	45.8	49.6	50.9	
of species-environment relation:	79.6	89.2	96.7	99.2	
Sum of all eigenvalues					0.417
Sum of all canonical eigenvalues					0.214

Intra-set correlations with Axes One and Two shows that elevation, silt, LOI and sand are highly correlated with Axis One, salinity and clay are jointly correlated with Axes One and Two and pH is highly correlated with Axis Two (Figure 5.11). Axis One therefore represents the major environmental gradient with high elevation and high silt contents plotting on the left (back mangrove) and high LOI and sand fractions plotting on the right (front mangrove).

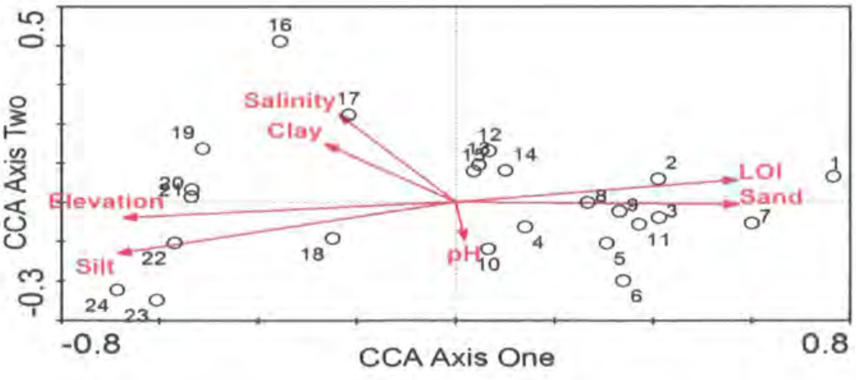


Figure 5.11 – Sample-Environment Bi-plot for Laulua

The species-environment bi-plot (Figure 5.12) shows the dominant front mangrove species *Rhizophora* plotting on the right towards the high LOI and sand fractions with the back mangrove species *Bruguiera/Ceriops*, *Avicennia*, *Heritiera* and *Lumnitzera* plotting to the left with high elevations and silt fractions. The *Bruguiera/Ceriops* signal is more complicated due to *Bruguiera* being a front mangrove species and *Ceriops* being a back mangrove species in the Wakatobi Marine National Park.

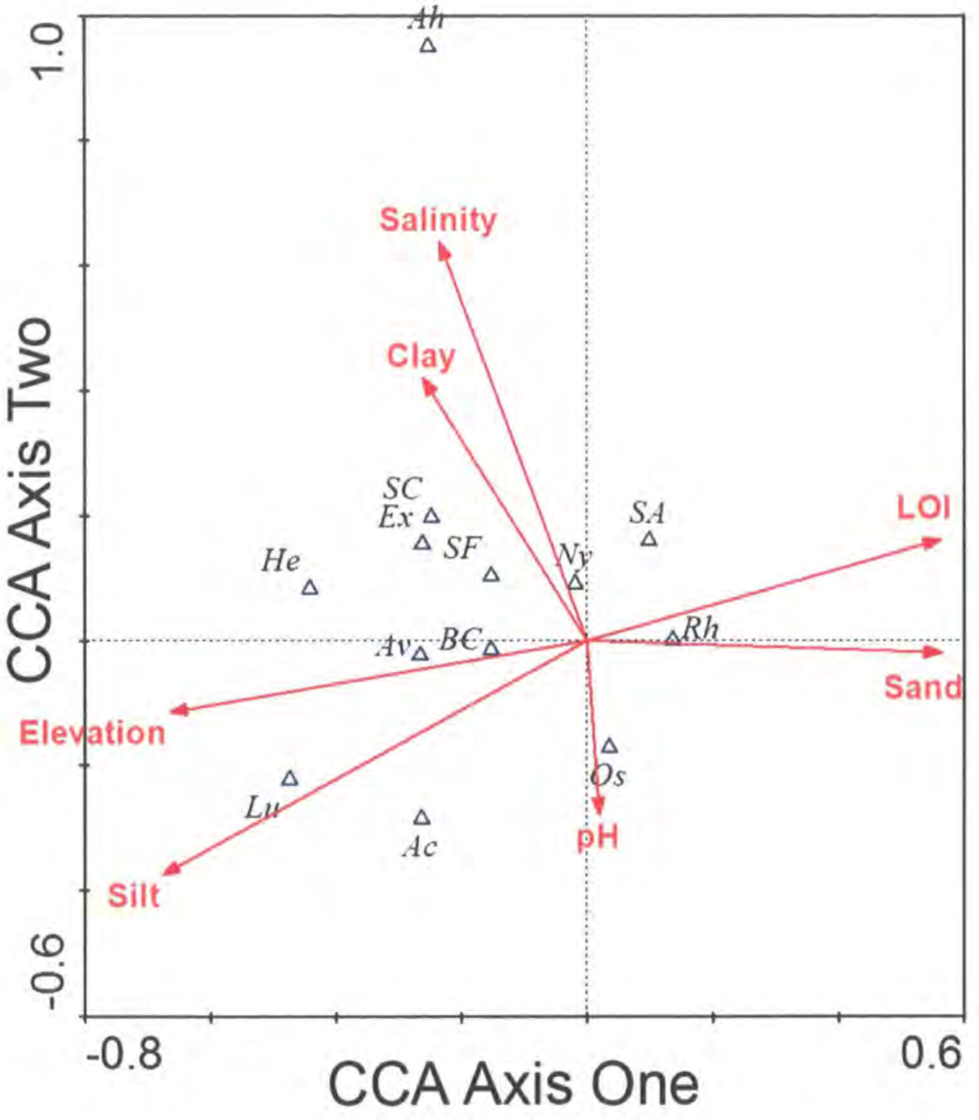


Figure 5.12 – Species-Environment Bi-plot for Laulua

The seven environmental variables explain 22.2% of the explained variance in the pollen data. Partial CCAs were carried out and show that the total explained variance is composed of 19.6% (silt), 19.2% (elevation), 13.9% (LOI), 13.6% (sand), 5.8% (salinity), 4.5% (clay) and 3.7% (pH). The associated Monte Carlo permutation tests (p=0.05, 499 permutations under reduced model) indicate that silt, elevation, LOI and sand are all significant.

5.4 Contemporary Characteristics of Kakenauwe Transect LA200401

5.4.1 Contemporary Pollen Distribution

15 mangrove species were identified from 14 sample sites at Kakenauwe (Figure 5.13). *Rhizophora*, *Heritiera* and *Sonneratia* are the dominant species. The Kakenauwe transect differs from Laulua and Mantigola as the mangrove is a 20m wide strip at the landward portion of a large tidal flat. Both the mangrove and the tidal flat were sampled. A number of pollen types were identified in the mangrove that did not related to the species found on the transect. The Kakenauwe transect was located close to a small river and it is possible that this may be contributing an allochthonous component at this site.

Rhizophora shows a linear progression at *Kakenauwe* with low counts on the tidal flat with a steady increase as you move landwards on the tidal flat to the centre of the dominant *Rhizophora* mangrove at 36m and 39m. The maximum count of 104 is at 39m with the lowest count of 21 at 6m. The pattern of *Heritiera* is the opposite of the *Rhizophora* pattern with high counts on the tidal flat, the maximum of 112 being achieved at 6m. The counts follow a general decline as the transect moves through the tidal flat and into the mangrove with the lowest count of 16 being recorded at 39m.

Both species show an anomaly at 42m where the mangrove ended and rose into a terrestrial environment, with a decrease in *Rhizophora* and an increase in *Heritiera* which both go against the pattern described as you move along the transect. *Sonneratia* is present all along the transect though the counts on the tidal flat are noticeably lower than those as you move towards the mangrove at 21m. The maximum *Sonneratia* count of 16 is recorded at 39m and the minimum of 1 is recorded at 6m. *Bruguiera/Ceriops* is also generally present on the transect with a minimum count of 0 at 15m. The maximum counts of 13 occur at 18m and 33m and are associated with the transition from tidal flat to the front of the mangrove strip. The presence of *Bruguiera/Ceriops* pollen at this point in the transect demonstrates its indication of a nearby mangrove when present in counts of above 3. All other species showed limited representation and/or no general pattern across the mangrove.

The patterns of distribution of the major species at Kakenauwe are shown in Figure 5.14.

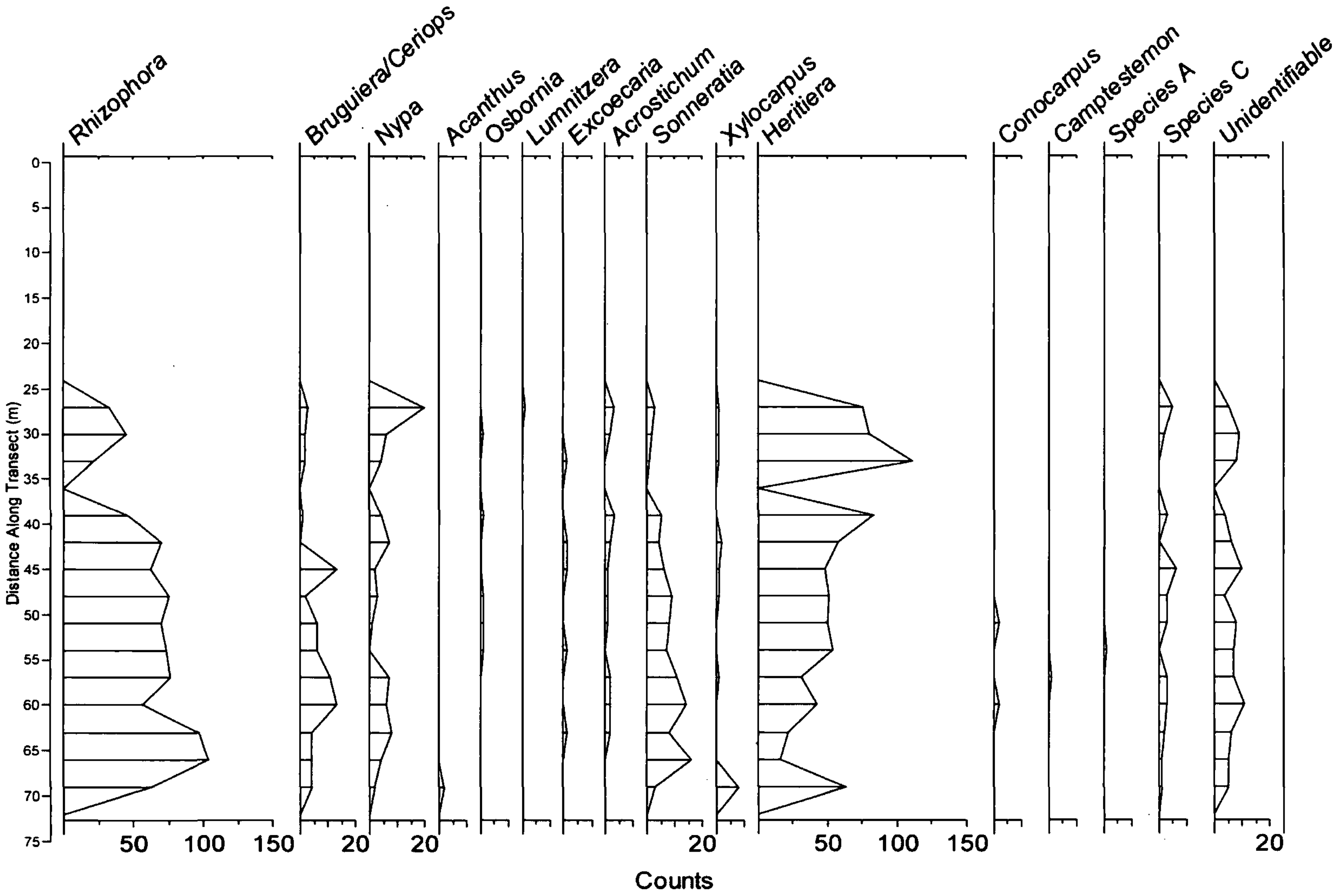


Figure 5.13 - Contemporary Distribution of Pollen at Kakenauwe LA200401

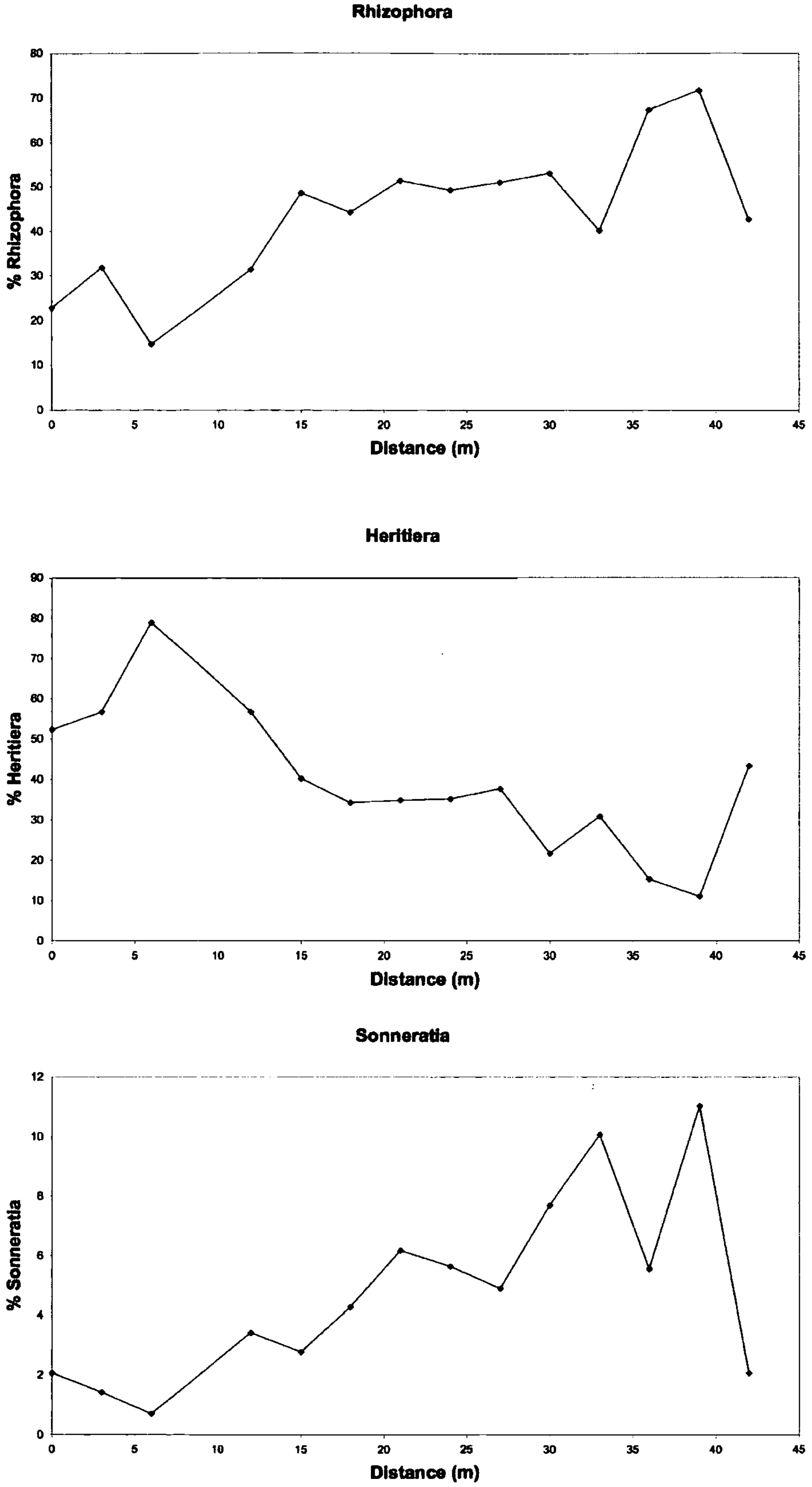


Figure 5.14 Distributions of the Three Major Species at Kakenauwe

5.4.2 Cluster Analysis and Detrended Correspondence Analysis

Following the outlined methodology, the number of species for statistical analysis was reduced to 8. The transect demonstrates three zones which are supported by both cluster analysis (CONISS, unconstrained with Unweighted Euclidian Distance, Figure 5.15) and DCA (Figure 5.15).

Zone K1 encompasses 4 samples and represents the front of the tidal flat. The zone is defined by *Rhizophora* abundances of below ~30% and *Heritiera* abundances of over 50%. Other species appear intermittently throughout this zone. Zone K3 encompasses 2 samples at the landward edge of the mangrove system which are dominated by *Rhizophora* and *Sonneratia.* The zone possesses high abundances of *Rhizophora* (over 60% of total pollen sum), much reduced abundances of *Heritiera* (below 15%) and the presence of *Sonneratia* pollen (over 5%). Other species influences within Zone K3 are minimal. Zone K2 encompasses 8 samples and represents the middle of the tidal flat. *Rhizophora* abundances fluctuate around 50% with an increased presence of *Bruguiera/Ceriops* pollen compared to Zones K1 and K3. *Sonneratia* is consistently present throughout up to a maximum of 10% total pollen sum. Zone K1 has an elevational range of 0.81m-0.885m above IHD, Zone K3 from 1.52m-1.66m above IHD and Zone K2 from 0.92m to 1.365m above IHD. The elevational range of Zone K2 is greatly extended due to the presence of samples LA1-24 at 1.82m IHD (Figure 5.15).

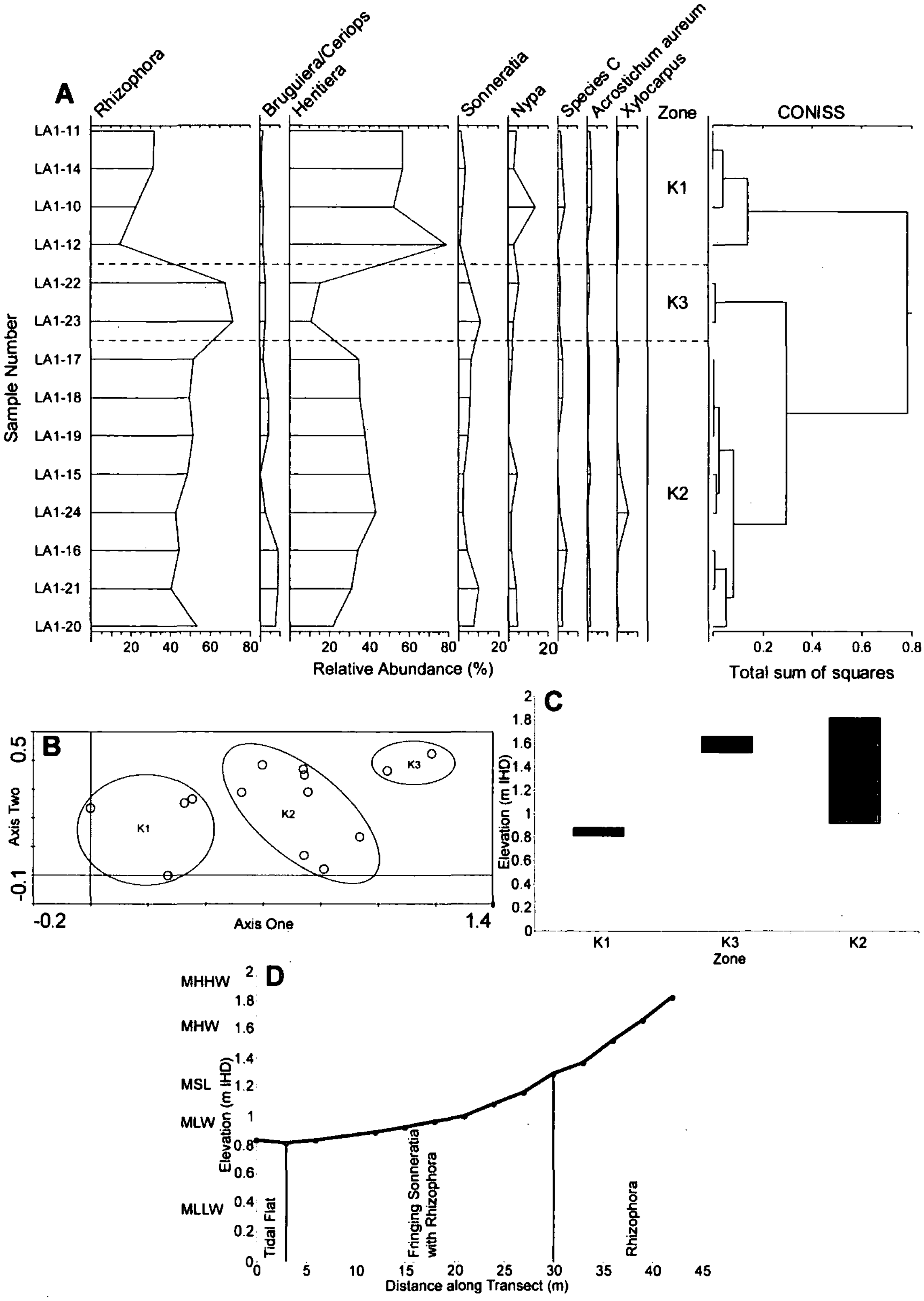


Figure 5.15 - CONISS Cluster Analysis, DCA Analysis, Zone Elevation Ranges and Vegetation for Kakenauwe

5.4.3 Environmental Variables

The front of the transect at Kakenauwe is dominated by the sand fraction with increasing importance of the silt fraction as you move from the tidal flat towards the mangrove (Figure 5.16). All the associated grain size fractions show little variation on the tidal flat with increases in clay and silt and a reduction in the sand fraction within the mangrove. The sand fraction reaches its maximum at 12m of 77.7% and a minimum of 1.4% within the mangrove at 39m. The silt fraction shows a decrease as you move from the front tidal flat to the mid tidal flat, from 47.8% at 0m to 18.02% at 12m. This remains steady through the tidal flat, before rising at the back of the tidal flat and front of the mangrove to a maximum value of 78.3% at 39m. Organic content is low between 0m and 30m, ranging between 5% and 10% before increasing rapidly as the transect moves into the mangrove to a maximum value of 62.8% at 42m. pH shows a general decreasing trend moving from the tidal flat through to the mangrove with maximum value of 8.1 at 6m and the minimum value of 7.4 between 33m and 39m. Salinity levels are steady on the tidal flat at around 6 before increasing rapidly to a maximum of 10.5 within the mangrove at 39m.

5.4.4 The Relationship between Pollen and the Environmental Variables of Kakenauwe

CCA Axes One (eigenvalue=0.125) and Two (eigenvalue=0.03) explain 64.3% of the total variance in the pollen data and 86.2% of the species-environment relationship (Table 5.4), the highest proportion at all three transects. Intra-set correlations with Axes One and Two show that clay, silt, sand and pH are highly correlated with Axis One and elevation, salinity and LOI are jointly correlated with Axes One and Two

(Figure 5.17). Axis One therefore represents the major environmental gradient with high pH and sand fractions plotting to the right (tidal flat) and high silt and clay fractions plotting to the left (mangrove). The species-environment bi-plot (figure 5.18) shows the front mangrove species of *Rhizophora* and *Sonneratia* plotting to the left with high silt and clay fractions, whilst *Heritiera* plots to the right hand side with high sand fractions and pH values.

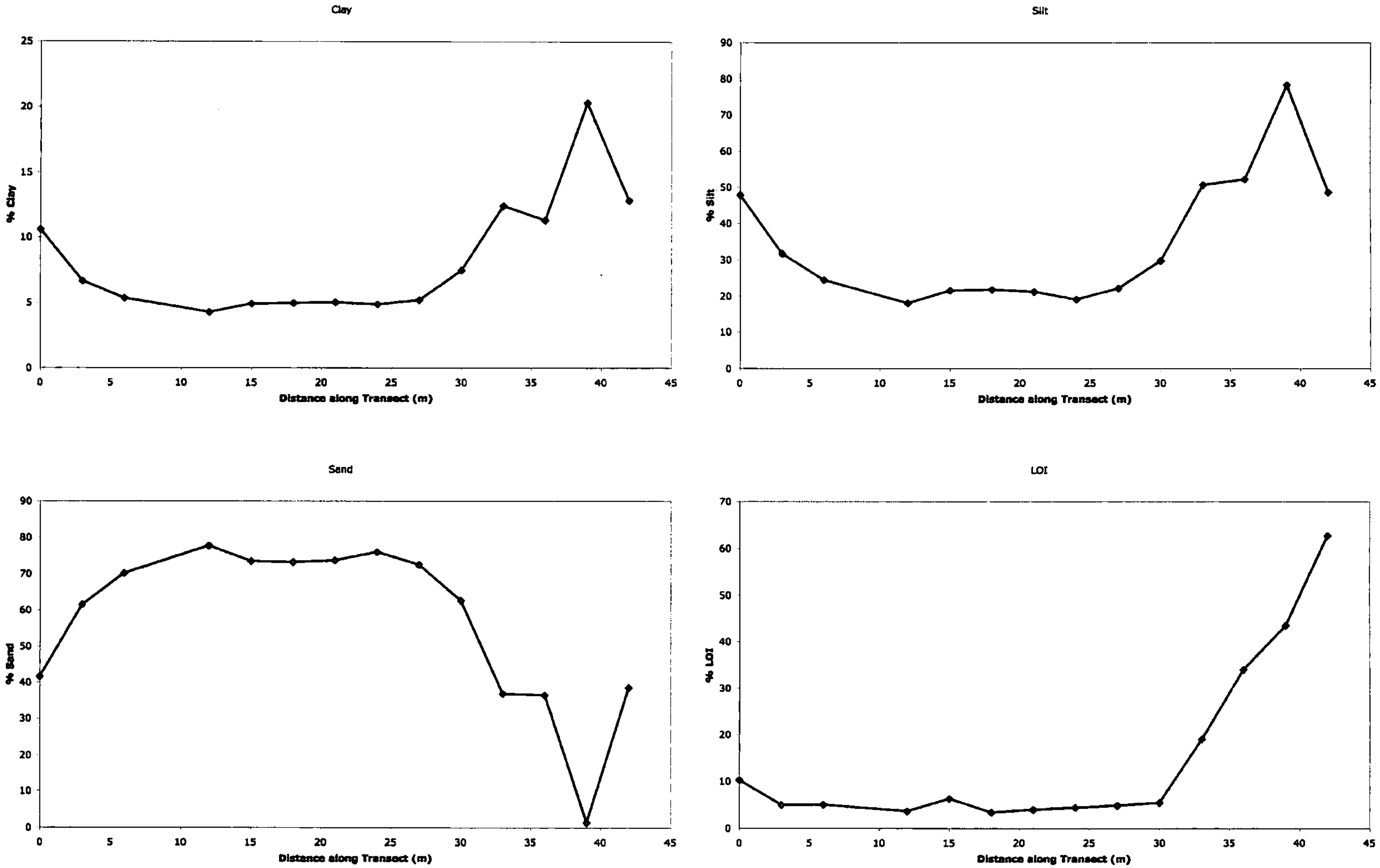


Figure 5.16 - Environmental Variables for Kakenauwe

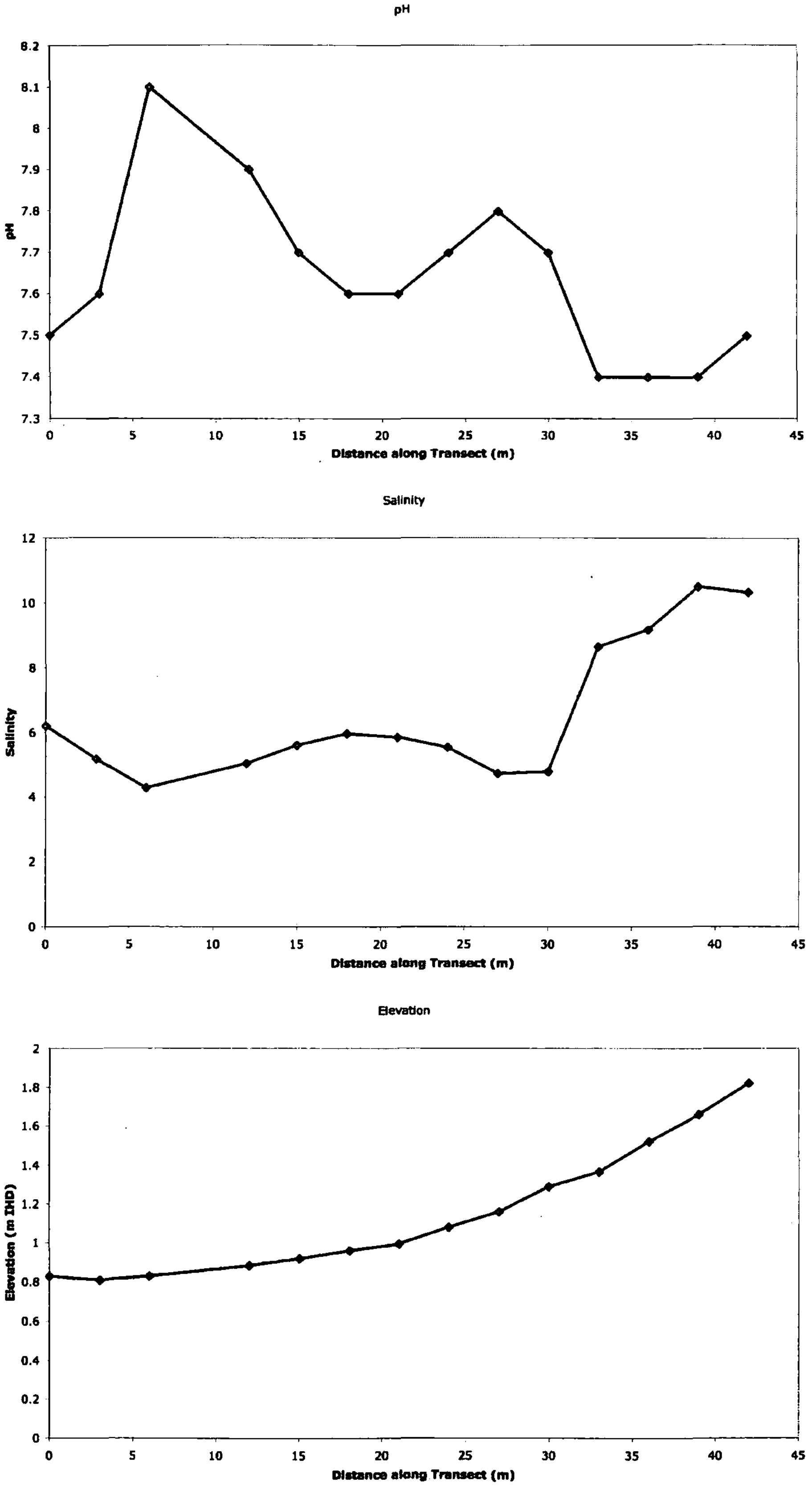


Figure 5.16 - Environmental Variables for Kakenauwe (Continued)

Table 5.4 - Kakenauwe CCA Summary Statistics

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.125	0.030	0.018	0.004	0.240
Species-environment correlations:	0.943	0.919	0.830	0.597	
Cumulative percentage variance					
of species data:	52.0	64.3	71.7	73.5	
of species-environment relation:	69.7	86.2	96.2	98.6	
Sum of all eigenvalues					0.240
Sum of all canonical eigenvalues					0.179

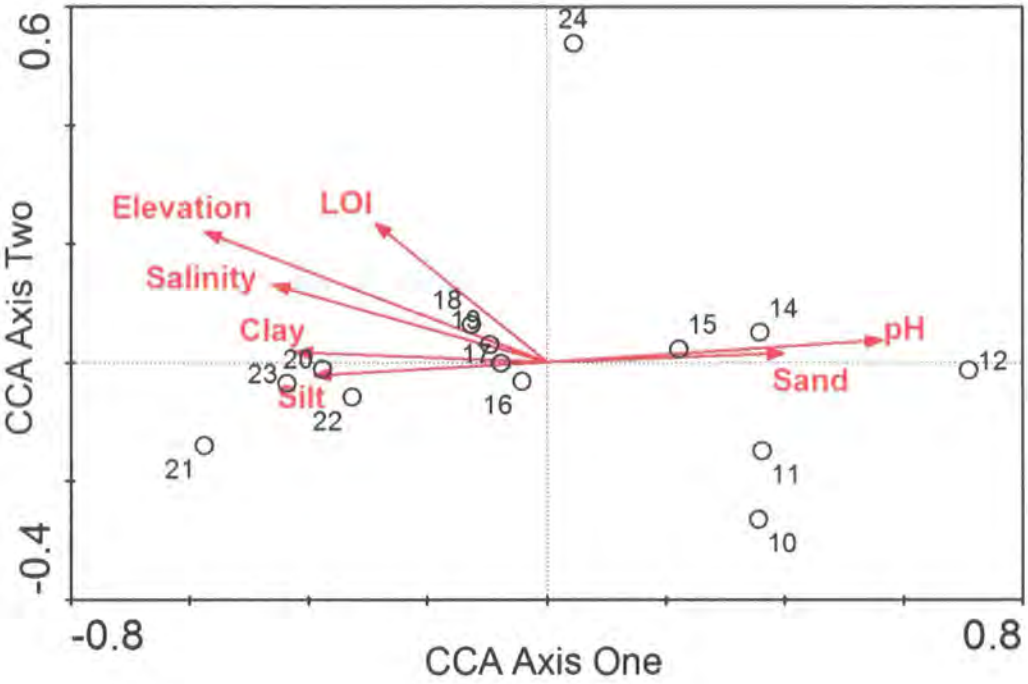


Figure 5.17 – Sample-Environment Bi-plot for Kakenauwe

The seven environmental variables explain 20.7% of the explained variance in the pollen data. Partial CCAs were carried out and show that the total explained variance is composed of 28.6% (elevation), 26.6% (pH), 18.8% (salinity), 15.6% (clay), 14.5% (sand), 14.2% (silt) and 12.5% (LOI). The associated Monte Carlo permutation tests (p=0.05, 499 permutations under reduced model) indicate that elevation, salinity and clay are all significant.

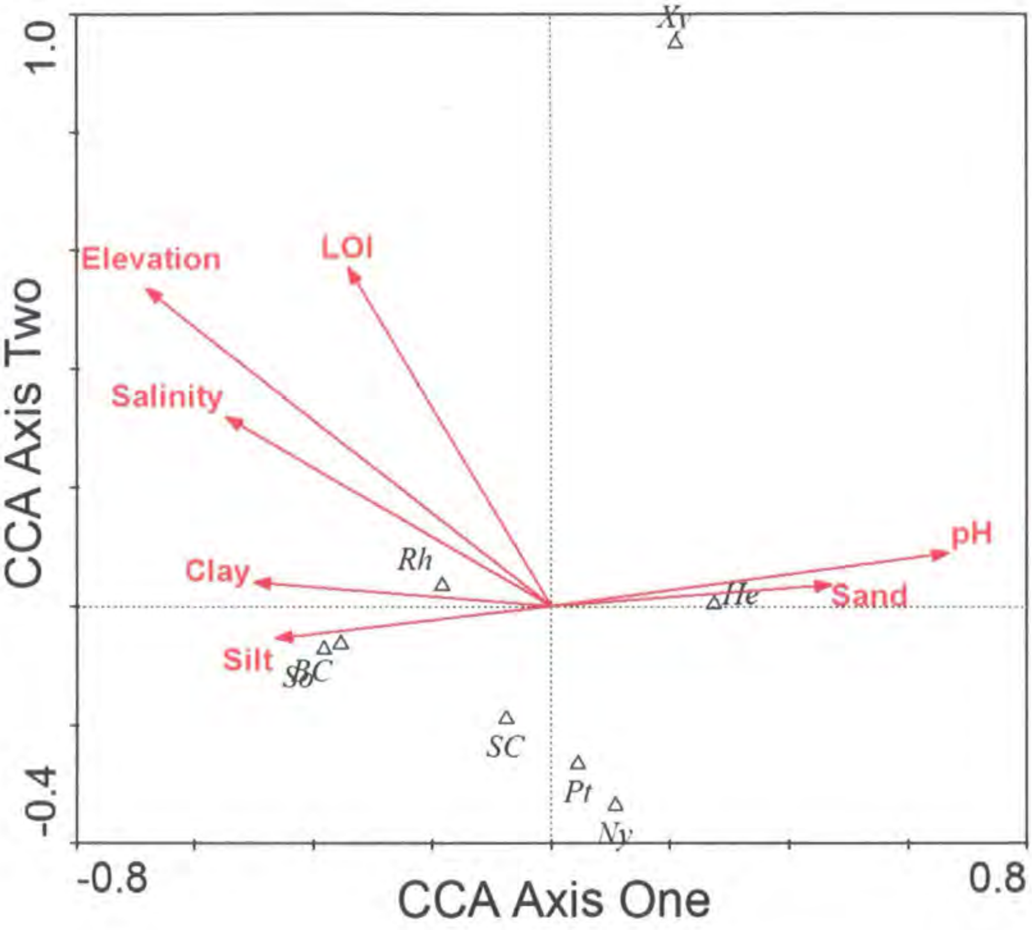


Figure 5.18 – Species-Environment Bi-plot for Kakenauwe

5.5 Discussion

Belperio (1979) used mangrove peats to reconstruct past sea-levels. However, this was limited to the use of macrofossils to identify a peat as mangrove in origin and then assigning an elevational range relating to the upper and lower limits of the mangrove facies within the modern mangrove (Grindrod, 1985). Whilst this approach is useful in highlighting the tendency in large scale sea-level movements, to further enhance the precision and accuracy of sea-level reconstructions based on mangrove peat, it has become necessary to focus on the microfossil content. This allows for the identification of specific mangrove forest types and their relationship to elevation above sea-level. It is therefore necessary to highlight the links between elevation and mangrove pollen species and also to demonstrate that the mangroves sample for this study are both representative of the mangroves found in S.E. Sulawesi and also that they are representative of the mangroves that are to be found in Southeast Asia and northern Australia.

As demonstrated from all three sites, *Rhizophora* is the consistently dominant mangrove species. Ellison (1989) states that to further minimise the errors associated with reconstructions using mangrove pollen, it was necessary to constrain the elevational range of *Rhizophora* from a selection of different locations. Figure 5.19 shows the elevational range of samples where *Rhizophora* accounts for over 60% of the total pollen sum.

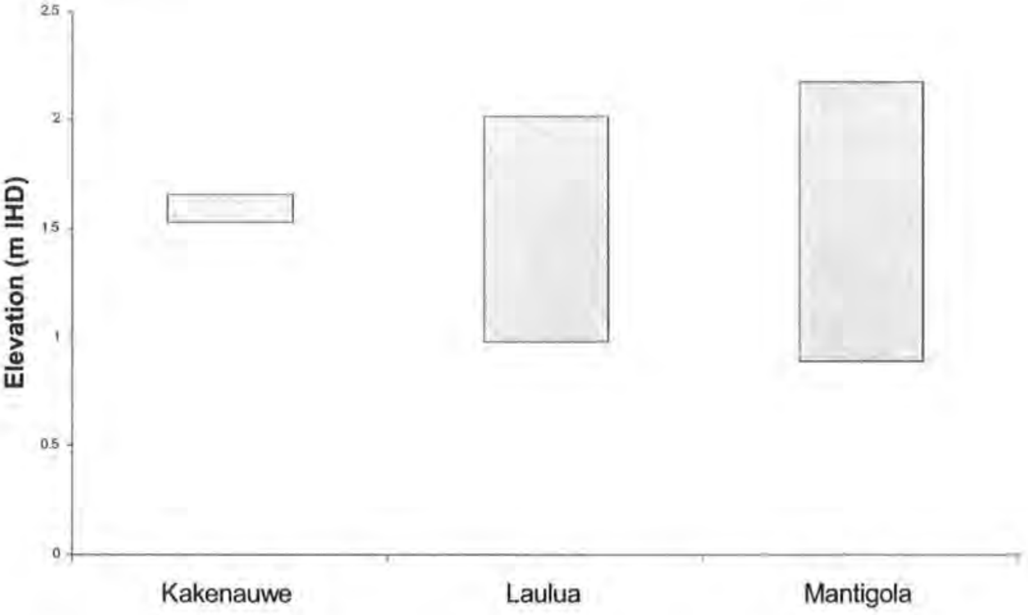


Figure 5.19 – Range of Rhizophora Abundances over 60% at All Sites

From the three sites examined, *Rhizophora* shows a maximum elevational range of 1.2m. with Laulua and Mantigola both showing extremely similar elevational ranges.

The upper limit of the Kakenauwe elevational range is constrained by a coral terrace which inhibits further mangrove development inland. The lower limits of its elevational range may be explained by its location. Laulua and Mantigola are both offered protection by low-lying coral reef flats which protect the mangrove by reducing the effect of tide and wind actions on the coastline. Kakenauwe on the other hand does not have this protection and the subsequent higher energy environment may be inhibiting the deposition of *Rhizophora* propagules and restricting the lower elevational range.

The pollen assemblages at Kakenauwe are further complicated by the presence of *Heritiera* pollen on the tidal flat. At Mantigola and Laulua, *Heritiera*, whilst sometimes present in the front mangrove assemblages, is primarily a species of the back mangrove. The assemblages at Kakenauwe show an extremely large presence of *Heritiera* on the extreme front of the tidal flat (*Heritiera* was not present in the mangrove strip at the rear of the tidal flat). Kakenauwe differs from Mantigola and Laulua in that is located 200m from the mouth of a small mangrove fringed river. The presence on the tidal flat of species not noted in the adjacent mangrove and that are uncharacteristic of the elevations suggests that pollen assemblages are potentially being washed in from inland riverine mangroves or from terrestrial *Heritiera* species. The presence of terrestrial pollen species on the tidal flat but not in the mangrove itself, would also suggest the possibility that a proportion of the assemblages found on the tidal flat are allochthonous in nature. In the mangrove itself, it is possible that the large production of autochthonous grains such as *Rhizophora* will hide this 'noise' in the dataset.

As highlighted earlier in this section, it is necessary to compare the pollen distributions of the three transects studied to the wider literature on mangrove palynology. Blasco (1996) suggests that eastern hemisphere mangroves all occupy a broadly similar pattern of zonation moving seaward to landward of *Rhizophora* (though *Sonneratia* and *Avicennia* may be present), to monospecific stands of *Avicennia*, then mixed *Bruguiera*, *Heritiera* and *Xylocarpus* followed by a landward zone of *Ceriops* with *Lumnitzera* and *Avicennia*. Woodroffe (2000) highlights a different zonation for South-East Asia of *Avicennia* and *Sonneratia*, followed by *Rhizophora*, then a zone of *Bruguiera* and *Ceriops* with a landward zone of *Avicennia*. Whilst these zonations may differ slightly, they both show the same species occupying the same portion of the mangroves. *Rhizophora* is the dominant front to mid-mangrove species and in certain environments *Sonneratia* and *Avicennia* may be found forward of this species. *Bruguiera* is then to be found at the rear of the *Rhizophora* stand, where *Avicennia* may also be found. *Ceriops*, *Lumnitzera* and *Avicennia* then form the back mangrove zone.

The three contemporary transects studied all adhere to this general pattern. Kakenauwe is the only transect that contains a large number of the species *Sonneratia*, which is to be found at the front of the *Rhizophora* stand, in line with the zonations suggested by Blasco (1996) and Woodroffe (2000) and hence justifying its inclusion so that all the suggested dominant mangrove species are present in the regional dataset. Grindrod (1988) states that Northern Australia mangroves are dominated by *Rhizophora*, *Ceriops* and *Bruguiera*, in line with the major species present in the transects studied. *Avicennia*, *Lumnitzera*, *Excoecaria* and *Xylocarpus* are also identified as common constituents. All but *Xylocarpus* are found routinely in the mangroves studied. In an earlier study, Grindrod (1985) identifies a zonation of *Rhizophora*, followed by *Rhizophora* and *Bruguiera* with a landward zone of *Ceriops* at Princess Charlotte Bay, North Queensland. In the mangroves in Sulawesi, *Bruguiera* is found at the front of the *Rhizophora* zone. This switch in zonation may be explained by the different hydrological setting of the Sulawesi mangroves. At both Laulua and Mantigola, there is little or no influence from freshwater due to the size of the islands, making them unsuitable for supporting freshwater hydrological systems. This is in stark comparison to the hydrological regime of the North Queensland mangroves.

Stevenson (2004) in New Caladonia, Kamaludin (1993) in Malaysia and Moss, Kershaw and Grindrod (2005) in north Australia all confirm that the mangroves of the area are dominated by the Rhizophoraceae family and *Rhizophora* and *Bruguiera* in particular. Grindrod, Moss and van der Kaars (1999) suggest that all of north Australia, Indonesia and the West Pacific are similar in terms of mangrove composition with *Rhizophora* the most prominent species. Ellison (2005) studied mangroves in West Papua, Indonesia. This study differs from all the others in that it uses aerial reconnaissance to ascertain the zonation of species and applies this as the proxy for sea-level and not through the use of contemporary pollen counts. Ellison highlights similar species to those found at the sites in Sulawesi in both the contemporary mangrove and also within the fossil core.

Several studies have attempted to quantify stands of *Rhizophora* by the proportion of *Rhizophora* pollen found in the surface sample. Wijmstra (1969) identifies that a 90% proportion of *Rhizophora* is indicative of a *Rhizophora* stand and Grindrod (1988) identifies over 90% *Rhizophora* as within the *Rhizophora* zone and 44-59% as immediately landward. The studies in Sulawesi would not support such high proportions of *Rhizophora* as being indicative of a *Rhizophora* stand. This is in line with the findings of Ellison (1989) at Tongatapu which showed a 50% proportion of

Rhizophora in a pure *Rhizophora* stand. The difference may be explained by the smaller tidal range of Sulawesi and Tonga. This would result in the *Rhizophora* zone occupying a smaller horizontal range bringing its central area into closer proximity with the surrounding floral zones. Ellison (1989) also identifies *Bruguiera* as being a poor indicator due to its ubiquitous distribution across the mangrove. This is demonstrated at Mantigola where the small stand of *Ceriops* at the rear results in similar levels of *Bruguiera/Ceriops* pollen across the transect. At Laulua, where *Ceriops* is a dominant species with a large presence at the rear of the mangrove, the *Bruguiera/Ceriops* signal is more dominant and renders the species as a more useful sea-level indicator.

Laulua shows considerable overlap of zones due to different species occupying the same elevations in the rear mangrove. The elevational overlap of zones seen at Laulua is not a phenomenon specific to Laulua. Ellison (1989) reports a similar levelling off in elevation at the back of the mangrove at Tongatapu, Tonga. Ellison (1989) concludes that distance from open water is also an important environmental variable along with elevation due to the controls on pore water salinity. Whilst this demonstrates that elevation is not the sole control on species distribution within the mangrove, the statistical analysis shows that elevation is a strong and significant control on pollen distribution in the surface samples. Elevation is not as strong a control on pollen distribution as it is on foraminifera distribution in the WMNP but is stronger than that demonstrated by the diatom distributions from the WMNP (Horton, Pers. Comms.)

The issue of spatial, temporal and taphonomic processes are of prime importance to the validity of the contemporary distributions outlined in this chapter. Spatial factors are particularly important in validating the findings of the study as a rogue species on the transect i.e. one that is present only on the transect and not either side of the transect in other areas, may diminish the validity of the findings. All three mangroves were subject to reconnaissance before sample collection and the transects chosen based on their representiveness of the surrounding mangrove. Both Laulua and Kakenauwe showed no evidence of a species appearing on the transect that did not appear in that location elsewhere in the mangrove and are therefore unlikely to be subject to strong spatial influence. Mantigola showed a more complicated zonation with certain species appearing in the pollen record in small numbers where the species was not recorded on the transect (*Sonneratia*). Whilst this may suggest spatial processes are at work, it may also indicate that pollen distribution is not affected greatly by spatial processes as pollen is found both in the immediate vicinity of its parent tree and also at the same elevation where the parent tree is not present. Horton et al. (2005) identify spatial differences in foraminiferal distributions in the Wakatobi Marine National Park. Pollen is likely to be subject to greater spatial issues due to the process of pollen release, vectoring and deposition and as such further study is required to ascertain the influence of spatial processes.

Temporal processes are affected by the flowering season of the mangroves and the pollen production outside of the flowering season. The duration of the fieldwork (less than 6 weeks) limited the extent to which a temporal study could be carried out. Further study is necessary to fully evaluate the temporal effects. Horton and Edwards (2003) undertook seasonal sampling of foraminifera at Cowpen Marsh, UK, sampling once a month over a 12 month period. Whilst this is the ideal, pollen analysis is more time consuming that Foraminiferal analysis and such frequent sampling is not practical. Sampling in the spring, summer, autumn and winter as suggested by Horton and Edwards (2003) is more practical though the logistical constraints of access to the study area would currently preclude this option. Further study will be necessary to elucidate the issue of temporal effects on the pollen surface distribution.

5.6 Conclusions

75 samples were collected from three transects at Mantigola, Laulua and Kakenauwe, of which 63 were analysed and contained 41 pollen types. Mantigola is dominated by *Rhizophora*, *Bruguiera/Ceriops*, *Heritiera* and *Avicennia*. Laulua is dominated by *Rhizophora*, *Bruguiera/Ceriops* and *Avicennia*. Kakenauwe is dominated by *Rhizophora*, *Heritiera* and also *Sonneratia*, which was only present consistently at this site.

Three pollen zones were identified at Laulua and Kakenauwe and two pollen zones were identified at Mantigola. Significant overlaps of the elevational ranges were found at Laulua and Kakenauwe. This can be explained at Kakenauwe by the sample being taken slightly above the mangrove, in terrestrial sediments, which may prove to be poor at preserving pollen. The overlap at Laulua is due to the rear mangrove being flat and as such, different species and zones occupy the same elevational range due to control by other environmental variables such as distance from open water.

Analysis of the environmental variables shows that silt is the dominant fraction throughout the sites. Clay and sand show an inter-relation at all three sites, with a decrease in the sand fraction inversely producing a dramatic increase in the clay fraction. LOI values are high within major *Rhizophora* zones, often in excess of 40%.

The multivariate analysis demonstrates that elevation is a significant explanation of the species distribution demonstrated at each site. The data presented highlights that it is possible to identify changes in elevation through the composition of mangrove pollen. This confirms the hypothesis that pollen species are highly correlated to elevation and as such, pollen is highly suitable for the production of precise and accurate relative sea-level reconstructions using a transfer function approach.

Chapter 6 – The Development and Application of a Transfer Function, S.E. Sulawesi, Indonesia

6.1 Introduction

The Wakatobi Marine National Park lies in the middle of a biodiversity hotspot, 200 miles off the Southeast coast of Sulawesi and occupies 1.39 million hectares, making it the second largest marine protected area in Indonesia. The National Park is composed of many reefs, mangroves and seagrass beds whose survival is innately tied to sea-level. Rapid changes in sea-level such as those predicted by the IPCC (2001) would seriously endanger these delicate environments.

Traditionally, studies relating microfossils to elevation above sea-level were qualitative or semi-quantitative in nature (Shennan et al. 1983; Ellison 1989; Yokoyama et al. 2000; Wang and Chappell 2001; Ellison 2005). This approach resulted in reconstructions with large errors and indicative meanings and prohibited the use of regional datasets to further improve the precision and accuracy of reconstructions. As interest in small-scale sea-level changes has increased, it has become necessary to develop more precise methods of reconstruction, as using traditional methods results in errors greater than the change in sea-level that is being investigated. Recent research has focused on the use of transfer functions (Zong and Horton 1999; Edwards et al. 2004; Horton and Edwards 2005; Hamilton and Shennan 2005; Horton and Edwards 2006), quantifying the relationship between microfossils and the environmental variables. Horton and Edwards (2005) highlight the potential of this technique to reconstruct high-resolution sea-level records from small-scale biostratigraphic changes in inter-tidal sedimentary sequences.

Whilst transfer functions have been commonly applied to foraminifera (Edwards et al., 2004; Horton and Edwards, 2005) and diatoms (Zong and Horton, 1999; Hamilton and Shennan, 2005), the technique has not been applied to pollen data. In part, this is due to the controls of pollen distribution and transport, which can result in spurious reconstructions due to the addition of allochthonous components. Mangrove pollen suffers less from these problems due to local deposition, minimal transport and a correlation between the pollen found in contemporary samples and the surrounding vegetation. Mangrove pollen shows distinct zonations, which are strongly controlled by elevation and the frequency of tidal inundation. As such, mangrove pollen has the potential to reconstruct mangrove elevation changes over the Holocene. A regional transfer function approach is taken due to the incorporation of a greater variety and range of modern analogues, leading to less "no good analogue" situations (Boomer and Horton, 2005).

This chapter aims to:

1. Develop an inter-tidal transfer function based on mangrove pollen.
2. Apply the pollen transfer function to two fossil cores taken from the WMNP and covering the mid to late Holocene.
3. Compare the two reconstructions and validate the use of a mangrove pollen transfer function.

6.2 POL1 Transfer Function Development

A regional dataset was created for S.E. Sulawesi by combining the three local datasets to create a regional dataset of 63 samples and 16 species groups. Horton and Edwards (2006) develop a Foraminiferal transfer function and conclude that whilst local datasets may offer more precise reconstructions than regional datasets, the increase in 'no modern analogue' situations affects the reliability of the reconstructions. Ellison (1989) argues that to improve the uncertainty margin using pollen analysis, it is necessary to understand the degree of variation in mangrove zone elevations. Partial CCAs on the contemporary datasets show that elevation is a strong control on pollen distribution. Foraminifera studies from the region show a stronger relationship with elevation but pollen demonstrates a stronger relationship than the diatom studies from the region (Horton, Pers. Comms.). It is necessary to look at species distribution from as large a range of mangroves as possible to understand the influence of other environmental variables on species distribution. As such, the regional transfer function approach is selected as the most suitable method for sea-level reconstruction using pollen in S.E. Sulawesi.

To be useful as a sea-level indicator, mangrove pollen must have a consistent relationship to a fixed position within the tidal frame. As demonstrated the mangroves of Southeast Sulawesi demonstrated species zonations parallel to the shoreline with elevation being highlighted as a significant control on the pollen assemblages at all three sites. To confirm that the contemporary transects are suitable to be incorporated into a combined dataset, the three transects were combined and analysed using CCA. Figure 6.1 shows the sample-environment bi-plot. There is a clear pattern with samples of low elevation and high sand, pH and LOI values plotting to the left and samples with high elevation, high salinities and high silt contents plotting to the right. CCA axes one (eigenvalue = 0.135) and two (eigenvalue = 0.067) explains 31.1% of the pollen data. These two axes represent 88.8% of the species-environment relationship. The seven environmental variables account for 26.4% of the explained variance in the pollen data. This explained variance is composed of 14.5% elevation, 7.8% distance from open water, 6.3% salinity, 6% pH, 5.7% LOI, 4.9% silt, 2.3% sand and 1.3% clay. The associated Monte Carlo permutation tests indicate that the elevation gradient accounts for a significant portion of the total variance in the pollen data (p = 0.002, 499 permutations under the reduced model).

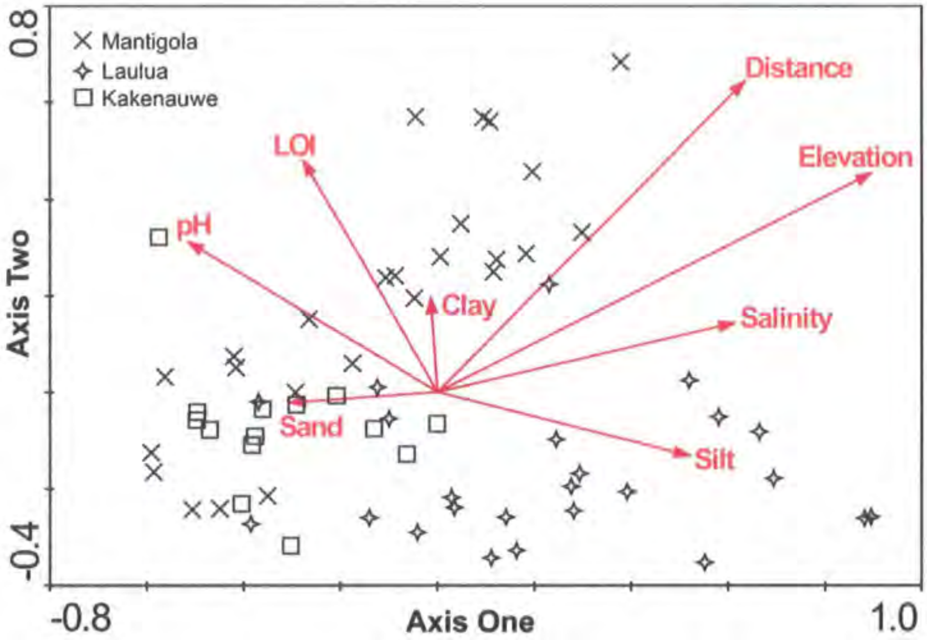


Figure 6.1 – Sample-Environment Bi-plot for the Regional Mangrove Pollen Dataset

As such, a statistically significant transfer function quantifying the relationship between the pollen assemblages and elevation can be constructed. It must be noted that 59% of the explained variance is composed of intercorrelations between the environmental variables and therefore elevation cannot be considered to be completely independent of other environmental variables. 71% of the total variation in pollen data is not explained by the seven environmental variables. This may be due to stochastic variation or temporal and spatial effects that this study does not take into account. The explained variance is similar to other datasets (Zong and Horton 1999) and coupled with the information from partial CCAs, indicates that a statistically significant transfer function can be developed for elevation.

Birks (1995) identifies two taxon-environment response models that are relevant. The first is the unimodal response where species are presumed to occupy a Gaussian distribution across the transect, with a peak at the optimal environmental variable (in this context, elevation). The second response model is a linear distribution with species increasing or decreasing in abundance in accordance with elevational changes. It is important to select the model that best describes the pollen distribution within the dataset (Horton and Edwards, 2006). Detrended Canonical Correspondence Analysis (DCCA) is used to assess the length of the environmental gradient. Birks (1995) states that if the length of the environmental gradient is less than 2 S.D. units, then a linear response model is appropriate and if it is greater than 2 S.D. units, then a unimodal response model is appropriate. DCCA was applied to the training set with elevation as the only environmental variable (Birks, 1995) and showed an environmental gradient length of 0.771 S.D. units, indicating that the species environment response is linear in nature. Ter Braak (1987) states that species environment relationships are unimodal in nature, as species cannot survive in areas where an environmental variable is too low or too high. The species-environment response is different in the mangroves of S.E. Sulawesi due to the dominance of

Rhizophora. The presence of pollen within a sample does not indicate that the species was growing at that position but merely that the species was present in the vicinity of the sample. If the transect were to be extended through to sub-tidal zones at the front of the mangrove and through to terrestrial zones at the back of the mangrove, then the species response would be unimodal, with low *Rhizophora* counts in the sub-tidal and terrestrial zones and high counts in the mangrove zone. However, as the transect concentrates only on the mangrove zone, the species response is linear.

Maximum Likelihood (ML) regression and calibration "can be regarded as the most statistically rigorous approach to environmental reconstruction" (Birks, 1995). Telford and Birks (2005) also state that transfer functions using ML are "easier to fit, and provide more robust transfer functions". The ML approach generates individual ecological response curves for each species and is suitable for linear species response. These response curves are then combined to 'calculate the probability that a given value of elevation would occur for a particular...assemblage" (Horton and Edwards, 2006).

Using a method known as 'jack-knifing' or 'leave one out' assesses the predictive ability of the transfer function that has been generated. This method removes a sample from the dataset and then uses the remaining samples to predict the value of that sample. The transfer function can then be evaluated through comparing the predicted and observed values of that sample to give an error value ($RMSEP_{jack}$) for the entire dataset. The transfer function was also run using bootstrapping to generate sample specific errors for the reconstruction.

Initial data screening was undertaken on the dataset. At Kakenauwe (LA200401), the *Heritiera* component of the mangrove was allochthonous. This can be ascertained by the lack of *Heritiera* species within the mangrove at the rear of the tidal flat. The *Heritiera* species were removed from the dataset for LA200401. The percentages for the remaining species were then calculated from total pollen sum (TPS) and not from TPS minus *Heritiera*. Sample LA1-24 is also removed from the dataset due to its terrestrial location and potential for selective preservation as described in Chapter 5. The transfer function was then developed using the modified dataset. After the initial run of the transfer function, the dataset was further screened to remove those samples where residuals were shown to be greater than the standard deviation of the elevation of the samples. The data screening results in a final regional dataset of 54 samples, comprising 19 species to be used in the transfer function.

6.3 Results

The initial dataset consisted of 62 samples taken from three separate study sites (Mantigola, Laulua and Kakenauwe). Analysis was undertaken using C2 version 1.4.2 (Juggins, 2005). Table 6.1 demonstrate the summary statistics for the initial run and figure 6.2 highlights the observed versus predicted values generated by the dataset.

RMSE (m)	RMSEP (m)	r^2	r^2_{jack}	Max Bias (m)	Max Bias$_{jack}$ (m)
0.278	0.295	0.71	0.67	0.395	0.424

Table 6.1 - Initial Transfer Function Summary Statistics

The initial results highlight a number of samples with potential reconstructive issues due to the large residuals between observed and predicted values. However, the RMSEP is in line with previous studies employing foraminifera and diatoms. A clear pattern can be seen with the larger residuals occurring at low to mid elevations, with lower residuals in the upper elevations of the mangrove. A large number of samples with observed elevations of ~1m show significant over predictions within the transfer function.

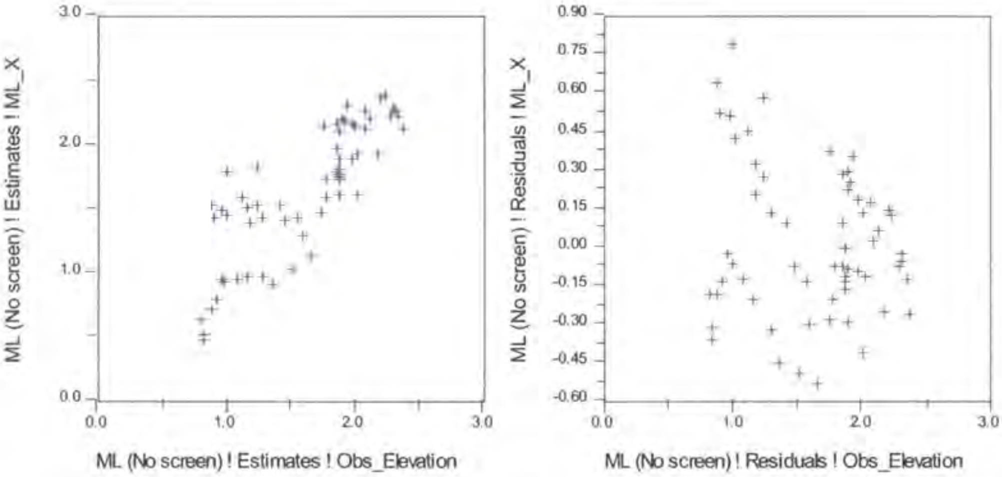


Figure 6.2 - Scatter Plot Illustrating Observed versus Predicted Values for Initial Transfer Function POL1 and the Associated Residuals

Data screening to remove those samples with residuals greater than the standard deviation of elevation in the dataset (0.48m) removes 8 samples to leave a final dataset consisting of 54 samples. This removal is justified by the small change in tolerance and optima of the diagnostic species *Rhizophora* (0.45 to 0.43 and 1.67 to 1.59) indicating that the removal of the samples had little effect on the predictions of the transfer function with the benefit of improved performance. 6 of the samples removed are from the lowest elevations of the Mantigola transect with the lowest sample at Laulua also being removed. This may highlight a potential for post-depositional change and the addition of allochthonous pollen grains at the front of the mangroves where exposure to tidal and wave action is at its greatest.

Table 6.2 shows the summary statistics for the screened dataset, whilst Figure 6.3 highlights the observed versus predicted values for this dataset.

RMSE (m)	RMSEP (m)	r^2	r^2_{jack}	Max Bias (m)	Max $Bias_{jack}$ (m)
0.194	0.214	0.83	0.8	0.271	0.303

Table 6.2 - Final Transfer Function Summary Statistics

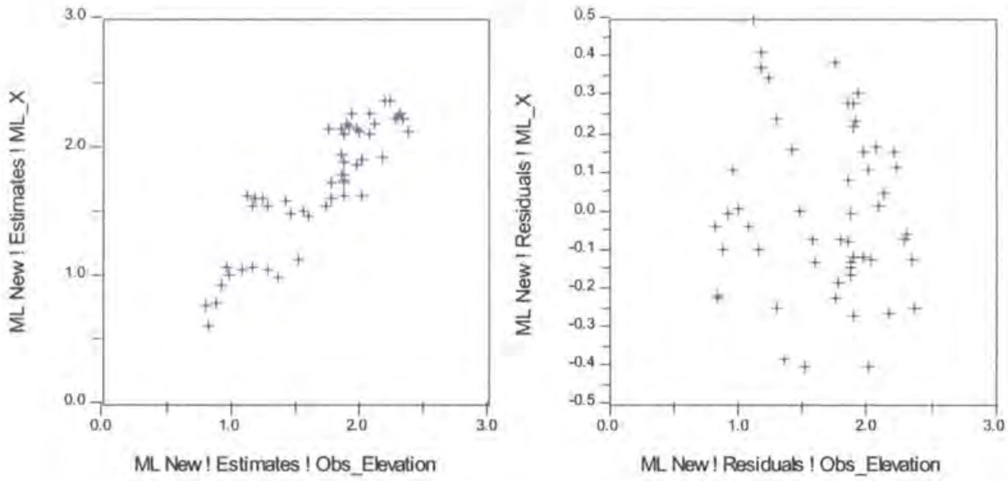


Figure 6.3 - Scatter Plot Illustrating Observed versus Predicted Values for Final Transfer Function POL1 and the Associated Residuals

The final transfer function shows improved performance, with a reduction in the RMSEP of 8cm and an increase in the r^2_{jack} value to 0.8. The transfer function now produces its lowest residuals at the lowest and highest elevations with a random spread of residuals in the middle of the elevational range.

6.4 Litho- and Bio-stratigraphic Data for cores BA/03/4C and AM/03/2A

Core BA/03/4C is a 2.73m core extracted from a small mangrove system at Llagiyye, Kaledupa. The site is located within 1km of the contemporary transect at Laulua but is no longer representative of pristine mangrove with significant human disturbance due to the use of the mangroves as a timber source. The core is located at the fringe of the mangrove at an elevation of 1.38m IHD. The site is protected by a headland to the south and also by a coral flat, exposed at low tide, 100m from the shore. The biostratigraphy and lithostratigraphy is highlighted in figure 6.4.

The core shows a number of changes in lithostratigraphy. The base of the core is characterised by stiff yellow-brown clay, which is characteristic of sub-aerial exposure and associated oxidation of the clay minerals. This is overlain by a ~0.6m tenacious light blue-grey clay. The clay is overlain by a small well-humified organic unit leading into a ~1m section of dark brown peat. The top of the core is characterised by a movement from the organic peat unit to a silty organic, into a grey silty clay, through to an organic silty sand at the top of the core.

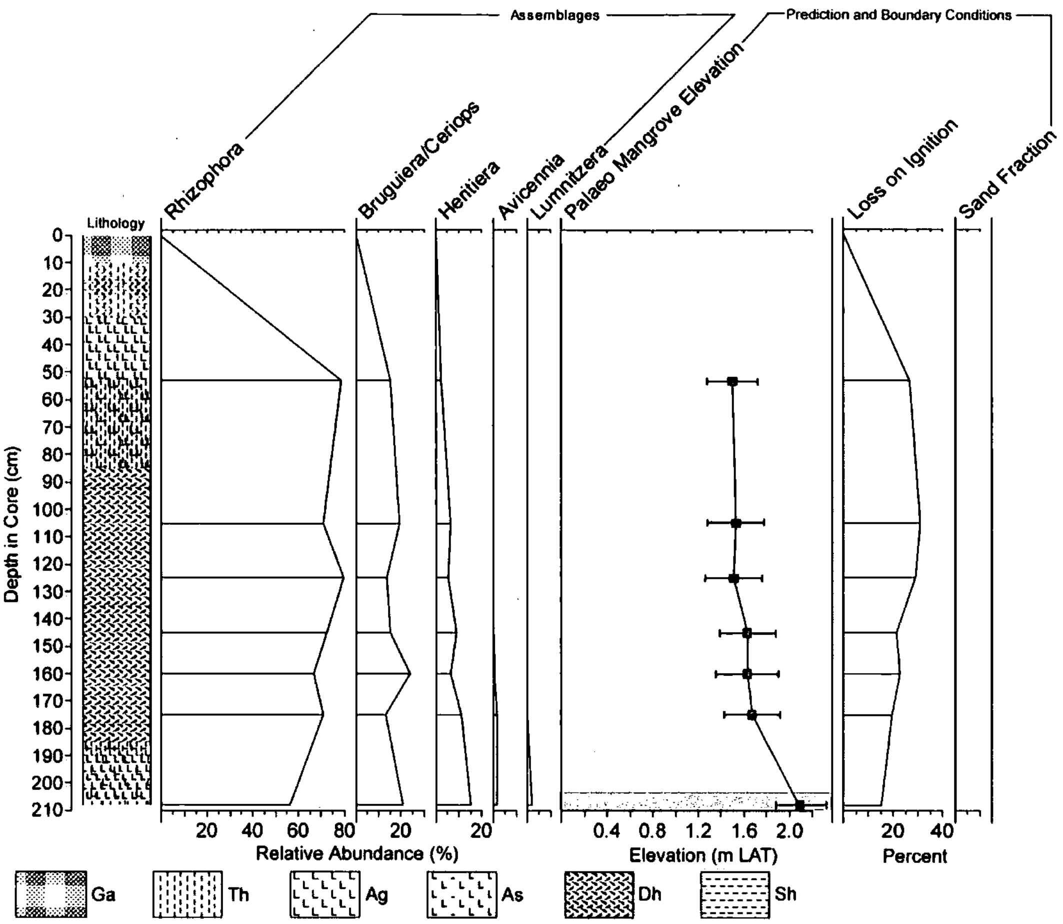


Figure 6.4 – Distribution of Major Pollen Species within Core BA/03/4C and Palaeo Mangrove Elevation predictions (Llagiyye)

The core is dominated by the species *Rhizophora*, *Heritiera* and *Bruguiera/Ceriops*. *Rhizophora* counts are lowest at the bottom of the core with a general pattern of increase to the mid-core section at 125cm, which shows the highest abundance of *Rhizophora* pollen in the entire core, ~80%. Pollen is absent from the core at 110cm and this is also associated with a qualitative assessment of a large increase in the amount of foraminiferal test linings observed in the sample. All the foraminiferal tests observed are planktonic and are notable by their absence in all other samples. *Heritiera* is consistently present throughout the core, though it does show higher counts as the bottom of the core. *Bruguiera/Ceriops* also shows higher counts in the bottom of the core, than at the top. dominates the sample. The environments shown in the core are similar to those found in the present day inter-tidal zone and it is interesting to note that *Rhizophora* has dominated the mangroves at Llagiyye throughout the core.

Core AM/03/2A is a 4.5m core extracted from a fringing mangrove environment within 200m of core BA/03/4C. The top of the core lies at an elevation of 1.57m above IHD. The site is protected by a headland to the south and by the coral reef flat located 100m from the shoreline. The biostratigraphy and lithostratigraphy is summarised in figure 6.5.

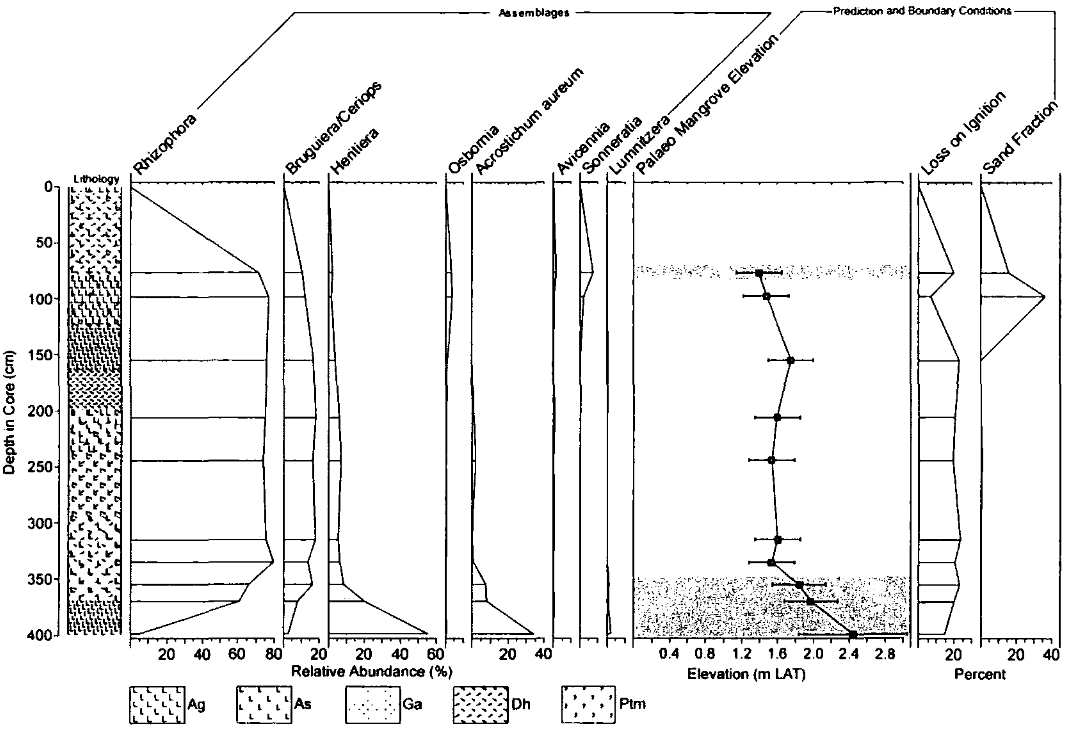


Figure 6.5 - Distribution of Major Pollen Species within Core AM/03/2A and Palaeo Mangrove Elevation predictions (Ambeau)

The core possesses a number of lithostratigraphic units. The base of the core is a stiff orange clay which is in turn overlain by a tenacious blue clay. This is followed by a thick peat layer which accounts for over half of the core. The peat layer is overlain by a shelly clay with a thin peat layer above it before a return to a shelly clay. This is overlain by the final peaty clay unit which grades into a silty peat unit at the top of the core.

The core is dominated by *Rhizophora*, *Bruguiera/Ceriops*, *Heritiera*, *Acrostichum aureum* and *Sonneratia*. *Rhizophora* abundances are lowest at the bottom of the core at 399cm with a relative abundance of ~4% coupled with a high abundance of *Acrostichum aureum* and *Heritiera*. *Rhizophora* abundances rise rapidly to over 60% at 370cm and do not fall below this abundance upwards of this point in the core. *Sonneratia* is not present in the core in high abundances until the sample at 98cm. *Heritiera* is present throughout the core but decreases in abundance as you move upwards through the core. As in the BA/03/4C core, there are three samples where the presence of pollen is limited and associated with a large qualitative increase in planktonic foraminiferal test linings. This core supports the conclusion from Llagiyye that *Rhizophora* has dominated the mangroves of this area during the time frame covered by both cores.

6.5 Application of the Pollen Transfer Function

It has been demonstrated that an inter-tidal mangrove pollen transfer function has the potential to reconstruct palaeo mangrove elevations in S.E. Sulawesi, Indonesia. The transfer function produces a palaeo mangrove elevation for each fossil sample, which explains the samples position in the tidal frame relative to sea-level at that time.

Transfer function POL1 was applied to 17 fossil samples from the Llagiyye and Ambeau cores, generating palaeo mangrove elevations for these samples. The reconstructed palaeo mangrove elevations for core AM/03/2A and BA/03/4C are shown in figure 6.6 and 6.7 respectively. The transfer function was evaluated through the use of the Modern Analogue Technique (MAT). This approach was not used for prediction but as a method to validate the predictions generated by POL1. MAT produces a minimum dissimilarity coefficient (minDC) for the contemporary dataset and then for each individual fossil sample. Birks et al. (1990) state that fossil samples with a dissimilarity coefficient within the 10th percentile of the contemporary training set can be said to have a good modern analogue within the contemporary samples. MinDC's in the contemporary training set were compiled using the 5 nearest analogues due to the small size of the dataset (Southall et al. submitted). Figures 6.4 and 6.5 demonstrate the samples that do not have modern analogues in the dataset with grey shading. Samples without modern analogues must be treated with caution when interpreting the data.

The palaeo mangrove elevations presented show a pattern of generally decreasing mangrove elevation from the bottom to the top of the core. There are a number of fluctuations though the errors, which vary around ±10cm, may nullify these as points of interest. The RWL's predicted vary by only 0.7m in the Llagiyye core and by 1m in the Ambeau core from maximum to minimum due to the small tidal range of the Wakatobi Marine National Park.

The Ambeau core paleo mangrove elevations show a general pattern of decrease from 2.11m LAT at 3.99m depth to 1.38m LAT at 0.77m depth. Palaeo mangrove elevations in the samples dominated by *Rhizophora* with no *Acrostichum aureum* are consistently around 1.5m LAT with an increase to 1.75m LAT at 1.55m depth associated with a change in core sediment from clay with some organics to an organics dominated layer. The two samples near the top of the core (0.77m and 0.98m) show decreasing palaeo mangrove elevations in keeping with the change in biostratigraphy to lower *Rhizophora* abundances and the presence of *Sonneratia*, indicating a fringing mangrove depositional environment. The Llagiyye core also shows a pattern of decrease over time from a maximum of 2.06m LAT at 2.08m depth to 1.46m LAT at 1.05m depth.

The MAT results demonstrate that five of the seventeen samples do not have modern analogues within the contemporary training set. With the exception of the sample at 0.77m in the Ambeau core, the samples with no modern analogues are located in the deepest sections of the cores (Ambeau: 3.55m, 3.7m and 3.99m, Llagiyye: 2.08m) and are identified by high abundances of *Acrostichum aureum* and *Heritiera* (Ambeau) and *Heritiera* (Llagiyye) with reduced abundances of *Rhizophora*. Ellison (1989) identifies samples with high *Acrostichum aureum* as indicative of grassland above the mangrove forest, an environment that was not sampled on the transects. As such, the predictions assigned to these samples must be treated with caution. However, presuming that the tidal regime has not changed, these samples must have been deposited above the marine limit, indicating that they should have palaeo mangrove elevations above the maximum error predicted by the transfer function. As such the palaeo mangrove elevations generated are beyond the range of the transfer function and so must be considered unreliable. Sample 0.77m at Ambeau does not have a modern analogue due to the high abundances of *Sonneratia* and *Rhizophora*. Further sampling of mangroves in the region with *Sonneratia* as a fringing mangrove component will be necessary to rectify this issue.

Whilst the mangrove pollen transfer function has demonstrated its ability to reconstruct palaeo mangrove elevations, a number of factors must be considered when interpreting the reconstructions. When dealing with pollen assemblages, spatial and temporal variability must be considered. Spatial variability within the contemporary transects is a possible issue, with species represented within the mangroves but not on the transect removed from the surface pollen assemblages. For example, at Mantigola, *Sonneratia* pollen was found in small numbers within the surface assemblages even though there was only one *Sonneratia* tree identified within 100m of the transect, suggesting that pollen vectors within the mangroves diffuse the issue of spatial variability. However, Grindrod (1988) does state that *Sonneratia* pollen is overrepresented in mangrove sediments compared to its surface distribution and as such, spatial issues may cause problems with less prolific pollen producers. As with all flowering plants, seasonal effects may affect the relative abundances of surface pollen assemblages with Tomlinson (1979) suggesting that species in the family Rhizophoraceae have distinct flowering seasons in Queensland.

As demonstrated in the Kakenauwe transect, the introduction of an allochthonous component is a possibility that must be considered. Comparing the three sites, it would appear that the important factor is the presence of a fluvial system in the vicinity of the mangrove, which allows the inwash of terrestrial or riverine mangrove pollen on to the tidal flat. The effects do not seem to be as great within the mangrove where the prolific autochthonous production of pollen by *Rhizophora* drowns out the 'noise'. However, this is of some concern when considering reconstructions outside of the WMNP, as it is not possible to identify whether a sample within a fossil core was within close proximity to a similar system. The signature of the allochthonous component is not representative of a mangrove ecosystem within the region, as *Heritiera* dominates it. Whilst the genus *Heritiera* does contain a number of mangrove species as demonstrated at Mantigola, it is also a genus of the tropical rainforest. As this study only identifies pollen to genus level, it is not possible to interpret whether the source of the *Heritiera* pollen is from a terrestrial species or has been washed in from a riverine mangrove. As such, great care must be taken when applying the transfer function with further analysis of the output to determine whether predictions are realistic.

Whilst it has been highlighted that the use of mangrove pollen has some potential issues when reconstructing palaeo mangrove elevation, the first ever mangrove pollen transfer function demonstrates that fossil samples within mangrove environments can be reconstructed precisely and improves on the reconstruction errors typically associated with tropical environments utilising corals and qualitative pollen analysis. The errors of ±0.3m suggested by Ellison (1989) were equal to the tidal range of Tongatapu. This is in comparison to this study with errors of ±0.22m in a tidal range of 1.5m. This is a significant improvement. This allows for analysis of lower magnitude changes due to the precision of the transfer function (±0.22m).

6.6 Conclusion

Following from the conclusions drawn in Chapter 5, a transfer function quantifying the relationship between mangrove pollen and elevation has been developed. The transfer function shows a strong relationship between the observed and predicted values (r2 = 0.8).

The transfer function has been applied to seventeen fossil samples taken from two cores in the Wakatobi Marine National Park, Llagiyye and Ambeau. The palaeo mangrove elevations for both cores show similar patterns of change with a general decrease in palaeo mangrove elevation as you move upwards through the cores, consistent with sea-level rise being greater than sedimentation over this time period.

The similar predictions generated for two separate cores supports the use of the mangrove pollen transfer function as both sites should be expected to show similar patterns of change due to their proximity to each other. The predictions generated by the transfer function are consistent with the appearance of *Sonneratia* in the top section of both cores, indicative of a front mangrove depositional environment.

Both cores possess no modern analogue situations with samples that are of dubious mangrove origin due to the presence of high abundances of *Heritiera* and/or *Acrostichum aureum*. As such, it is necessary to highlight that whilst the transfer function is able to precisely predict palaeo mangrove elevations, it currently cannot be applied to situations where samples may be deposited behind the mangroves. Further sampling in these environments will be required to extend the application of the transfer function before the development of mangroves on the fossil sites in the Wakatobi Marine National Park.

The limitations of this new technique are identified and must be taken into account when interpreting the predictions of the transfer function. However, this new technique allows for reconstructions of palaeo mangrove elevations in situations where other microfossil groups may be subject to post depositional change and therefore prove to be unreliable predictors of past elevations. The quantification of the relationship between mangrove pollen and elevation has led to more precise predictions with the error reduced from 100% of the tidal range (Ellison 1989) to 29% of the tidal range. This technique has the potential to reconstruct sea-level changes on a Holocene timescale and thus improve our understanding of the timing and magnitude of the melting of the polar ice caps and the spatial variability in sea-level changes on the earth over this period.

7 - Conclusion

7.1 Conclusion

Three contemporary mangrove environments were selected from the Wakatobi Marine National Park (Laulua and Mantigola) and the island of Buton (Kakenauwe) in Southeast Sulawesi, Indonesia. These environments were chosen due to their differing floristic composition and environmental characteristics.

Contemporary surface samples were collected from all three sites for pollen and environmental variable analysis. Five environmental variables were collected at each station (elevation, LOI, grain size, pH and salinity) to determine the environmental variables controlling pollen distribution. Palynological analysis reveals that the mangroves of Southeast Sulawesi are dominated by the family Rhizophoraceae and in particular the genus *Rhizophora*. *Bruguiera*, *Ceriops*, *Avicennia*, *Heritiera* and *Sonneratia* are also important genera within the mangroves.

Cluster analysis using CONISS demonstrates clear zones of pollen assemblages. These clusters are also supported by DCA, highlighting that they are significant and not due to a particular statistical method of clustering. Laulua and Kakenauwe possess three pollen assemblage zones within the mangrove, whilst Mantigola demonstrates two assemblage zones. Laulua and Kakenauwe both exhibit overlap within the assemblage zones which extend the elevational ranges of the zones.

Multivariate analysis using CCA demonstrates that elevation is a significant control on pollen assemblage distribution at all three sites. Multivariate analysis on the entire contemporary dataset shows that elevation is a highly significant control on pollen assemblages (p=0.002).

The combined dataset was utilised to generate a regional training set of mangrove pollen assemblages to develop the first mangrove pollen transfer function utilising the Maximum Likelihood method. The results show there is a strong relationship between the observed and predicated elevations (r2=0.8), once again demonstrating the strong relationship between elevation and the pollen assemblages.

The transfer function POL1 was applied to 17 fossil samples from two cores taken at Llagiyye and Ambeau in the Wakatobi Marine National Park. The reconstructed reference water levels show a general decreasing trend over this time period in both cores, indicating that sea-level rise may been greater than sedimentation during this time period (presuming no subsidence) and supporting the use of mangrove pollen in a quantitative sea-level reconstruction.

The study presented does have a number of limitations that need to be considered when evaluating its use. Both spatial and temporal factors, which may be significant, are not evaluated in this study. There is also a potential issue of the introduction of allochthonous pollen assemblages in systems with a fluvial input nearby, however this can be accounted for in the current study. However, the transfer function demonstrates that it can precisely reconstruct palaeo mangrove elevations with smaller vertical errors than those typically associated with sea-level reconstruction in tropical environments such as coral.

7.2 Future Research

The use of mangrove pollen demonstrated in this study has demonstrated that it has the potential to precisely reconstruct former mangrove elevations. However, further research is recommended to continue to validate the approach and to improve the error bars and no modern analogues associated with the current dataset. The current transfer function is limited by its small contemporary dataset containing only 54 samples. Further research is required to increase the size of this dataset to at least 100 samples after screening to further improve the range of modern analogues presented here and to potentially reduce the errors associated with the reconstruction. Sampling further landward of the mangrove is also recommended where possible to identify modern analogues for the *Heritiera* and *Acrostichum aureum* zones identified at the bottom of the Ambeau core.

The reconstruction of palaeo mangrove elevations is the first step in the reconstruction of relative sea-level through the Holocene. This study has highlighted the potential of this technique for reconstructing sea-level from mangrove sediments. This can be achieved through radiocarbon dating of the two cores presented in this research and through the further sampling of basal peats from the Wakatobi Marine National Park to assess the impact of compaction on the palaeo mangrove elevations that are reconstructed.

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