Holocene mangrove dynamics and sea level changes: records from the Tanzanian coast

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Abstract

Tanzanian mangrove ecosystems have been, and are presently, influenced by changes in climate and sea level. Fluctuations in these environmental conditions lead to adaptations and changes in ecosystem structure and composition. In this thesis mangrove environments are investigated and used to unravel the Holocene environmental history of the Tanzanian coast. Palaeoecological data from sediments abstracted from three different mangrove locations (the Rufiji Delta, Makoba Bay and Unguja Ukuu) are analysed for fossil pollen and charcoal and combined with stratigraphical investigations and radiocarbon dating allow a detailed environmental reconstruction to be undertaken.

The relationship between pollen in surface samples and the surrounding vegetation is used to interpret fossil pollen records. Changes in the relative proportions of mangrove pollen under different inundation regimes are used to reconstruct mangrove dynamics and provide estimates of past sea level changes and infer specific changes in sea level altitude.

Palaeoecological records reveal that mangroves in the Rufiji Delta occurred at the central sites from at least ~5600 cal yr B.P. until the late Holocene when mangroves covered the landward site and were succeeded by terrestrial vegetation to the present day. The Zanzibar records reveal fluctuating mangrove compositions from ~8000 cal yr B.P. to the present day with noticeable changes in mangrove composition during the mid Holocene. A reconstructed sea level curve from the three sites document an early-mid to mid Holocene sea level rise from ~ 8000 cal yr B.P. to around 4600 cal yr B.P. with potential highstands at 5800 cal yr B.P. and 4700 cal yr B.P. Sea level fluctuations occurred in the last thousand years with a potential highstand at ~ 530 cal yr B.P. before falling to a lower than present level at ~140 cal yr B.P. The earliest intensive human interactions within the mangroves was recorded in Zanzibar after ~530 cal yr B.P; a time of increased settlements and overseas trade along the Swahili coast. The Rufiji Delta records also demonstrate the impacts of damming and the destruction of mangrove areas for rice cultivation during the last millennium.

The palaecological data have helped unravel the environmental history of the Tanzanian coast and have the potential to assist in the development of policies and/or public awareness for the sustainable utilization and management of mangrove ecosystems under predicted future sea level and climate changes.

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Author's Declaration

This doctoral thesis consists of four independent papers which will be referred to in the text from Chapter 2 to 5.

List of papers

Chapter 2	Punwong, P., Marchant, R., Selby, K., 2012. Holocene mangrove dynamics and environmental changes in the Rufiji Delta, Tanzania. Vegetation History and Archaeobotany. doi:10.1007/s00334-012-0383-x.
Chapter 3	Punwong, P. Marchant, R., Selby, K. 2013. Holocene mangrove dynamics and sea level changes in Makoba Bay, Zanzibar Palaeogeography Palaeoclimatology Palaeoecology: DOI: 10.1016/j.palaeo.2013.04.004.
Chapter 4	Punwong, P., Marchant, R., Selby, K., 2013. Holocene mangrove dynamics from Unguja Ukuu, Zanzibar. Quaternary International. doi: 10.1016/j.quaint.2013.02.007.
Chapter 5	Punwong, P., Selby, K., Marchant, R., Holocene sea level changes in Tanzanian coast. Manuscript in preparation to Quaternary Science Reviews.

I hereby declare that this thesis represents my own work, except where due acknowledgement is provided. Rob Marchant and Katherine Selby contribute to the interpretation and discussion of all four papers. I have played the dominant role in initiating and conducting the fieldwork, collecting data, analysis and writing.

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Chapter 1: Introduction

Coastal habitats, a dynamic environment of key socio-economical importance, comprise biologically diverse ecosystems that mangroves. Mangrove ecosystems, like other coastal habitats, are subjected to sea level fluctuations. Changes in sea level have varied over a wide range of temporal and spatial scales (Pirazzoli, 1991; Pugh, 2004). Although studies of sea level changes since the Last Glacial Maximum are numerous (Pirazzoli, 1996) "far-field" locations, situated away from former ice sheets where glacio-isostatic effects are smaller (Clark *et al.*, 1978; Lambeck, 1993) remain under-researched. East Africa is one such location where sea level history remains poorly constrained. In addition to sea level influences, mangrove ecosystems are also sensitive to regional climate change, hydrology and human interaction. Hence, an understanding of the factors influencing these coastal ecosystems change can be useful in reconstructing current and for providing context for predicted future changes along the East African coast.

The coast of Tanzania, bordering the Southwest Indian Ocean of East Africa, extends approximately 800 km in length from southern Kenya to northern Mozambique and includes numerous islands, several rivers, creeks and bays (Figure 1.1). The Tanzanian coast contains biologically diverse areas characterised by deltas, estuaries, mangroves, beaches, and fringed by coral reefs (Francis and Bryceson, 2001; Gustavson *et al.*, 2009). The mangrove forests along the coast of Tanzania, cover about 115,500 ha on the mainland with the majority occurring in the Rufiji Delta (Semesi, 1992; Nshubemuki, 1993) and about 18,000 ha in Zanzibar (Francis and Bryceson, 2001). Mangrove ecosystems in Tanzania, particularly in the Rufiji Delta are recognised as the largest, continuous and best-developed estuarine mangroves of the East African coastline (Nshubemuki, 1993; Fisher *et al*., 1994; Richmond *et al.*, 2002; Masalu, 2003) and are important to the livelihood of coastal people as they provide environmental goods and services (Semesi 1992; Turpie 2000; TCMP 2001; Doody and Hamerlynck 2003; FAO 2007). The Tanzanian mangrove ecosystems provide habitats for flora and fauna and are considered among the most threatened habitats in the world, as a result of the increase in tree cutting for poles, charcoal and fuel wood, agriculture and prawn aquaculture (Semesi, 1992; 1998). Moreover, the Tanzanian coast has been and is presently influenced by climate change, sea level change, sedimentary dynamics and many other variables resulting in biologically rich but highly dynamic wetlands (Kamukala, 1993). Changes in these environmental conditions lead to adaptation in structure and composition of the ecosystems. Information on long-term ecosystem change can provide insights into environment–ecosystem relationships of the past, present environmental changes, and help predict future changes for the management of the areas (Hamilton, 1982; Ellison, 2008). In this thesis, the environmental history of coastal mangrove ecosystems along the East African coastline is investigated.

Aim and objectives

The overall aim of this study is to reconstruct the Holocene environmental history at three locations along Tanzanian coast using a multi-proxy palaeoecological approach. The results of this study will further our understanding of how mangroves reflect environmental variables and establish how humans have interacted with mangrove ecosystems over the recent past. Moreover, this study will provide a new coastal palaeoenvironmental study from Tanzania where very little is known about the Holocene mangrove dynamics and contribute to the body of evidence for sea level fluctuations in the Southwest Indian Ocean. To achieve this aim, several specific objectives have been identified:

1. To characterise mangrove ecosystem dynamics at three key locations along the Tanzanian coast.
2. To establish the relationship between mangrove tree distribution, pollen deposition and inundation frequency with respect to sea level to aid in the reconstruction of past environments and sea level changes.
3. To reconstruct Holocene environmental history including the influences of sea level and climate changes.
4. To investigate the nature and timing of human interaction on mangroves and possible inter-connections to ecosystem-societal developments along the Tanzanian coasts.

Structure of the Thesis

The majority of the thesis (chapters 2 to 5) is presented as site-specific scientific papers. Within these sections, there is some necessary overlap between the introductory and methodological sections.

Chapter 1

This chapter provides an introduction to the Tanzanian coastal environment. The literature on mangrove ecosystems, particularly on palaeoenvironmental studies, and sea level research undertaken in the Southwest Indian Ocean, are critically reviewed.

Chapter 2

The Rufiji Delta contains the largest, continuous and best-developed estuarine mangroves of the East African coastline and is influenced by climate, via changes in rainfall-river discharge which transports freshwater and nutrient inputs from both upstream and estuarine sources, sedimentary erosion and re-deposition and human activities in addition to inundation frequency. Chapter 2 presents reconstructed mangrove dynamics from the Rufiji Delta, which reflect environmental changes during the Holocene to the present.

Chapter 3

This chapter presents Holocene mangrove dynamics from Makoba Bay, Zanzibar. It develops a relationship of indices between mangrove pollen in surface samples and documents vegetation dynamics with respect to mean sea level. This relationship is used to aid in the interpretation of fossil mangrove pollen to characterise the inundation of mangrove assemblages and reconstruct sea level changes.

Chapter 4

This chapter presents mangrove dynamics from Unguja Ukuu to reconstruct Holocene sea level changes and emphasises the history of human settlement and the interactions on mangrove ecosystems.

Chapter 5

This chapter synthesises key findings from the three locations described in chapters 2-4 to reconstruct sea level changes for the Tanzanian coast based on new evidence presented in this study and places them in a wider context.

Chapter 6

This chapter presents and discusses the research within the context of the original aims and objectives, and suggests future directions for palaeological research along the East African coast.

Environmental setting of Tanzanian coast

Geology and climate of the Tanzanian coast

Tectonic movement following the break up of Gondwanaland (Kent *et al.*, 1971) during the Permian and Early Tertiary caused rifting along the coast of Tanzania (Mpanda, 1997). During the Mid Jurassic marine transgressions and regressions resulted in changing positions of the shorelines and the formation of the Indian Ocean. As a result the geology of the East African coast consists of the Mesozoic and Cenozoic marine sediments separated from the terrestrial Karoo rocks (Kent *et al.*, 1971; Schlüter, 1997). From the Mid Tertiary onwards, uplift and subsidence led to the creation of monocline hills, a low-level coastal plateau and fluctuating sea levels (Schlüter, 1997; Burgess and Clarke, 2000). Volcanic activity accompanied rifting during the late Tertiary and Quaternary creating several young volcanic mountains on the plains (Griffiths, 1993).

The climate in East Africa is controlled by the biannual migration of the Inter-tropical Convergence Zone (ITCZ). The ITCZ migrates northwards and southwards causing the northeasterly monsoon from October/November to February/March and the southwesterly monsoon from March/May to August/September (Halminton, 1982; Burgess and Clarke, 2000). The ITCZ migration also results in a bimodal rainfall pattern in East Africa (Goudie, 1996, Hastenrath, 2001; Nicholson, 2001) with long duration rains between March to May and short duration rains from October to December on the north coast (4-8 °S). The southern coast (8-12 °S) experiences a single rainy season between November and April (Kijazi and Reason, 2005). Sea surface temperature (SST) variation in the Indian Ocean also influences the rainfall pattern (Saji *et al*. 1999; Behera *et al*. 2003; Marchant *et al*. 2007). The mean annual rainfall varies from about 1200 mm yr^{-1} (Semesi, 1992) in the Rufiji Delta to 1500-1800 mm yr^{-1} in Zanzibar. The average temperature throughout the year is 24-31 °C in the Rufiji Delta (Richmond *et al.* 2002) and about 27-30 ºC in Zanzibar (Machiwa and Hallberg, 1995).

Warm and wet conditions prevailed in East Africa during the early Holocene (Thompson *et al.*, 2002; Stager *et al.*, 2003; Kiage and Liu, 2006; Rucina *et al.*, 2009) corresponding to a period of maximum monsoon intensity occurring across the Southwest Indian Ocean region from 10000 ^{14}C yr B.P. (Overpeck *et al.*, 1996) until the mid Holocene (Gasse *et al.*, 1989; Thompson *et al.*, 2002; Stager *et al.*, 2003; Trauth *et al.*, 2003). After the mid Holocene, drier conditions were recorded across East Africa commencing around 4500-4100 ^{14}C yr B.P. (Haberyan, 1987; Hassan, 1997; Bonnefille and Chalie, 2000; Thompson *et al*., 2002; Kiage and Liu, 2006; Rijsdijk *et* al., 2011). Such a drought would have had an effect on the hydrological regimes across Africa (Gasse, 2000; Marchant and Hooghiemstra, 2004). The arid phase occurred until around 2700 cal yr B.P. when the climate was variable. A shift towards wetter conditions was recorded after 2000 cal yr B.P. (Russell and Johnson, 2005) until 1200 to 500 cal yr B.P. when drier conditions occurred (Alin and Cohen, 2003; Vincens *et al*., 2003; Rucina *et al*., 2010). The Medieval Warm Period (MWP), represented by arid conditions from A.D. 1000 to A.D. 1270 (950-680 cal yr B.P.), was followed by wetter conditions occurring around A.D. 1270 to A.D. 1850 (680-100 cal yr B.P.) representing the Little Ice Age (LIA) period (Verschuren *et al.*, 2000; Alin and Cohen, 2003; Driese *et al*., 2004). Some records also indicate dry conditions during the LIA from 600 to 200 cal yr B.P. (Stager *et al*., 1997; Bessems *et al*., 2008).

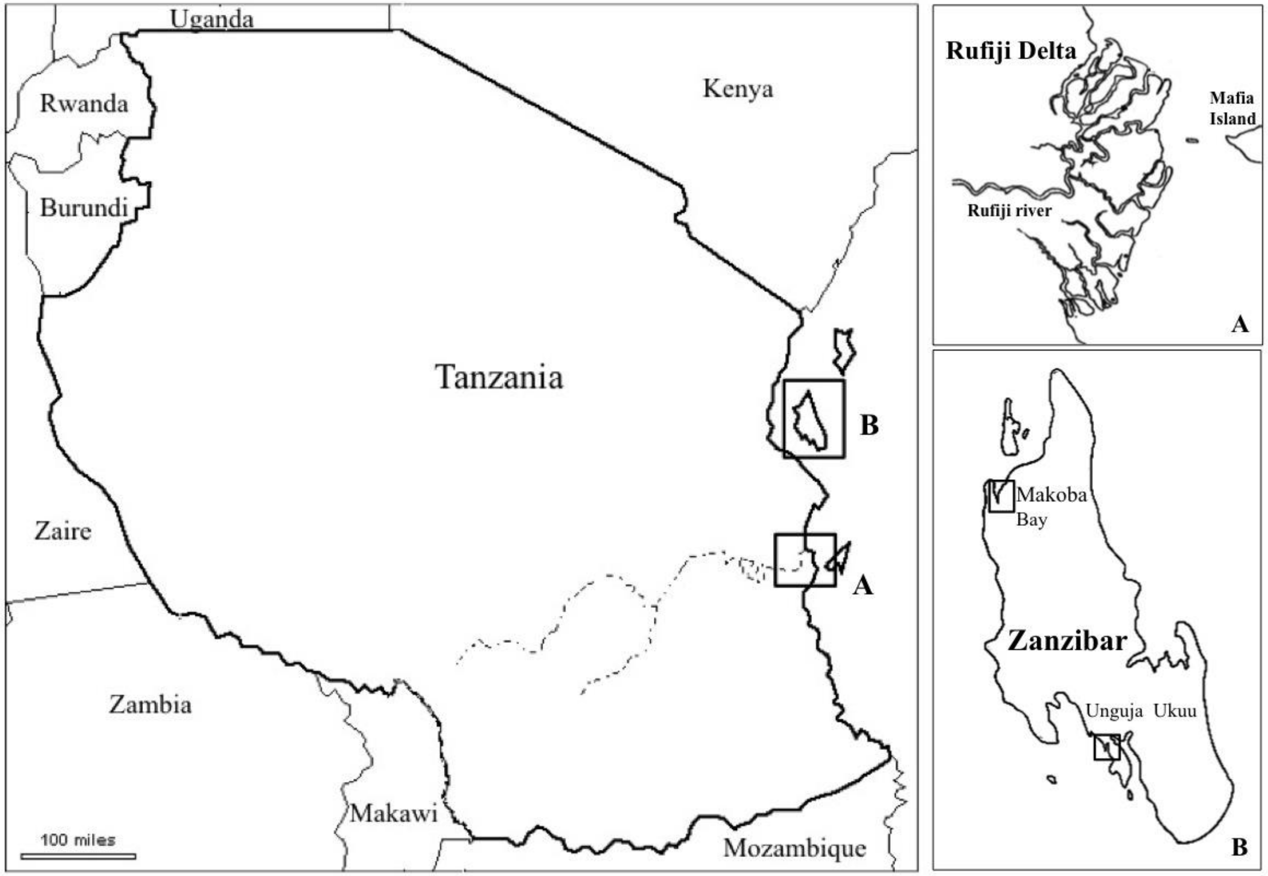

Figure 1.1. Map showing the coastline and study areas in Tanzania; (A) map of Rufji Delta (B) map of Zanzibar showing the location of two sites.

Floristic classification

The floristic composition of coastal Tanzania, from 200-300 km inland to the coast, belongs to the vegetational sub-region, the Zanzibar-Inhambane mosaic (White, 1983). The forests of coastal Tanzania are categorised according to altitude (White, 1983; Sheil, 1992) as follows:

- mountain forests at altitudes above lowland forests,
- mountain associated lowland forest,
- lowland forest referred to as coastal forest and sub-divided into Zanzibar-Inhambane lowland rain forest occurring at the base of the Eastern Arc montane blocks; Swamp forest which is limited to poor-draining, often rocky, conditions; Zanzibar-Inhambane scrub forest; and Zanzibar-Inhambane undifferentiated forest,
- mangrove forest.

Mangrove ecology

Mangrove definition and characteristics

The term "mangrove" is used to refer to the individual plants as well as a forest community (Tomlinson, 1986). According to Duke (1992) and Hogarth (1999), mangroves are evergreen trees and shrubs growing in the intertidal zone. Mangroves are found in the intertidal area (between mean sea level and high water spring level) along the coastline, in estuaries, lagoons and on river banks growing in soft substrate such as mudflats. Mangroves are halophytes which are able to tolerate high salinity and complete their life cycles under saline conditions. Mangroves prevail over freshwater plant species in brackish and/or estuarine areas. Salinity in the mangrove environment varies from marine water (35 parts per thousand (‰)) in the lowest intertidal area to upstream rivers (less than 1 ‰) (Smith, 1992). The salinity variations depend on the gradient of the flood tide and freshwater runoff (Ball, 1988; Hogarth, 1999; Krauss *et al.*, 2008). In the high intertidal area, the pattern of salinity is more complex; salinity in the water may reach 90 ‰ in arid areas but less than that of sea water (35 ‰) in freshwater runoff areas. Mangrove plants have special physiological characteristics and morphological adaptations (e.g. aerial roots, salt excretion glands and viviparous seeds) to the saline environment and are found along subtropical and tropical coastlines (Thanikaimoni, 1987; Woodroffe and Grindrod, 1991; Blasco *et al*., 1996; Ellison and Farnsworth, 2001; Yulianto *et al.*, 2004; Ellison, 2008; Abel and McConnell, 2009; Pinet, 2009). Although mangrove plants have developed common physiological features for coping with habitat preferences and high salt concentrations such as salt excretion glands and aerial roots, they are not genetically or taxonomically classified (Duke, 1992).

Mangrove taxonomy

Mangrove ecosystems throughout the world comprise 69 species belonging to 26 genera across 20 families (Duke, 1992) with the families of Rhizophoraceae and Avicenniaceae dominating. Tomlinson (1986) has described mangroves in three categories; major or true mangroves, minor mangroves and mangrove associates. The important features that true mangrove species possess are morphological adaptations to saline-influenced environments. The true mangroves play a major role in the structure of communities and usually form pure stands. The minor elements are separated from true mangrove species by their appearance in peripheral mangrove habitats and they rarely form pure stands (Table 1.1). Mangrove associates include herbaceous, non-woody terrestrial plants without adapted features to the intertidal environment and also tropical beach plants. The mangrove associates are not strictly confined to mangrove habitats and often found in transition zones.

Table 1.1. List of mangrove components (Tomlinson, 1986)

Family	Genus	Number of species
Major mangroves		
Avicenniaceae	*Avicennia*	8
Combretaceae	*Laguncularia*	1
	Lumnitzera	2
Palmae	*Nypa*	1
Rhizophoraceae	*Bruguiera*	6
	Ceriops	2
	Kandelia	1
	Rhizophora	8
Sonneratiaceae	*Sonneratia*	5
Minor mangroves		
Bombaceae	*Camptostemon*	2
Euphorbiaceae	*Excoecaria*	2
Lythraceae	*Pemphis*	1
Meliaceae	*Xylocarpus*	2
Myrsinaceae	*Aegiceras*	2
Myrtaceae	*Osbornia*	1
Pellicieraceae	*Pelliciera*	1
Plumbagianaceae	*Aegialitis*	2
Pteridaceae	*Acrostichum*	3
Rubiaceae	*Scyphiphora*	1
Sterculiaceae	*Heritiera*	3

Mangrove habitat and functional ecology (Forest type)

A functional classification of mangrove forests has six categories based on the interaction of different geological and hydrological processes (Lugo and Snedaker, 1974). A simple classification (Cintron *et al.*, 1985) recognises four types; fringe mangroves including overwash mangroves, riverine mangroves, basin mangroves and dwarf (or scrub) mangroves including hammock mangroves (Figure 1.2).

Fringe mangroves are found along the fringes of shorelines and islands with a steep elevation gradient (Wolanski *et al.*, 1992). *Rhizophora* is dominant and occurs along shorelines where elevations are higher than mean high tide and exposed to daily tides, and occasionally affected by strong winds. Overwash mangroves are a special type of fringe mangroves and found on smaller islands and finger-like projections of larger land masses occurring in areas of high salinity close to sea water and characterised by *Rhizophora* (Woodroffe, 1992). At the seaward edge, maximum salinity is that of sea water (Medina, 1999). In these areas, the tidal flow is high enough to wash away the debris and leaf litter into the adjacent areas.

Riverine mangroves occur along the edges of coastal rivers and creeks up to several miles inland from the sea. Riverine mangroves are tall floodplain forest with dominant *Rhizophora* (Woodroffe, 1992) and often fronted by a fringe forest occupying the drainage slope. Riverine mangroves are affected by inundation of the highest tides and flooded during the wet season. Therefore, riverine mangroves are influenced by freshwater and retrieves nutrient inputs from both upstream and estuarine sources and are highly productive with large mangrove trees.

Basin mangroves occur in inland areas often behind fringe mangroves where the water flow is slow. Basin mangroves appear with mixed mangrove plants, or *Avicennia*-dominated mangroves (Woodroffe, 1992). Basin mangroves are flooded by the highest tides and remain flooded for long periods, and the soils have low oxidation and reduction reactions.

Scrub or dwarf mangroves are located in an environment above mean high water with inundation only during the wet season and high evaporation throughout the year. They appear in the area with low nutrients or freshwater inflows where the mangroves growth is stunted, and often less than 2 m tall (Woodroffe, 1992). The nutrient-poor environment is due to sandy soils or limestone substrates. Hammock mangroves are located in isolated areas, forming small islands and have characteristics of both basin and scrub mangrove associations. Peat accumulates over time and results in the increase in altitude of the mangrove surface over the limestone forming small islands.

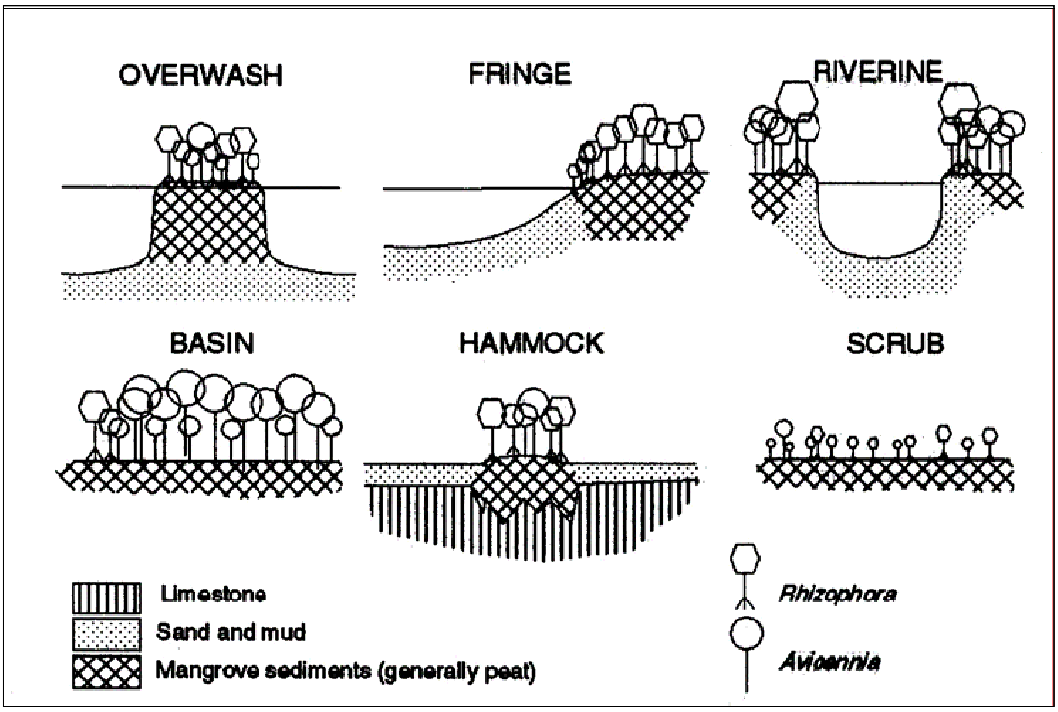

Figure 1.2. Different types of mangroves based on hydrological conditions (after Woodroffe, 1992)

Mangrove zonation

An important feature of mangrove forests found throughout the world is that of zonation. Mangroves grow in the intertidal zone between mean sea level (MSL) and high water spring level (HWSL) (Ellison, 2008). Behind "true" mangroves are so-called transition zones where various vegetation associations can be found depending on the freshwater input (Chapman, 1976, Santisuk, 1983). At the seaward edges, mangroves are subject to conditions similar to the open sea water (Lear and Turner, 1977; Woodroffe, 1992). In landward areas of mangrove between HWSL and the level of occasional flooding by the sea with little freshwater seepage and high evaporation rates, halophytic shrubs, herbs and grasses can be found (Chapman, 1976; Ellison and Stoddart, 1991; Burger, 2005). The transition zone may be characterised by brackish water taxa, freshwater swamp or lowland rain forest where freshwater surface flow and rainfall dominate (Chapman, 1976). The competition between species in habitats established by external forces is the main cause of the zonation pattern (Woodroffe, 1992). The zonation of different mangrove species responds to the amount of inundation, salinity and nutrient availability (Blasco *et al.*, 1996). Tidal influence as well as salinity determines mangrove zonation (Chapman, 1976; Hogarth, 1999; Blasco *et al.*, 1996).

In many parts of the world, different species of mangroves tend to grow in zones along physical gradients; these zones have characteristic tidal inundation regimes. A classification based on inundation (Watson, 1928; Krauss *et al.*, 2008) recognises five mangrove associations: inundation by all high tides (1), inundation by medium high tides (2), inundation by normal high tides (3), inundation by spring high tides (4) and occasional inundation by highest astronomical tides (5) (Table 1.2).

Table 1.2. Watson's (1928) tidal inundation classes based on the frequency and duration of tidal flooding.

Inundation class	Area flooded by	Times flooded per month	
		From	To
1	All high tides	56	62
2	Medium high tides	45	56
3	Normal high tides	20	45
4	Spring high tides	2	20
5	Highest astronomical tides	-	2

Santisuk (1983) classified mangrove distribution with respect to its appearance and response to tides defining true mangroves (swampy mangroves) and back mangroves. True mangroves are plants found in coastal tropical regions along the margins of the sea and lagoons; they reach up to the edges of the rivers where the water is saline and grow in swampy soils and are as covered by the sea during high tide. Back mangroves are plants growing in the areas reached by the sea water only during spring high tides, exceptional high tides, or during cyclones. They consist of other species, which tend to occur in more inland areas, such as freshwater swamps, peat swamps, salt flats, and in dry land forest. Such plants associated with mangroves are classified as part of the back mangrove association. Santisuk (1983) classified mangrove ecological distributions as swampy mangroves and back mangroves corresponding to Watson's classes 1-3 and 4-5, respectively (Table 1.3 and 1.4). Therefore, the species components of major mangroves and true mangroves, minor mangroves and back mangroves are very similar.

Salinity is the other physical variable influencing species zonation. Each mangrove species has a different physiological tolerance to salinity (Tomlinson, 1986; Hogarth, 1999) and therefore has an optimal salinity range (Table 1.5). Some species grow in salinities less than that of sea water (<35 ‰) whilst others can survive in soil, which has a high salinity (Clough, 1992). Variations in the frequency and duration of the tidal inundation creates gradients in salinity (Clough, 1992; Hogarth, 1999). The relationship between shore level and salinity is not straightforward (Hogarth, 1999). The variation in salinity at the coast is site-specific dependant on tidal regimes, freshwater drainage from rivers and creeks and seasonal climatic conditions (Chapman, 1976; Clough, 1992; Wolanski *et al.*, 1992; Matthijs *et al.*, 1999 Hogarth, 1999). In arid coastal areas with little or no freshwater and high evaporation rates, salinity tends to increase in the landward direction. Salinity in landward areas strongly fluctuates; it is significantly higher than that of sea water during the dry seasons probably exceeding 90 ‰ (Smith, 1992; Hogarth, 1999) due to low freshwater inflow and high evaporation rates, and has a low salinity in the rainy season (Smith, 1992; Hogarth, 1999; Wolsanski *et al.*, 1992; Hogarth, 1999; Medina, 1999). It seems that mangroves can withstand hypersaline conditions which are greater than the annual average, for short periods (Clough, 1992). In areas with abundant freshwater inflow from the land, by contrast, salinity decreases landwards and has its maximum close to that of sea water (35 ‰) at the seaward edge.

Table 1.3. List of recorded mangrove species and their ecological distribution (modified from Santisuk, 1983). Swampy mangrove refers to Watson's (1928) classes 1-3 and Back mangrove refers to Watson's classes 4-5.

Scientific name	**Ecological preference**		**Found in Tanzania (Taylor *et al.*, 2003)**
	Swampy mangrove	**Back mangrove**	
Acrostichum aureum		✓	✓
Aegiceras corniculatum	✓	✓	
Avicennia alba	✓		
Avicennia marina	✓		✓
Avicennia officinalis	✓	✓	
Bruguiera cylindrical	✓	✓	
Bruguiera gymnorrhiza	✓	✓	✓
Bruguiera parviflora	✓	✓	
Bruguiera sexangula		✓	
Ceriops tegal	✓		✓
Excoecaria agallocha		✓	
Kandelia candel	✓	✓	
Lumnitzera littorea		✓	
Lumnitzera racemosa	✓	✓	✓
Nypa fructicans	✓	✓	
Pemphis acidula		✓	
Rhizophora apiculata	✓		
Rhizophora mucronata	✓		✓
Sonneratia alba	✓		✓
Sonneratia caseolaris	✓	✓	
Sonneratia ovata	✓	✓	
Xylocarpus granatum	✓	✓	✓

Table 1.4. Watson's (1928) inundation classes of mangrove plants found in Tanzania along a tidal transect (after Santisuk, 1983) (× represents the optimum ecological distribution in each inundation class).

Species	**Watson's inundation classes**				
	1	**2**	**3**	**4**	**5**
Acrostichum aureum			××	××××××	××××××
Avicennia marina	×××	××××××	××××××		
Bruguiera gymnorrhiza			××××××	××××××	××××××
Ceriops tagal			××××××	××××××	
Heritiera littoralis				××	××××××
Lumnitzera racemosa			×××	××××××	××××××
Rhizophora mucronata	×××	××××××	××××××		
Sonneratia alba	××××××	××××××	××		
Xylocarpus granatum			××××××	××××××	××××××

Table 1.5. Summary of the relative tolerances of some mangroves in Tanzania to salinity, aridity, and tidal level. Range of tolerances from +++++ = very tolerant, to + = not tolerant, H = High, M = Mid, L = Low (after Clough, 1992) and salinity data obtained from Smith (1992); MS = Maximum Porewater Salinity measured in the field at sites where species were growing, OG= salinity for Optimum Growth based on culture studies (after Smith, 1992); ? = unknown range.

Species	Salinity			Aridity	Intertidal level
	MS (‰)	OG (‰)	Range of tolerances		
Avicennia marina	85	0-30	+++++	+++++	H, M, L
Bruguiera gymnorrhiza	50	8-34	+++	+++	H, M
Ceriops tagal	45	0-15	+++	+++	H, M
Heritiera littoralis	?	?	++	++	H, M
Lumnitzera racemosa	78	?	++++	++++	H
Rhizophora mucronata	40	8-33	++	++	M, L
Sonneratia alba	44	??	+++	+++	M, L
Xylocarpus granatum	34	8	+++	+++	H, M

Mangrove vegetation in Tanzania

Typically throughout the world, the seaward zone of mangroves is occupied by pure stands of genus *Avicennia*, *Rhizophora* and *Sonneratia* considered as pioneer species and backed by mixed stands of *Bruguiera, Heritiera* and *Xylocarpus*. *Ceriops* and *Lumnitzera* are found in the more landward zone. In the transition zone, minor mangroves and/or back mangroves are usually found (Tomlinson, 1986; Limi *et al.,* 2003). Although 55 mangrove species are found from the Indian Ocean (Kathiresan and Rajendran, 2005), the East African coast has a low biodiversity due to high salinity, anaerobic sediments, acidic soil, and unstable substrates (Wang *et al.*, 2003) with only nine mangrove species found in Tanzania (Taylor *et al.*, 2003; Wang *et al.* 2003; Kathiresan and Rajendran, 2005). Mangroves in Tanzania show a distinct zonation (Taylor *et al.*, 2003) and correspond to other sites in East Africa (Chapman, 1976). Specifically, *Sonneratia alba* is often found as a pioneer of exposed areas along outer mangrove margins.

Rhizophora mucronata commonly occurs in large homogeneous stands with muddy sediment along rivers and creeks. *Ceriops tegal* appears in the upper intertidal and dry areas. *Bruguiera gymnorrhiza* grows in wet areas between the *Rhizophora* and *Ceriops* zone. *Lumnitzera racemosa* is found on arid landward edges. *Xylocarpus granatum* occurs in landward fringes where there is a greater freshwater influence. *Avicennia marina* can be commonly found on firm sandy soils extending from exposed seaward areas to the landward belt. *Heritiera littoralis* is found on river banks with low salinity and landward areas usually flooded only by high spring tides. The following figure showing mangrove zonation is based on Watson's (1928) and Santisuk's (1983) inundation classes in Tanzania (Figure 1.3).

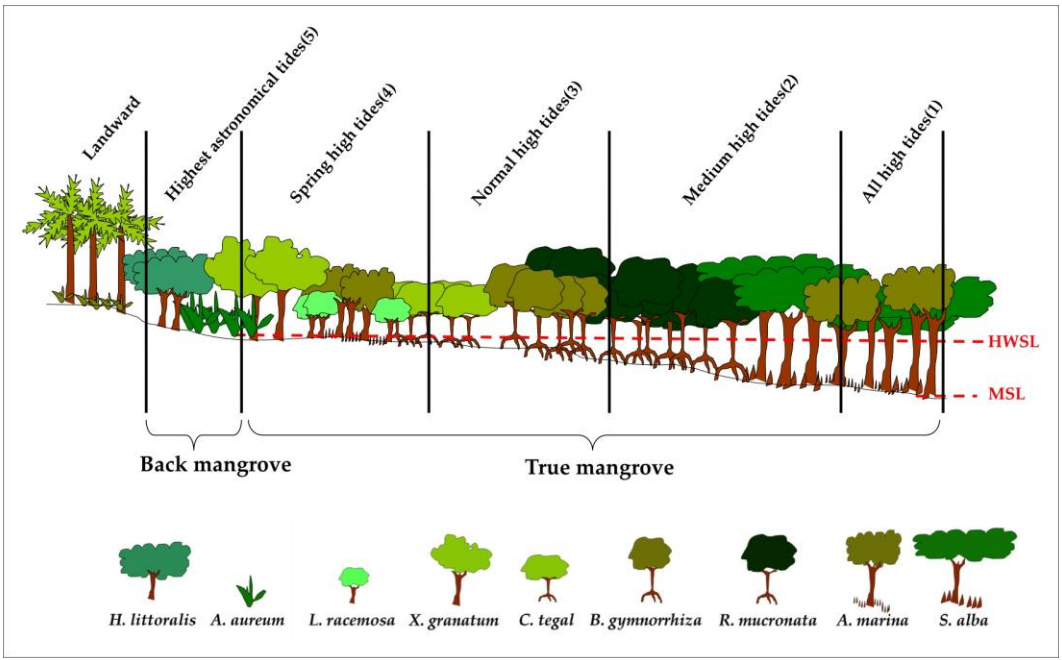

Figure 1.3. Summary cross section showing mangrove zonation in East Africa developed by using a combination of Watson's (1928) and Santisuk's inundation classes (1983).

Sonneratia alba J. Smith occurs within a soft mud or silt on open coasts (Gallin *et al.*, 1990; Taylor *et al.*, 2003). It is commonly found as a pioneer of the exposed area along outer seaward mangroves and forms a thick belt of mangrove margin flooded by every tide (Chapman, 1976; Tomlinson, 1986; Taylor *et al.*, 2003). This species prefers growing under tidal influence. The distribution range of *S. alba* is limited by the influence of freshwater runoff and found down stream where salinity is close to sea water (35‰) and remains constant during the wet and dry seasons (Duke, 1992).

Avicennia marina (Forsk.) Vierh. demonstrates bimodal distribution (Mattijs *et al.*, 1999; Duke *et al.* 1998) with respect to its tolerance to sea water inundation and wide range of salinity (2-90‰) (Chapman, 1976; Duke, 1992; Smith, 1992). *A. marina* is commonly found on firm sandy soils. It is commonly found in the most landward belt to the exposed seaward fringes as a primary colonist associated with *S. alba* (Chapman, 1976; Taylor *et al.*, 2003) or also extends along almost the entire length of the estuary (Duke, 1992). Due to the great difference in salinity, *A. marina* growing in the landward areas is smaller than the seaward individual, which is large when fully grown (Macnae and Kalk, 1962; Chapman, 1976; Mattijs *et al.*, 1990). In the landward zone flooded at the highest spring tides, salinity concentrations in the substrate become very high probably up to 2-3 times that of sea water (Chapman, 1976; Mattijs *et al.*, 1990).

Rhizophora mucronata Lam. is also a primary colonist occurring in large homogeneous stands on river mouths and creeks (Chapman, 1976; Taylor *et al.*, 2003). It usually grows in silty sediments in the tidal zone flooded daily by tides; areas that tend to be wet and muddy (Tomlinson, 1986). This species is also found upstream where some neap high waters may not cover the ground (Chapman, 1976). It occasionally may be found as a pioneer on open beaches flooded by all the tides (Macnae and Kalk, 1962).

Bruguiera gymnorrhiza (L.) Lamk. is typically a plant of the middle mangrove community, extending into the transition landward communities. It may be found on the exposed shores where the mangrove belt is thin (Tomlinson, 1976). It can be found as an independent belt between *R. mucronata* and the landward fringe where the rainfall is high whilst occuring between *R. mucronata* and *C. tegal* in more arid areas (Chapman, 1976). This species is recognised as a tolerant of low ranges of salinity (Ball *et al.*, 1988) and can be found in areas where the overall is salinity is lower (15-20 ‰) (Chapman, 1976).

Ceriops tegal (Perr.) C. B. Robinson is typically a plant of the upper intertidal mangrove (Tomlinson, 1986). This species is less capable of withstanding strong waves and currents due to its weaker root system. It appears in the upper intertidal and dry areas where salt water occasionally floods and high soil salinity is produced by evaporation (Matthijs, 1999; Tayler *et al*, 2003). *C. tegal* is considered as a highly salt tolerant plant (Ball *et al.*, 1988).

Xylocarpus granatum Koenig. commonly occurs in landward fringes of mangrove which are occasionally inundated by exceptional or equinoctial tides and there is a greater freshwater influence (Taylor *et al.*, 2003; He *et al.*, 2007). This species prefers growing in non-saline soils (Clough, 1992).

Heritiera littoralis (Dryand.) Air. is found on river banks and considered a constituent of the back mangrove which is flooded by spring or equinoctial high tides (Tomlinson, 1986; Taylor *et al.*, 2003; Wang, 2010) and may occupy the forest fringe. This species is intolerant to salinity and prefers growing in non-saline soils (Clough, 1992). Consequently, it grows in habitats with low salinity and does not occur in exposed areas and is thus limited to areas away from the sea. The substrate is firmer compared to those on which other mangrove species are found (Tomlinson, 1986, Clough, 1999; Semesi, 2001).

Lumnitzera racemosa Wild. is a characteristic of landward mangrove communities and can also be found at the upper landward mangrove (Tomlinson, 1986; Gallin, 1990; Su *et al.*, 2006). It is tolerant to high salinity soil up to 90‰ (Smith, 1992). This species is also associated with *C. tegal* and *A. marina* in dry areas (Gallin, 1990).

Acrostichum aureum Linnaeus is a typical constituent of back mangroves and associated with brackish conditions. This fern is opportunistic in disturbed areas where the mangrove has fallen (Chapman, 1976; Tomlinson, 1986). *A. aureum* dominates in the understory of back mangrove areas with relatively high rainfall and frequent desalinization of the upper soil layers (Medina *et al.*, 1990). It is not restricted to mangrove habitats and can survive in non saline conditions (Tomlinson, 1986; Wang, 2010).

Human occupation along the Swahili coast

The Swahili are recognised as the people living along the 3000 kilometer-long coast of East Africa extending from Mogadishu in Somalia to Mozambique and the offshore islands except Mauritius and the Seychelles (Kusimba, 1999; Horton and Middleton, 2001; Breen and Lane, 2003). As the Swahili coast is influenced by the seasonal migration of ITCZ, which reverses its direction every six months, it supports the trade from East Africa to Arabia, the Persian Gulf, India and Southeast Asia (Mitchell, 2004; Connah, 2006). Accordingly, monsoons caused by ITCZ facilitate the maritime trade with rapid sailing and return in the same year (Horton and Middleton, 2001; Breen and Lane, 2003). A variety of vegetation provides different resources important for human settlement and cultural development along the Swahili coast (Sinclair, 1991; Connah, 2006). Fisheries and the exploitation of mangrove and coral for building materials have been, and still are, common in coastal areas while agriculture, gathering, and hunting have been and are dominant in the hinterlands (Horton and Middleton, 2001; Connah, 2006).

Historical evidence including the famous documentary, *The Periplus of the Erythraean Sea* (Huntingford, 1980), has been recorded for the first settlement of the Swahili coast as early as 100 B.C. to the first century A.D. as well as an international trade connection via the Indian Ocean (Sinclair, 1991; Kusimba, 1999; Horton and Middleton, 2001; Phillipson, 2005). However, dates on shell beads, potsherds, domesticated chicken and cat bones from the Late Stone Age/Neolithic cave, Machaga, in Zanzibar represent the earliest habitation of this area and the first link to Asia dating back to around the third millennium B.C.

(4808-4423 cal yr B.P., 4120 ^{14}C B.P.). A hunting-fishing community around the last millennium B.C. is also recorded (Chami, 2001). Evidence for trade connection has been recorded from northern Somalia (Horton and Middleton, 2001), Kenya and Tanzania (Kusimba, 1999) and suggests that an early trade links existed between India and Red Sea around A.D. 100 and a shift of trade route between the Persian Gulf and the East Africa occurred at around A.D. 200-300 It is thought that the first Swahili people were iron workers originating from the farming people known as the Bantu who expanded across Africa (Chami, 1998; Kusimba, 1999; Chami, 2003). The later period around A.D. 300-1000 represents the Swahili expansion down the south coast, into Unguja Ukuu, and covering almost the entire Swahili coast at around A.D. 600-1000. The richness of archaeological records along the East African coast including in the hinterlands during A.D. 1000-1500 represents the pinnacle of the Swahili period and evidence of a vast trading network was dominated by the Islam culture (Horton and Clarke, 1985; Kusimba, 1999; Horton and Middleton, 2001; Kessy, 2003). During the colonial period (A.D. 1500-1950), the Swahili were controlled by the Portuguese, Oman and British powers in different regions (Horton and Clarke, 1985; Kusimba, 1999; Horton and Middleton, 2001; Kessy, 2003) and an increase in the abandonment of settlements occurring in the hinterlands and along the coast is recorded during this time. The Swahili culture deteriorated under the colonial rule with the export of slaves and ivory (Kusimba, 1999; Sheriff, 2002).

Site descriptions

As a single record of environmental change would not be representative of an entire ecosystem and region, several cores along a transect of altitudinal gradient within each site are used to detect spatial shifts in vegetation. Several cores with different environmental settings are used to provide evidence for ecosystem responses to a variety of environmental factors. In this study, three sites from the mainland and Zanzibar are investigated (Figure 1.1), *viz.* the northern Rufiji Delta (Tanzanian mainland), Makoba Bay and Unguja Ukuu (Zanzibar). This section provides background to the study sites.

The Rufiji Delta

The study area is located within mangroves and paddy field areas in the northern Rufiji Delta (Figure 1.1). The Rufiji Delta is located in the Rufiji District along the east coast in southern Tanzania (Semesi, 1992) and is the most important wetland area in East Africa (Francis, 1992; Semesi, 1992; Doody and Hamerlynck, 2003). The deltaic plain formed at the Indian Ocean by the Rufiji river is approximately 65 km wide and extends 123 km inland (Figure 1.4). The Rufiji river is one of the largest rivers in East Africa and drains 20% of mainland Tanzania (Semesi, 1992; Erftemeijert and Hamerlynck, 2005). The river branches out into a series of channels forming a delta that is divided into two main parts forming the northern areas which extend approximately 23 km north to south and 70 km east to west (Fisher *et al.,* 1994; Doody and Hamerlynck, 2003) and the southern areas. The delta supports the largest area and best-developed mangroves in Tanzania (Nshubemuki, 1993; Richmond *et al.* 2002), approximating 53200 ha of mangrove forest found along tidal channels and in numerous tidal creeks (Francis, 1992). According to Semesi (1992), the delta is mainly covered by sand, silt and clay derived from the alluvial system and transported from the Rufiji basin. A series of sand spit islands and submerged sand bars formed parallel to the seaward margins exists (Fisher *et al*., 1994). The mangrove substrata are formed approximately 2.5 m above mean sea level (Fisher *et al.*, 1994). The sediments of mangrove areas are generally clayey silts and silty clays with sandy clays more dominant at higher elevations, and containing more organic matter. According to Francis (1992), the average tidal range, controlled by the semi-diurnal tide between the mangrove swamps and the ocean through the channels and creeks, is 2-2.5 m and approximately 3.3 - 4.3 m on high spring tides (Fisher *et al.,* 1994; Richmond *et al.* 2002). The salinity of the water in the channels and in the soil of the delta ranges from 10.60 ‰ to 32 ‰ (Francis, 1992; Fisher *et al.* 1994). The lowest recorded value corresponds to the ebb tide period while the highest value occurred during the flood tide.

A major river drainage shift in the 1970s (Semesi, 1992; Fisher *et al.* 1994, Erftemeijert and Hamerlynck, 2005) caused the river to divert from south to north. It is believed that the diversion, caused by sedimentation is the result of deforestation in the higher elevations of catchment together with sediment erosion produced by heavy rain. This diversion resulted in some channels becoming larger and others becoming blocked (Semesi, 1992) and has an effect on an increased freshwater outflow. It also changes the salinity pattern throughout the whole of the delta. Consequently, people living in the north delta deforest mangrove areas in order to expand their rice cultivating areas (Fisher *et al.*, 1994).

Upstream from the delta of the Rufiji flood plain is cultivated for rice by farmers living in the elevated regions. The Rufiji Delta provides habitat to flora which is valuable for trade (Semesi, 1992). Mangrove wood is used for poles, timber for fences, houses, boats, fish traps and firewood (FAO, 2007). Mangroves also provide a habitat and nursery grounds for fauna such as fish, shrimps and crabs supporting a productive fishery (Turpie, 2000). The shoreline is also protected from wave and coastal erosion by mangrove forests (TCMP, 2001).

Zanzibar

Zanzibar is a group of islands that includes the large major island of Unguja colloquially called Zanzibar and Pemba located in the Indian Ocean about 40 km off the coast of Tanzania separated by the Zanzibar channel. Zanzibar is about 85 km long and 39 km wide with an area of 1,660 km^2 (Mustelin *et al.*, 2009). The island is surrounded by fringing coral reefs, rocky inlets or sandy beaches and mangroves found along the western shores, particularly within embayments, and covering approximately 6,000 hectares (Francis and Bryceson, 2001).

Zanzibar is located on the continental shelf and was connected to the mainland when sea level was 30-40 m below present mean sea level (Shaghude and Wannäs, 1998; 2000). Sea level transgressions during interglacial periods caused Zanzibar to become an island (Ingrams, 1931; Arthurton *et al*., 1999) and the last connection to the mainland probably occurred from the last glacial period prior to 10-15 ka B.P. (Hamilton, 1982; Camoin *et al*., 2004). Most of Zanzibar consists of Pleistocene reef limestone often appearing towards the east coast and commonly referred to as “coral rag” (Shunula, 2002) with alluvial deposits found in some areas (Schlüter, 1997; Arthurton *et al*., 1999). Zanzibar is generally flat and low-lying, covered by quartz sand (Arthurton *et al*., 1999) without large rivers (Shunula, 2002) and influenced by a semi-diurnal tide, ranging from 2 m on neap tide to 4 m on spring tide (Mwandya *et al*., 2010). The shores form 1-3 km intertidal platforms and support mangrove development in sheltered bays (Arthurton *et al.*, 1999). Zanzibar possesses a variety of ecosystems including coastal forests (bush, coral rag forests), mangrove swamps, intertidal zones (seagrass beds and lagoons), and marine habitats (coral reefs) (McIntyre and McIntyre, 2009). Mangrove areas in Zanzibar cover about 5% of the total land area especially on the west coast where creeks and shallow bays occur (Shunua, 2002).

The study areas are located in the northwest of Makoba Bay and the east Makime headland of Unguja Ukuu about 25 km northwest and south of Zanzibar town respectively (Figure 1.5, 1.6). Makoba Bay is covered by a 100-700 m (in width) belt of dense mangroves occurring in a north-south alignment with the majority of trees up to 4 m in height and some of the regeneration vegetation reaching heights of between 1 and 2 m. The site is restricted to the west by the steep ancient coral terrace approximately 4 m in height along the mangrove landward areas in a north-south alignment, to the north and east by the sea, and to the south by small villages and the mariculture ponds of the Institute of Marine Science of the University of Dar es Salaam. These ponds used to be salt evaporation pans owned by the Prisons Department of Zanzibar but have since abandoned (Kyewalyanga and Mwandya, 2004). The area is characterised by shallow unconnected tidal creeks with minimal freshwater input from terrestrial runoff during the heavy rainy season and may therefore experience a temporary decrease in salinity (Mwandya *et al*., 2010) (Figure 1.5).

The second study area is located in Unguja Ukuu, which is covered by a belt of dense mangroves varying from approximately 75-120 m in width and approximately 1 km in length occurring in a north-south alignment with the majority of trees reaching heights of between 1 and 2 m. The site is restricted to the south by the sea, to the west by a ridge of deep sands about 3 m in height aligned in a north-south direction, and to the north by the villages of Unguja Ukuu and a creek bank in front of the mangrove area with a narrow sandy beach (Figure 1.6). The first archaeological evidence of inhabitants was recorded from Unguja

Ukuu, the former capital of Zanzibar (Horton and Clark, 1985) from around A.D. 500. Trade connecting the town with other sites on the mainland, islands and the wider Swahili coast of East Africa have contributed to the development of Unguja Ukuu (Horton and Clark, 1985; Juma, 2004). Unguja Ukuu was abandoned, probably due to the civil war, after around A.D. 900 and was re-occupied as an Islamic settlement around A.D. 1450-1600 (Juma, 2004). The Portuguese arrival in Zanzibar was recorded by the 15 century and developed a trade community around Zanzibar Town. In the 18th century, Zanzibar was ruled by Oman leading to the rapid urbanisation of Zanzibar Town which became the centre of trading, particularly in slavery and ivory, on the East African coast and then the capital of Oman (Sheriff, 2002; Kessy, 2003; McIntyrn and McIntyrn 2009). Zanzibar became a British protectorate from 1890, and obtained independence in 1963. It became a new state of Tanzania being ruled as a semi-autonomous state (Kessy, 2003; McIntyrn and McIntyrn 2009).

The three sites investigated all possess different geological and hydrological processes and anthropogenic histories. The Rufiji Delta is characterised by a large area of riverine mangroves connected to the mainland and influenced by water discharge and terrestrial inputs along with tidal inundation. The two other sites in Zanzibar represent areas of fringing mangroves unconnected to a river. Long-term anthropogenic activities have impacted greatest at Unguja Ukuu and the northern Rufiji Delta and less at Makoba Bay. The record from Makoba Bay is therefore theoretically ideal for investigating mangrove responses to sea level changes, the record from Unguja Ukuu for investigating mangrove response to sea level as well as anthropogenic history and the record from the Rufiji Delta ideal for investigating mangrove responses to a combination of sea level changes, terrestrial influences and human interactions. By combining these site characteristics with the records of coastal and environmental changes, a regional pattern can be established for the Holocene.

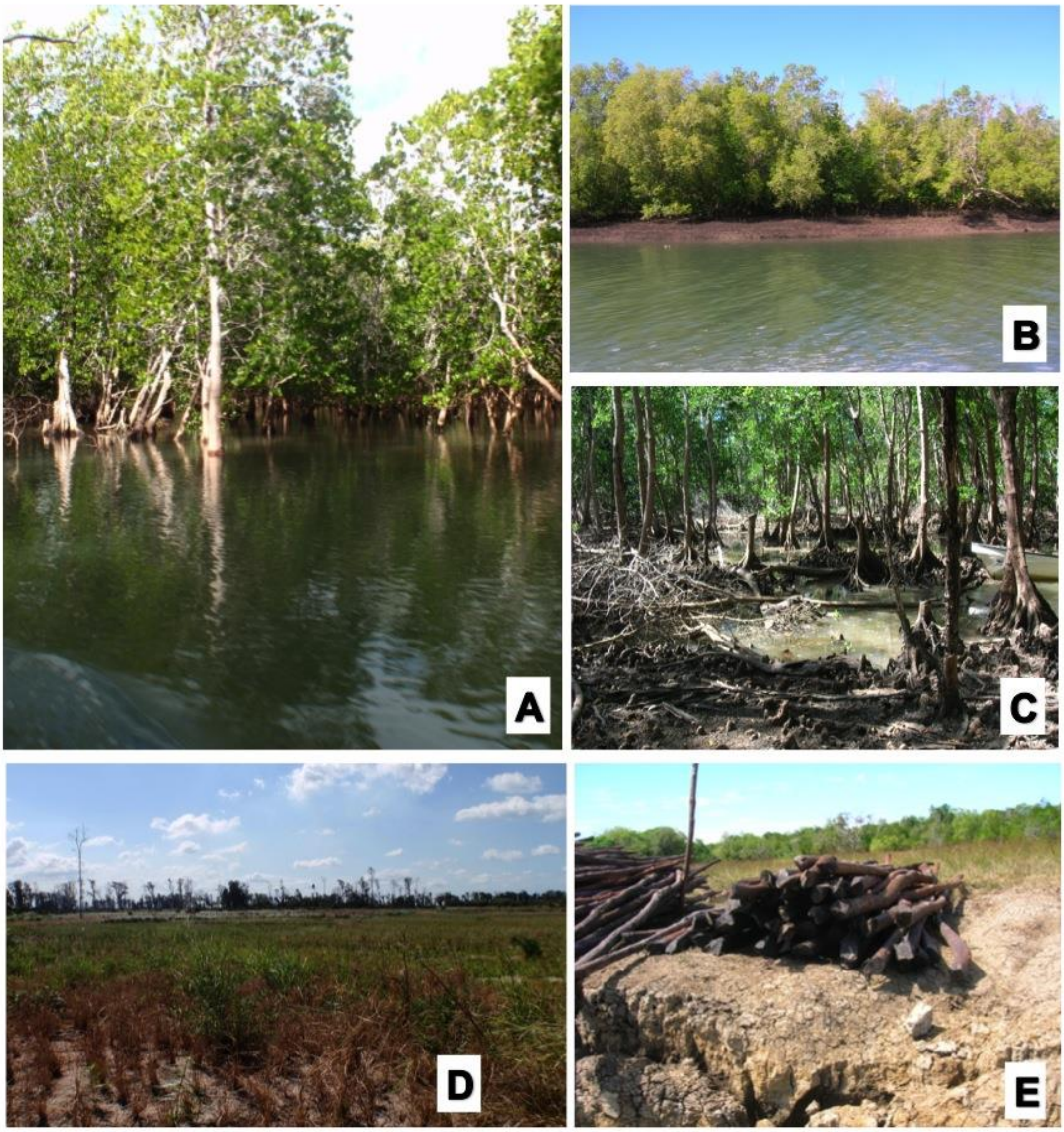

Figure 1.4 The Rufiji Delta showing mangrove habitats (A-C), paddy field (D), cutting of mangrove wood for poles (E)

Figure 1.5 Makoba Bay showing mangrove habitats (A-C), abandoned salt pans (D), fringing mangrove showing erosion of shoreline (E), preparation of charcoal from mangrove wood (F).

Figure 1.6 Unguja Ukuu showing mangrove habitats (A-B), preparation of charcoal from mangrove wood (C), cutting of mangrove wood from Unguja Ukuu region (D).

Literature review

This review focuses on the use of mangrove pollen as a tool for environmental reconstruction of past mangrove ecosystem dynamics and how these ecosystems react to environmental factors such as fluctuations in sea level and precipitation. Regional sea level changes in the Southwest Indian Ocean are reviewed to compare and contrast the temporal range of studies. All uncalibrated radiocarbon ages are calibrated to calendar year before present (cal yr B.P.) using the southern hemisphere calibration Shcal04 curve (McCormac *et al.*, 2004) and the software OxCal v4.10 (Bronk-Ramsey, 2009). Original radiocarbon dates are cited in parentheses. However, due to some ambiguities of the standard errors (±1 sigma) for the original radiocarbon ages some ages are not possible to calibrate.

Review of threats to mangroves

Mangrove ecosystems are influenced by various environmental factors such as sea level, climate including precipitation, temperature, atmospheric CO_2 concentration, hydrology, geomorphology, storms and anthropogenic activities (Field, 1995; Duke *et al.*, 1998; Alongi, 2008; Gilman *et al.*, 2008). Changes in any of these factors, or a combination of factors, will result in the mangrove composition and distribution altering.

Sea level changes

Sea level fluctuations have occurred throughout geological time resulting in transgressions and regressions of sea water caused by a combination of eustatic and isostatic components (Gilman *et al.*, 2008). Eustasy and isostasy result from the absolute changes of water mass in the oceans and adjustment of earth's crust in response to change in mass loading respectively (Woodroffe and Horton, 2005; Gilman *et al.*, 2008, Abel and McConnell, 2009). Eustatic sea level change is the absolute change in global sea level resulting from fluctuations in the total ocean volume or in the volume of an ocean basin (Church, 2001; Bell and

Walker, 2005; Gilman *et al.*, 2008; Abel and McConnell, 2009). These fluctuations result from the transfer of ice from glaciers, ice sheets and ice caps as water to ocean basins, and are referred to as glacio-eustasy and "steric" thermal expansion of sea water as the ocean warms (changes in ocean volume resulting from temperature-induced density of sea water changes). Isostatic changes occur on regional and local scales and refer to changes in the level of the land masses due to rheological responses of the earth's crust which maintains equilibrium when the the crust is depressed by sediment, ice, and water and may imply no real change in the volume of water in the oceans (Pirazzoli, 1996; Bindoff *et al.*, 2007). The crustal adjustment caused by the weight of large ice sheets is known as glacio-isostasy, while the melting of ice sheets releases a large amount of water and is referred to as hydro-isostasy (Pirazzoli, 1996; Church, 2001; Haslett, 2001; Bell and Walker, 2005; Woodroffe and Horton, 2005; Gilman *et al.*, 2008).

Mangrove ecosystems and species associations (Table 1.3) do not necessarily keep pace with changing sea level. The following scenarios may occur:

- <u>Sea level is stationary relative to the mangrove surface</u>. The mangrove community has to adjust towards equilibrium leading to the mangrove vegetation achieving stability (Figure 7A).
- <u>Sea level is falling relative to the elevation of mangrove surface</u>. Mangrove margins migrate seaward and possibly expand laterally if those areas adjacent to the mangrove provide conditions suitable for mangrove establishment (Gilman *et al.*, 2008). The main result of sea level fall is a prograding shoreline that produces different conditions and substrates resulting in other landward or terrestrial species establishing which are more suited to grow on non-marine sediments (Ellison and Stoddart, 1991). Therefore, mangrove ecosystems decrease at the original margin (Figure 7B).
- <u>Sea level is rising relative to the mangrove sediment surface</u>. The obvious impacts of sea level rise are coastal erosion, increased salinity, increased inundation by saline water, and increased depth of inundation resulting from increased sea water level and estuary

or embayment infilling (Blasco *et al.*, 1996). In order to cope with rising sea level, rates of sedimentary accretion within the mangrove should equal rates of sea level rise (Ellison, 1993), otherwise mangroves may undergo *in situ* drowning leading to weakened root structures, dieback and disappearance (Gilman *et al.*, 2008). Mangroves migrate to higher elevations and possibly laterally expand as the mangrove species re-establish in new habitats with suitable hydrology and sedimentary conditions (Figure 1.7C). The critical rate of mangrove peat accretion needed to ensure sustainability is variable from 0.8-6 mm yr^{-1} depending on the nature of terrestrial sediment input (Ellison, 1989; 1993; Ellison and Stoddart, 1991; González *et al.*, 2010). Mangroves are currently vulnerable as they are experiencing loss of habitat from shoreline erosion due to sea level rise (Ellison and Stoddart, 1991). Global mean sea level is projected to rise at 1.2-2.2 mm yr^{-1} due to global warming during the 20th century, has accelerated in the last two decades (Bindoff *et al.*, 2007; IPCC, 2010) and is predicted to increase up to 13 mmy^{-1} in the next 100 years (Grinsted *et al.*, 2009).

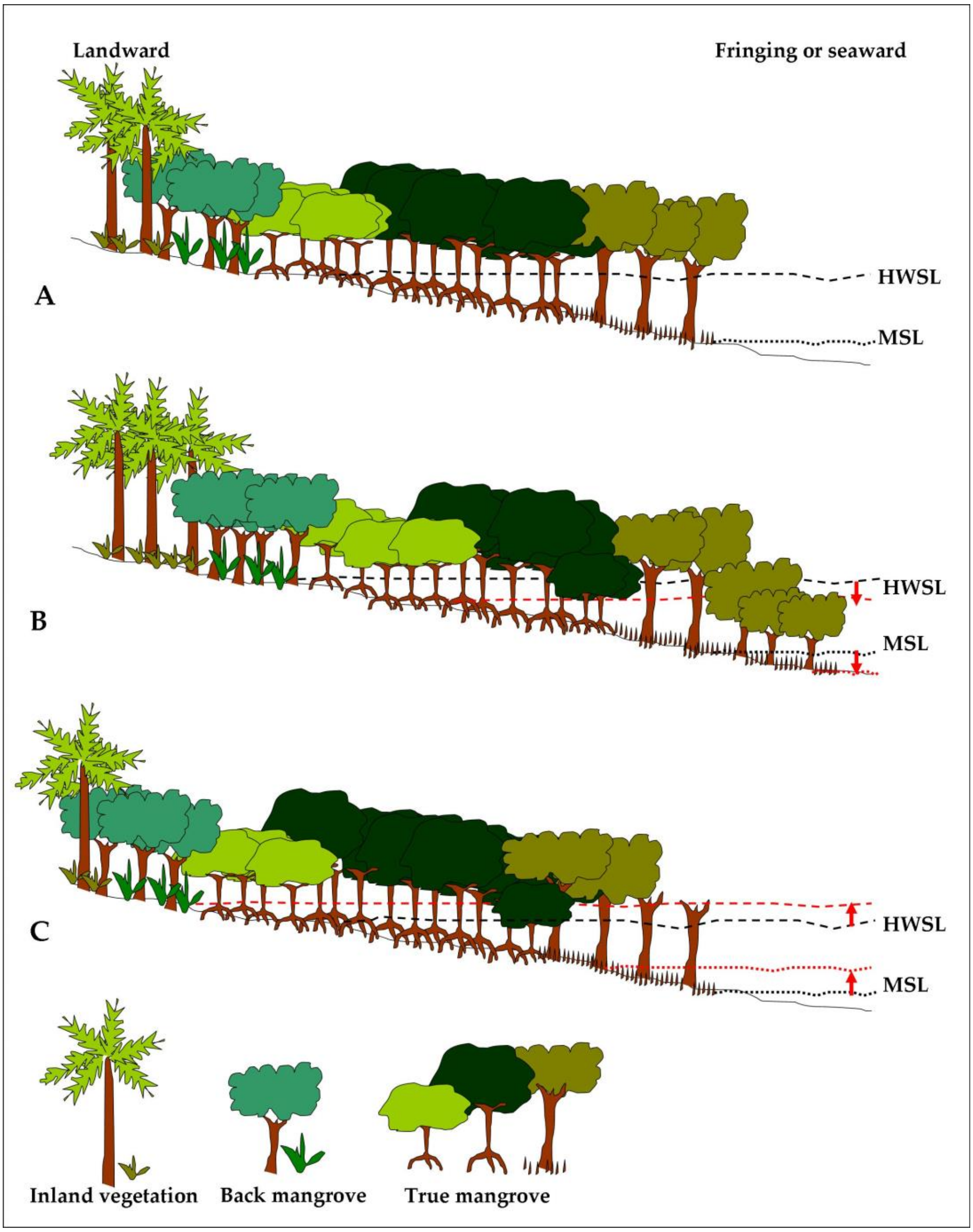

Figure 1.7. Schematic profile of mangrove responses to sea level changes (A) No change in sea level relative to mangrove surface results in no change in mangrove position. (B) Sea level fall relative to mangrove surface causes migration of mangrove and seaward margins seaward. (C) Sea level rise relative to mangrove surface causes mangrove seaward margin erosion and landward migration of landward and seaward margins.

Precipitation

In addition to sea level, the quantity and character of precipitation also influences ecosystem composition (Gilman *et al.*, 2008). Changes in rainfall pattern have a significant influence on freshwater runoff, fluvial sediment and nutrient inputs which affect the salinity and the resultant composition of the mangrove ecosystem (Nicholson and Flohn, 1980; Kjerfve, 1990; Hughes *et al.*, 1998; Saintilan and Williams, 1999; Saintilan and Wilton, 2001; Alongi, 2008; Gilman *et al.*, 2008; Eslami-Andargoli *et al.*, 2009). An increase in precipitation results in increased nutrient inputs and reduced salinity, which enhances growth rates, diversity and mangrove areas (Duke *et al.*, 1998). In areas with constant rainfall throughout the year, the salinity within soil is constant and supports mangrove development and diversity (Macnae, 1968). Conversely, drought can result in a decrease in mangrove development. Low duration and intensity of rainfall, combined with high evaporation rates, can result in hypersaline conditions (Snedaker, 1995; Ellison, 2000; Gilman *et al.*, 2008; Mikhailov and Isupova, 2008). A decrease in rainfall results in decreased mangrove diversity and extent of mangrove areas as the mangrove requirements for tolerance of high salinity in soil reduce growth rate and mangrove productivity (Field, 1995; Gilman *et al.*, 2008). Regional rainfall patterns therefore affect coastal and estuarine mangrove ecosystem composition and distribution.

Anthropogenic disturbance

Mangrove ecosystems are also sensitive to anthropogenic disturbance (Blasco *et al.* 1996; Hogarth 1999; Gilman *et al.* 2008). Mangroves are important to the livelihoods of coastal people as mangrove ecosystems provide a range of services including food, and protection from tidal and wave action by absorbing the wave energy, which in turn, protects coastlines from erosion (Spalding *et al*., 1997; 2010; Engelharet *et al.*, 2007;) and materials needed in everyday life e.g. timber for poles, fences, houses, boats, fish traps and a source of fuel (charcoal and firewood) (Omodei *et al.*, 2004; FAO 2007). The degradation and loss of mangrove areas has been increasing and around 35 % of mangroves have been lost all around the world in the last two decades (Valiela *et al.*, 2001). Most mangrove degradation is caused by increasing demand for land and wood leading to conversion of land to urban development, agriculture i.e. rice fields and aquaculture expansion and particularly shrimp ponds (Tomlinson, 1986; Spalding *et al*., 1997; 2010). One example of mangrove degradation within East Africa is the expansion of agriculture and grazing land which causes inland topsoil erosion being washed downstream and burying mangrove roots (Taylor *et al*., 2003). Over-exploitation of mangrove woods for timber and fuel is one of the major threats to mangroves (Taylor *et al.*, 2003; Spalding *et al*., 2010). The Tanzanian coast forms part of the Swahili coast with evidence of anthropogenic activities for thousands of years (Chami, 1999; Kusimba, 1999; Horton and Middleton, 2001). Mangroves in the Rufiji Delta and Zanzibar are vulnerable. Cutting of wood by local people for pole trading began during the ninth and tenth century across the Indian Ocean (Spading *et al.*, 1997; Horton and Middleton, 2000) for building material, firewood and charcoal for domestic uses particularly at Unguja Ukuu and around Chwaka Bay and for salt production from boiling sea water around Makoba Bay for many centuries (Ngoile and Shunula, 1992). The deforestation of mangroves has also led to the loss of fauna and other marine habitats and increased shoreline erosion (Ngoile and Shunula, 1992; Shunula, 2002) (Figure 1.5E-F and Figure 1.6C-D). Although mangroves in Zanzibar were listed as protected in 1968 (Semesi, 1998) and mangrove management is taken into account in policies, public awareness and conservation of mangrove resource (Nzioka, 2002; Taylor *et al.*, 2003; Spalding *et al*, 2010), there is still considerable concern for the sustainable utilization and management of ecosystems.

Review of mangrove pollen studies as indicators of sea level change

As mangrove zonation is related to environmental gradients, and tidal inundation (Blasco *et al.*, 1996), mangroves can be used as indicators of sea level changes (Woodroffe, 1990; Blasco *et al*., 1996;). Mangrove ecosystems enhance sedimentary deposition through their root structures (Woodroffe, 1992; Kristensen et al., 2008) and this can provide a useful archive to reconstruct environmental changes over time through the use of mangrove pollen. Mangrove pollen grains preserved in these sediments, therefore can be a useful tool for reconstructing patterns of ecosystem changes through vertical sediment accumulation. The surface pollen assemblages can be used as a modern analogue to interpret pollen records. Recently, Engelhart *et al.* (2007) studied mangrove pollen in Indonesia and assessed the relationship between the surface pollen assemblages and elevation. The surface samples which reflected species zonation were collected and the elevation measured along a transect in order to establish a relationship between mangrove zonation and altitude. Engelhart *et al.* (2007) developed a pollen transfer function from a modern analogue of surface pollen assemblages to predict the palaeo mangrove elevation.

Mangrove dynamics recorded in the Latin American region

Holocene vegetation changes in northern Brazil (Behling and Costa, 2001) revealed that by 7640 ^{14}C yr B.P. (at 565 cm depth) mangroves developed near the study area reflecting sea level rise. A subsequent decrease of *Rhizophora* after 7000 ^{14}C yr B.P. and increase of palm swamp suggested sea level then fell. There were some sea level fluctuations during 6620-3630 ^{14}C yr B.P. (at 400-155 cm depth) recorded by developments of palm swamp from 6620-6320 ^{14}C yr B.P. (at 400-350 cm depth) and 5790-4970 ^{14}C yr B.P. (at 300-245 cm depth) suggesting several oscillations of sea level change during this period. Around 3630 ^{14}C yr B.P. (at 155 cm depth), mangrove pollen increased indicating sea level transgression. During the last 1840 ^{14}C yr B.P. a fall in mangrove pollen suggests sea level is falling, or alternatively that human impact has affected this area as inferred by the presence of the modern shallow lake taxa after the road created an artificial dam and lake formation.

Sediment cores retrieved from the Bragança Peninsula, Northern Brazil (Cohen, *et al.*, 2005a; 2005b) recorded relative sea level changes occurring from the mid Holocene to late Holocene and the last millennium. The study suggested that mangroves developed at 5910-5660 cal yr B.P. (5115 ^{14}C yr B.P.) and the relative sea level was close to the present sea level at that time until falling sea level at around 1810-1610 cal yr B.P. to 930-800 cal yr B.P. (1830-1018 ^{14}C yr B.P.) occurred at a higher elevation area. Mangrove was replaced by terrestrial herbaceous taxa suggesting sea level then fell from around 470-320 cal yr B.P. (373 ^{14}C yr B.P.) (Cohen, *et al.*, 2005b). However, pollen analysis from other areas within the Peninsula indicated a lower sea level and/or drier conditions with less rainfall during the Little Ice Age. This study also revealed that mangroves shifted landward during the last decades suggesting a eustatic sea level rise due to global climate change and glacier melting.

Mangrove dynamics from Taperebal, Northeastern Pará State, Northern Brazil (Vedel *et al.*, 2006) suggested that a patch of coastal Amazon rain forest, restinga, salt marsh and some mangroves characterised by *Avicennia* covered this area during the early Holocene. Subsequently, mangroves characterised by *Rhizophora* succeeded in this area reflecting relative sea level rise from around 7420-7280 cal yr B.P. to 6850-6560 cal yr B.P. (6490 to 5946 ^{14}C yr B.P.). An hiatus between 115 and 85 cm possibly relates to a lower sea level during the late Holocene corresponding to other Brazilian coastal sites. Modern mangrove deposits above 85 cm suggest a rise in sea level in the last decades.

Mangrove dynamics in the Asian and Australian region

Hait and Behling (2009) studied mangrove and environmental changes at a coastal site in the Sundarban Biosphere Reserve, the western Ganga–Brahmaputra Delta, India. The high occurrence of mangrove pollen indicated an intertidal environment in this area during the last 10180-9530 cal yr B.P. (8800 ^{14}C yr B.P.). After 9400-9000 cal yr B.P. (8250 ^{14}C yr B.P.), mangrove forest disappeared suggesting a rapid transgression and a resultant shallow marine area. The re-colonization of mangroves suggests the return of an intertidal habitat at the site from 8420 (extrapolated date from 24.60 m depth) until 7560 cal yr B.P. (extrapolated date from 19.80 m depth,). Between 7560 (at 19.80 m depth) and 4850-4580 cal yr B.P. (4250 ^{14}C yr B.P.), the disappearance of mangrove, accompanied by the deposition of fluvial sediment indicated the loss of intertidal habitat due to sea level regression. The intertidal habitat reappeared again after 4850-4580 cal yr B.P. as evidenced by the presence of mangrove taxa.

The reconstruction of mangrove dynamics since the mid-Holocene in a coastal mangrove swamp of Hainan Island, southern China (Limi *et al.*, 2003) showed that mangroves occurred in this area during 7730-7180 cal yr B.P. to 6000-5330 cal yr B.P. (6650-5040 ^{14}C yr B.P.; at 760 to 488 cm depth) due to a highstand of sea level. The occurrence of mangrove plants decreased, concomitant with other terrestrial taxa increasing, after 6000-5330 cal yr B.P. (at about 488 cm depth) and until 3100 ^{14}C yr B.P. (extrapolated date from at about 300 cm depth) suggesting a slight regression of the sea. Mangroves developed with *Avicennia* and *Rhizophora* indicating sea level rise from 3100 ^{14}C yr B.P. (extrapolated date from at about 300 cm depth) to 2000 yr ^{14}C yr B.P. (extrapolated date from at about 210 cm depth). From this period to the present, mangroves declined and grasses increased, suggesting a lower sea level and probably recording the influence of human activities.

The palynological study of Senanivate housing area, Bangkok, central Thailand, by Somboon (1988) revealed that the freshwater taxa consisting of grasses and sedges were dominant before 8600-8420 cal yr B.P. (7800 ^{14}C yr B.P.) Mangroves subsequently replaced these suggesting an increase in sea level. This study also suggested that this area was situated on the coastline due to the mid Holocene marine transgression and that the sea covered most of the lower central plain of Thailand.

A study from Great Songkhla Lake, southern Thailand by Horton *et al.* (2005) revealed that this area was abundant in mangroves during 7920-7660 cal yr B.P. (6980 ^{14}C yr B.P.) and was subsequently replaced by freshwater swamps at 7920-7660 cal yr B.P. until 2700-2210 cal yr B.P. (2425 ^{14}C yr B.P.) when swamp forest developed as a result of a decrease in marine influence. Moreover, this study combined with other sea level index points from the Malay-Thai Peninsula was used to produce a sea level curve recording an increase in relative sea level from the early Holoocene to the mid Holocene highstand before falling to its present level.

The palynological investigation of the Songkhla Province, southern Thailand (Rugmai, 2006; Rugmai *et al.*, 2008), found that mangrove pollen were dominant indicating an intertidal zone from the Late Pleistocene at 34,450-33,330 cal yr B.P. (33870 ^{14}C yr B.P.) This suggests that the altitude of sea level was about 23 m below the present sea level and the shoreline had retreat about 2 km inland. From 34,450-33,330 cal yr B.P. to 9280-9000 cal yr B.P. (8,220 ^{14}C yr B.P.), few pollen were recorded due to a lower sea level and this area became dry causing oxidizing conditions as shown in the abundantly mottled sediment. After this period, the reoccurrence of mangrove pollen corresponds to a marine transgression during the mid Holcoene over the central Thailand (Somboon, 1988) before falling to the present sea level. The shoreline then retreated seaward when inland vegetation such as back mangrove, grasses, ferns, and lowland started to increase and replaced mangroves until the present day.

The study of two estuaries in Southern Irian Jaya, West Papua (Ellison, 2005) using mangrove pollen showed that mangroves occurred in two areas throughout the Holocene period. The elevation of the contemporary transition zone particularly represented by *Bruguiera*/*Rhizophora* provided the former mean sea level and was used to suggest a relative sea level rise during the late Holocene.

Mangrove dynamics in Africa

The study of the coastal sites from Bénin, West Africa (Tossou *et al.*, 2008) indicated that mangroves, characterised by *Rhizophora*, developed suggesting marine influence in this area during the Holocene from 8410-8170 cal yr B.P. to 2710-2340 cal yr B.P. (7529 to 2475 ^{14}C yr B.P.) This corresponded to the Nouackchottian transgression (5500 years). From 2710-2340 cal yr B.P. onwards, mangroves started to decline and were then completely replaced by freshwater vegetation representing less salinity due to a lower sea level during the late Holocene.

These studies demonstrate the use of pollen analysis to determine changes in mangrove compositions through the Holocene and demonstrate that mangrove dynamics can be used to infer past environmental changes including tectonism, climatic changes and also sea level fluctuations.

Review of the Holocene sea level history in East Africa

The East African coast situated in the Southwestern Indian Ocean (Woodroffe and Horton, 2005) lies in a "far-field" location considered to be situated at distances great enough that isostatic effects from large ice sheets are minimal (Clark *et al.*, 1978; Lambeck, 1993), and hence should provide a sensitive location in which to estimate eustatic sea level fluctuations. Eustatic sea level curves have been produced from various locations, and have used different proxies (Mörner, 1969; McMaster *et al.*, 1970; Fairbanks, 1989; Colonna *et al*, 1996). Eustatic sea level rise started to rise after the Last Glacial Maximum (20 Ka) (Mörner, 1971; 1992a). The record of sea level change from Barbados (Fairbanks, 1989) showed that the postglacial eustatic sea level was 120 m below the present sea level and continued rising with two rapid sea level rises relating to meltwater pulses and a transition phase around 11000 ^{14}C yr B.P. Sea level changes along the Southwestern Indian Ocean coast have been documented at various locations from a range of different proxies.

A study using cores from coral reefs, and dating and elevation of reef terraces on the Mayotte foreslopes in the Comoro Islands, Mauritius and Réunion Island (Camoin *et al*., 1997; 2004) produced a reconstruction of sea level change from the early deglaciation period (18,000-17,000 cal yr B.P.) and indicated that sea level had been 110-115 m below present sea level at that time. The evidence obtained from reef terraces also suggested a rapid sea level rise occurred from 10000 to 7500 cal yr B.P. and then a slower one until sea level stabilised at the present sea level around 3000 cal yr B.P. No higher sea levels than present sea level are recorded.

However, a more complex pattern of sea level change during the late Holocene was recognised from the coast of Mozambique. Jaritz *et al.* (1977) produced a sea level curve based on 20 radiocarbon dates. The sea level reached present sea level at 7000 ^{14}C yr B.P. and then recorded a highstand of 2.5-3 m above the present sea level about 6000 ^{14}C yr B.P. The sea level slowly declined to its present sea level between 2000-1000 ^{14}C yr B.P. Another study based on beachrocks along the southern Africa coastlines (Ramsay, 1995; Ramsay and Cooper, 2002) showed a highstand of 3.5 m above the present sea level at 5100 cal yr B.P (4650 ^{14}C yr B.P.). After 5100 cal yr B.P., fluctuations between marine regressions and transgressions continuously occurred. A minor highstand of 1.5 m above the present sea level at 1500 cal yr B.P. (1610 ^{14}C yr B.P.) was recorded before falling to its present sea level at 900 cal yr B.P. (910 ^{14}C yr B.P.). A study based on radiocarbon ages of sediment from a salt marsh on the southwest coast of Africa (Compton, 2001) suggested that there were two mid-late highstands of sea level. The first highstand occurred at 6700 cal yrs B.P. (5910 ^{14}C yr B.P.) and the second highstand occurred at 1200 cal yrs B.P. (1390 ^{14}C yr B.P.) corresponding to highstands recorded in Mozambique and southern Africa (Jaritz *et al.*, 1977; Ramsay, 1995). Moreover, a recent study using multi-proxy analyses from Macassa Bay, southern Mozambique indicates that two possible highstands occurred around 6600-6300 cal yr B.P. (5580 ^{14}C yr B.P.) and 4000-1100 cal yr B.P. (3740-1250 ^{14}C yr B.P.) before falling to present (Norström, *et al.*, 2012).

A study of massive fossil bones of giant tortoises and other vertebrates in Mauritius (Rijsdijk *et al.*, 2011) caused by mass mortality in a lake due to a lowering of lake water level suggested that sea level was 1.3 m below mean sea level between 4300-4100 cal yr B.P. measured by the maximum lowering of the groundwater level which can be approximated to the mean sea level. A megadrought event was subsequently inferred, a time that corresponds to the tropical African drought phase (Gasse 2000; Marchant and Hooghiemstra 2004). Sea level rose again after 4000 cal yr B.P. until it reached its present mean sea level inferred from the increase of mean water table.

Thus, there are discrepancies in the nature and timing of Holocene sea level fluctuations across the Indian Ocean. It is possible, however, that a more complex pattern of land uplift occurred along the East African coast related to the interplay of eustatic and isostatic and/or tectonic activities. Åse (1978; 1981) investigated geomorphological features of raised coastal terraces along the Kenyan coast. Eight levels were present probably relating to higher levels of the sea. The terraces at 10-11 m representing sea level 3000 years ago and the terraces at 1.5m dated to 500 years ago suggested that differential land uplift had occurred with greater uplift towards the north.

Studies of beach ridges and terraces along the Tanzanian and Zanzibar coastline (Alexander, 1969; Muzuka *et al.*, 2004) suggested minor sea level fluctuations and land uplift in the Wami Delta (the north Dar es Salaam) probably began 3600-6000 years ago following virtual cessation of eustatic sea level rise. The study of urbanization and sea level changes based on a archaeological data in East Africa including Zanzibar revealed no evidence for a Holocene highstand (Mörner, 1992). A sea level fall during the Medieval period around 600-800 cal yr B.P. corresponding to Åse (1981) was recorded. The study of shore terraces along the coastline of southern Kenya indicated that sea level fell in the late Medieval age *circa* 500 years ago (Åse, 1981).

It would seem that the studies on sea level changes within the Southwest Indian Ocean are conflictory on the magnitude of any fluctuations and there is considerable uncertainty on the timing and duration of Holocene sea level fluctuations for several reasons (Figure 1.8). The indicative meaning of the sea level index points may not be comparable and different reference datum levels may have been used. In addition, there may be differences in the isostatic history of the locations and these issues may be hampered by dating uncertainties.

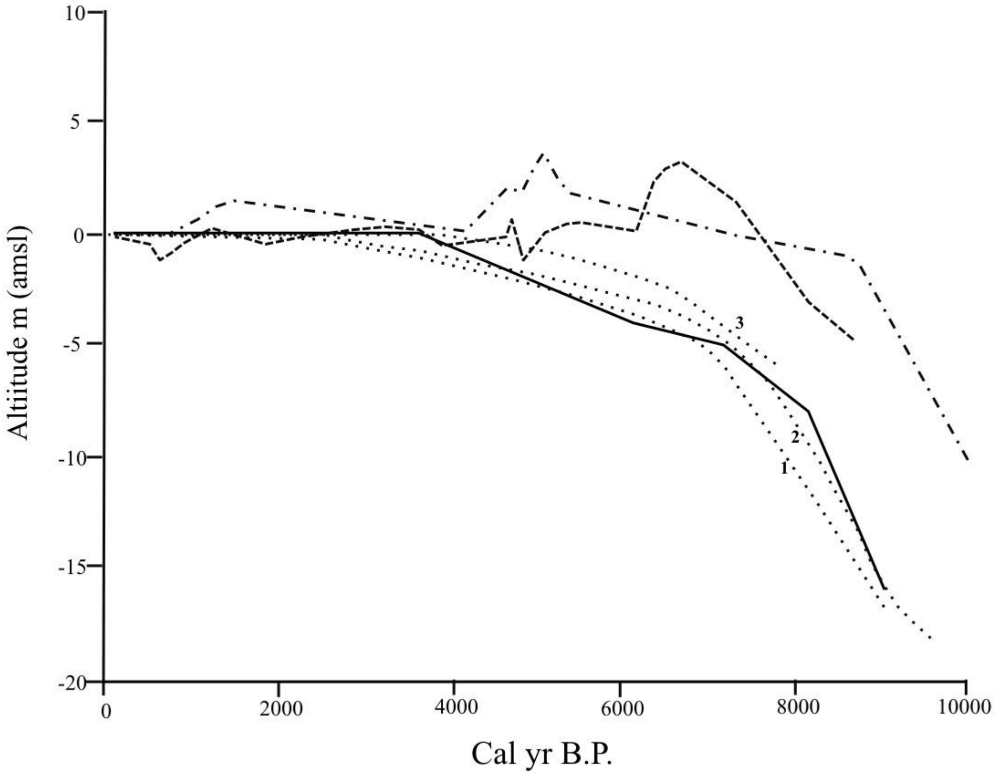

Figure 1.8. Composite diagram showing Holocene sea level curves in the Southwest Indian Ocean region (with calibrated dates). (Ramsay and Cooper (2002) in dash-dotted line and Compton (2001) in dashed line and Mauritius (1), Mayotte (2) and Réunion (Camoin et al. (1997; 2004) in dotted line and Zinke *et al*. (2003) in solid line.

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Chapter 2: Holocene mangrove dynamics and environmental change in the Rufiji Delta, Tanzania

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Abstract Holocene mangrove dynamics are reconstructed from pollen, sediment and radiocarbon analyses on three cores (ANR, BNR, CNR) located across a 20 km transect in the Rufiji Delta, Tanzania. At the base of the sediment sequence, dated to about 5600 cal yr B.P., the mangroves which are present suggest a low intertidal ecosystem in response to wet conditions and a higher sea level than at the present day. After around 5600 cal yr B.P. in core BNR, mangroves retreated seaward probably due to a lower sea level and drier environmental conditions. At around 4640 cal yr B.P., mangroves shifted landward suggestive of a phase sea level rise. In the late Holocene, mangroves became established at higher elevations of the Rufiji Delta, which is now a paddy field. Mangrove taxa decreased after 1170 cal yr B.P. suggesting drier conditions and less inundation frequency, possibly due to a lower sea level. Marked vegetation changes from mangroves to terrestrial vegetation occurred after around 750 cal yr B.P. possibly related to sea level regression and/or a desiccation phase recorded during the late Holocene. Paddy fields replaced mangroves in the landward part of the transect, reflecting an increase in human settlement in this area, a trend that continues to the present day. The recent decrease of mangrove species, particularly *Rhizophora mucronata*, could suggest less inundation by saline water and a lower sea level, although these changes may also be due to human activities during the last millennia as indicated by charcoal analysis.

Keywords Sea level · Holocene · Pollen analysis · Estuarine environment · Charcoal analysis

Introduction

Mangroves or mangrove communities comprise evergreen trees and shrubs that are physiologically and morphologically adapted to grow in the intertidal zone between mean sea level and high water spring level (Woodroffe and Grindrod, 1991; Blasco *et al.*, 1996; Ellison and Farnsworth 2001; Ellison 2008). Mangrove ecosystem composition reflects inundation frequency, salinity and nutrient availability (Blasco *et al.*, 1996; Hogarth, 1999) by migrating to landward or seaward with a rise or fall in sea level, respectively (Figure 2.1). Pollen analysis of vertically accumulated sediments can be used to reconstruct past mangrove dynamics (Cohen *et al.*, 2005; Horton *et al.*, 2005; Vedel *et al.*, 2006; Engelhart *et al.*, 2007; Ellison 2008; Tossou *et al.*, 2008; Hait and Behling, 2009). By reconstructing past vegetation changes, mangrove zonation can be established and related to sea level fluctuations through comparison with contemporary vegetation assemblages.

In addition to sea level, other factors such as precipitation and human interaction with mangroves also influence ecosystem composition (Gilman *et al.*, 2008). Changes in rainfall pattern have a significant influence on freshwater runoff, fluvial sediment and nutrient inputs which affects the salinity and the resultant composition of the mangrove ecosystem (Nicholson and Flohn, 1980; Kjerfve, 1990; Hughes *et al.*, 1998; Saintilan and Williams, 1999; Saintilan and Wilton, 2001; Alongi 2008; Gilman *et al.*, 2008; Eslami-Andargoli *et al.*, 2009). Conversely, drought can result in a decrease in mangrove development: low duration and intensity of rainfall, combined with high evaporation rates, can result in hypersaline conditions (Snedaker, 1995; Ellison, 2000; Gilman *et al.*, 2008; Mikhailov and Isupova, 2008). Regional rainfall patterns therefore affect coastal and estuarine mangrove ecosystems. Despite the considerable potential, only few records of Holocene sea level changes in Tanzania have been produced (Alexander, 1969; Muzuka *et al.*, 2004). Studies from the southwest Indian Ocean region using a range of different geomorphological proxies such as reef terrace and raised platforms (Alexander, 1969; Jaritz *et al.*, 1977; Åse, 1981; Ramsay, 1995; Camoin *et al.*, 1997, 2004; Compton, 2001; Ramsay and Cooper, 2002;

Muzuka *et al.*, 2004) are conflicting and there is considerable uncertainty on the timing, character and duration of Holocene sea level fluctuations. Coastal vegetation dynamics in East Africa are particularly poorly constrained with no pollen studies undertaken to date within the mangrove ecosystem. This study reconstructs mangrove dynamics from the Rufiji Delta, Tanzania using pollen and stratigraphical analyses, set within a chronological framework from radiocarbon dating.

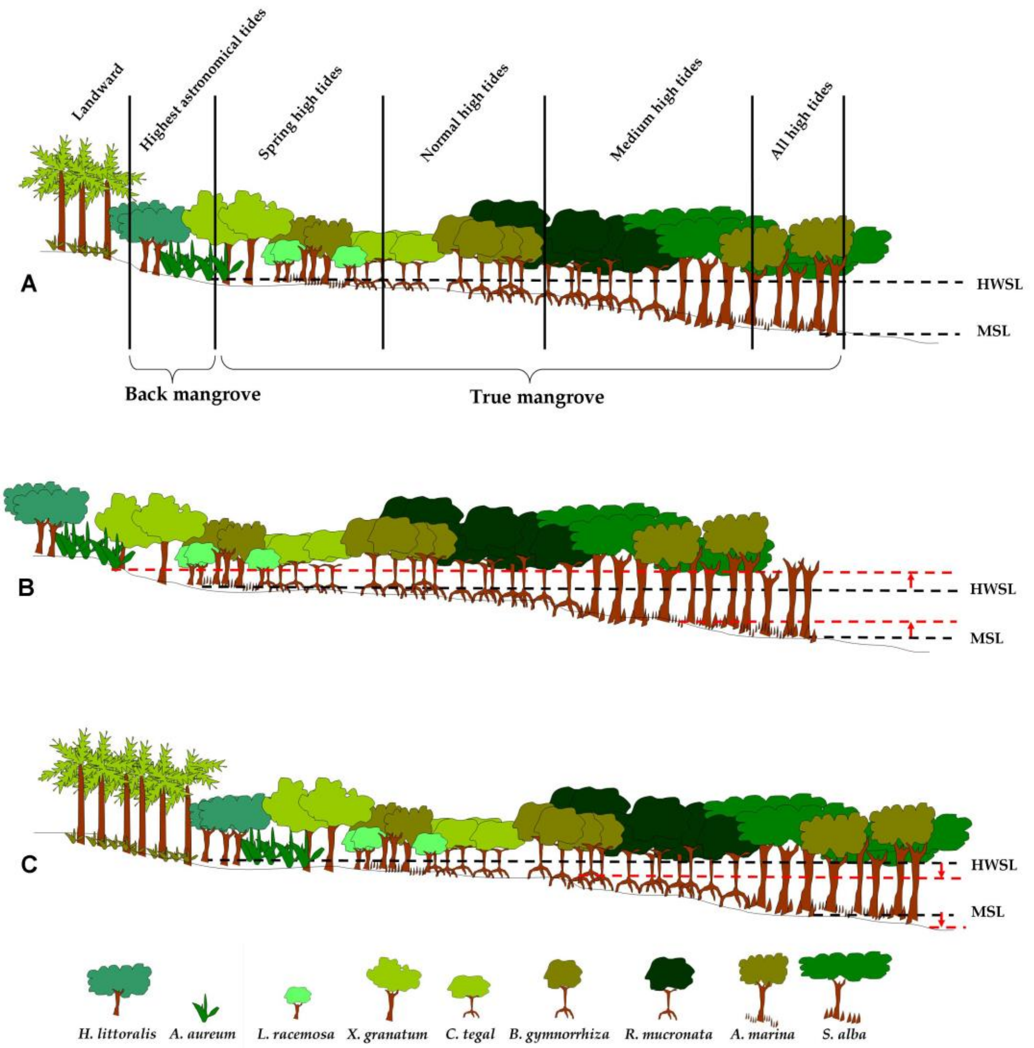

Figure 2.1. A typical association of Rufiji Delta mangroves showing response to sea level change. A, Summary cross section through mangroves showing typical zonation in the Rufiji Delta developed from Watson's (1928) and Santisuk's (1983) inundation classes and personal field observations; B, Sea level rise relative to mangrove surface causes seaward margin erosion and mangroves

migration of landward and seaward margins to landward. C, Sea level fall relative to mangrove surface causes migration of mangrove association to seaward

Study site

Location

The Rufiji Delta, situated on the Tanzanian coast (Figure 2.2), contains the largest, continuous and best-developed estuarine mangroves of the East African coastline (Nshubemuki, 1993; Fisher *et al.*, 1994; Richmond *et al.*, 2002; Masalu, 2003). The mangrove ecosystem extends to around 53,200 ha (Francis, 1992; Semesi, 1992) and can be divided between the northern and southern delta. The delta is crucial to the livelihoods of people living in the wider Rufiji region and is one of the most important wetland areas in East Africa (Doody and Hamerlynck, 2003). The Rufiji Delta mangroves provide poles, timber for fences, houses, boats, fish traps and firewood (Semesi, 1992; FAO, 2007) and are an important habitat and nursery ground for fish, shrimps and crabs, therefore supporting a productive fishery (Semesi, 1992; Turpie, 2000). Mangroves also provide protection against coastal flooding and wave erosion (TCMP, 2001).

Geology and geomorphology

The Rufiji deltaic sediments are mainly characterised by alluvial sand, silt and clay which is transported from the Rufiji basin into the Indian Ocean. A series of sand spit islands and submerged sand bars have formed parallel to the coast (Semesi, 1992; Fisher *et al.*, 1994). The delta is characterised by a large area of mangroves found along tidal channels and numerous tidal creeks. Upstream of the delta, rice cultivation is the main land use. The average semi-diurnal tidal range is 2-2.5 m, rising to approximately 3.3-4.3 m on high spring tides (Francis, 1992; Fisher *et al.*, 1994; Richmond *et al.*, 2002).

Climate

Climate within the Rufiji Delta is largely controlled by the north and south migration of the Inter-tropical Convergence Zone (ITCZ). The northeast monsoon dominates from December to April bringing abundant precipitation of an average of 100-280 mm month^{-1} (Goudie, 1996; Nicholson, 2001). The southeast monsoon prevails from May to November with an average monthly precipitation of 10-120 mm (Fisher *et al.*, 1994; Turpie, 2000; Richmond *et al.*, 2002; Doody and Hamerlynck, 2003). The other variable that also influences rainfall pattern is sea surface temperature variation in the Indian Ocean (Saji *et al.*, 1999; Behera *et al.*, 2003; Marchant *et al.*, 2007). The mean annual rainfall is about 1200 mm yr^{-1} (Semesi, 1992) and the temperature range throughout the year is 24-31 ºC (Richmond *et al.*, 2002).

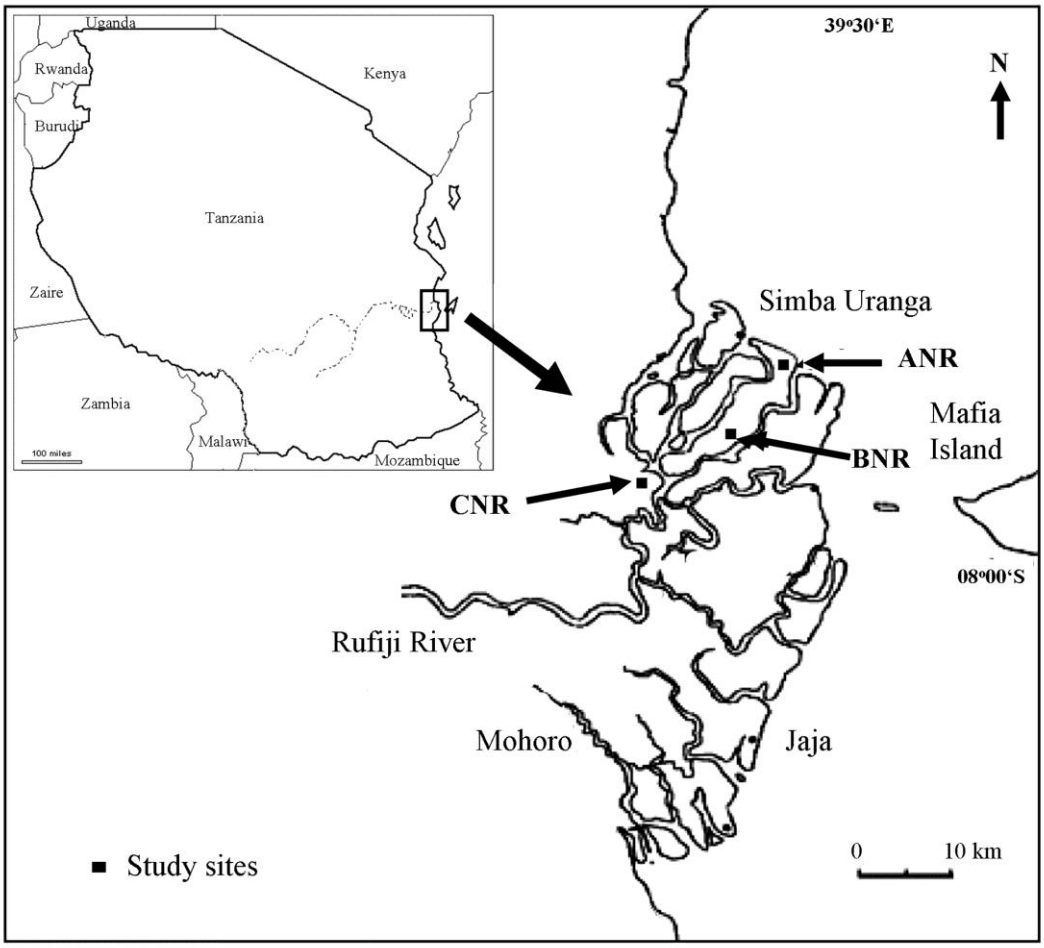

Figure. 2.2. Map of the Rufiji Delta showing the location of the study site and position of the sediment cores

Material and methods

Fieldwork and sampling

Three sediment cores, ANR (7°47'22"S, 39°23'59"E) seaward, BNR (7°51'25"S, 39°20'26"E) central, and CNR (7°54'07"S, 39°15'04"E) landward were extracted from the northern part of the Rufiji Delta along a seaward to landward transect in July 2009 (Figure 2.2). Altitudinal heights were obtained using a differential GPS (Leica TCRA Total Station). A peat auger was used to test the stratigraphy and identify the best location to extract a sample core from overlapping adjacent boreholes, using a Russian corer 50 cm long and 5 cm diameter. The characteristics of sediments were described using a modified version (Kershaw, 1997) of the Tröels-Smith (1955) classification. The sample cores were extruded into P.V.C. pipes, wrapped in aluminium foil and plastic sheet and then labelled and packaged for transport to the University of York, UK, where they were stored at -18ºC. A vegetation survey along the transect (altitudinal and horizontal gradient) was conducted, focussed around the core locations, to establish mangrove zonation in the Rufiji Delta. Modern mangrove specimens and anthers for pollen identification were collected under the supervision of a botanist while 10 m^2 vegetation plots were set up to establish plant percentages at each core location.

Chronology

Nine bulk sediment samples were selected for AMS dating and submitted to Radiocarbon Dating Laboratories at the University of Waikato, New Zealand and the CHRONO Centre, Queen's University Belfast, UK. Range-finder dates were analysed at the start of the laboratory work with targeted dating taking place once analytical work had been completed to date biostratigraphic changes. The dates were calibrated with the southern hemisphere calibration of Shcal04 curve (McCormac *et al.*, 2004) using the software OxCal v4.10 (Bronk-Ramsey, 2009).

Palaeoecological analysis

2 cm^3 of sediment was sub-sampled at intervals of 10 cm along the length of each core for pollen analysis and measurements of loss on ignition (LOI). LOI followed standard protocol (Heiri *et al.*, 2001) and included organic carbon and carbonate measurement by ignition at 550ºC and 950ºC respectively. Pollen and spores were extracted by a combination of an adaptation of the 'swirling technique' used by Hunt (1985) and Finch *et al.*, (2009) and the acetolysis method (Erdtmann, 1969; Fægri and Iversen, 1989). Sample residues were stored in Aquamount and silicone oil. Pollen and spores were identified by comparison with extant mangrove pollen specimens collected from the study areas and modern mangrove references (Thanikaimoni, 1987; Punwong, 2008) and more than 93% of grains were identified. However, most of the unidentified grains were separate taxa. *Bruguiera gymnorrhiza* and *Ceriops tegal* could not be distinguished under light microscopy (Grindrod, 1985) and were grouped together as *Bruguiera/Ceriops* type.

The East African coast has a low biodiversity due to high salinity, anaerobic sediments, acidic soils and unstable substrates (Wang *et al.*, 2003) and therefore to determine the optimal pollen grain count, pollen and spores in four samples from each site were counted and the number of taxa recorded every 20 grains up to count of 200 grains. After 80 grains regardless of sample location the number of new taxa did not increase, although up to this number there had been additional taxa with more grains counted (Figure 2.3). 150 pollen grains were counted per level after establishing that this number was sufficient to identify any new taxa through a series of plots of grains counted against number of taxa found, and by comparison to other mangrove studies (Ellison, 1989). The stratigraphic pollen data are presented as percentage pollen frequency diagrams using stratigraphically constrained cluster analysis, CONISS, to zone the pollen data based on the sum of pollen and spores. The diagrams were drawn using TILIA2 and TILIA*Graph (Grimm, 1991).

The pollen data, in combination with the radiocarbon chronology, suggest that human impacts were recorded within the sediment from the CNR core site. This core was therefore selected for charcoal analysis. Charcoal content and size analysis on the pollen slide were conducted to reconstruct fire history using the size class of microscopic charcoal modified from Tinner and Hu (2003). The charcoal counts for each size class are presented as the total number of fragments enumerated within a complete slide. The total charcoal accumulation is expressed for each size class and totalled, summing the multiples of the mean length of each size class with the quantity of fragments per calculated area of each sample slide. The microscopic size class charcoal analysis can potentially be used for separation between local and regional charcoal signals (Clark, 1988). Samples were also prepared for diatom analysis, but there was very low diatom preservation in all three sediment cores, probably due to diatom dissolution affected by the high salinity and temperature conditions in the mangrove environment, which prevented a complete count being undertaken (Barker *et al.*, 1994; Reed, 1998).

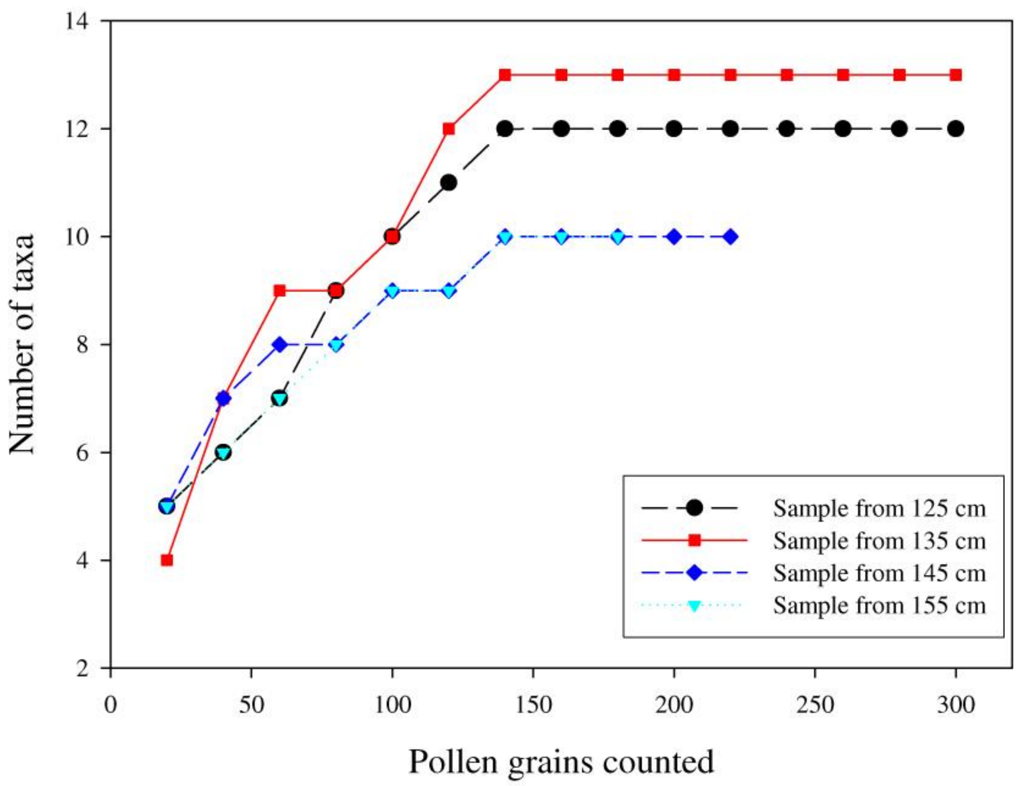

Figure 2.3. Graph showing the number of taxa against pollen grains counted from BNR core

Results

Vegetation observation and site description

Mangrove ecosystems in the Rufiji Delta are characterised by a variety of species growing along the fringes of shorelines and the edges of rivers and creeks. Nine common mangrove species are found in the Rufiji Delta, which form a distinct vegetation zonation depending on inundation frequency and the amount of freshwater input to the estuarine system. A zonation of the Rufiji Delta mangrove ecosystems has been developed based on a combination of Watson's (1928) and Santisuk's (1983) inundation classes and field based observations (Figure 2.1). The understanding of the contemporary mangrove zonation is used to aid the interpretation of ecosystem and environmental changes through the fossil record. *Avicennia marina* and *Sonneratia alba* are pioneer species found at the seaward edges inundated by medium to all high tides, although *A. marina* also appears in more landward locations. *Rhizophora mucronata* and *Bruguiera gymnorrhiza* form a thick belt in the inner mangroves. *R. mucronata* sometimes occurs in large homogeneous stands along the creeks. *B. gymnorrhiza* is typically found in the middle mangroves between *R. mucronata* and *Ceriops tegal* and appears in the area inundated by normal high tides. *C. tegal* and *Lumnitzera racemosa* appear in the upper intertidal and dry areas inundated by normal to spring high tides. *Xylocarpus granatum* is a high intertidal species which occurs in landward fringes where environmental conditions are less saline but inundated by spring high tides. *X. granatum* is tolerant of more freshwater influence. These seven species are categorised as "mangrove" while *Heritiera littoralis* and *Acrostichum aureum* are characterised as "back mangrove". *H. littoralis* is found on river banks characterised by low salinity and on landward areas usually flooded only by the highest astronomical tides. *A. aureum* appears in a transition zone to freshwater swamp.

The ANR core site is located 2.93 m above mean sea level (amsl) on a long large intertidal flat area about 300 m from the Indian Ocean, where sand bars run parallel to the seaward edge. ANR is exposed to considerable wave action and the surrounding area is dominated by *Avicennia marina* trees (100%). The BNR core site is located in the middle of dense mangrove forest about 10 km away from the Indian Ocean and 3.44 m amsl. This area is influenced by both tidal inundation and freshwater flow, the influence of fluvial activity being particularly important in the wet season. Surrounding the core site *Xylocarpus granatum* trees (75%) form a dense canopy and are associated with *Acrostichum aureum* (5%), *Ceriops tegal* (5%) and *Rhizophora mucronata* (15%). The CNR core site is located at the landward margin of the mangrove ecosystem approximately 1.3 km away from the influence of the main tributary, about 21 km from the sea and 3.51 m amsl. It is located on a large flat area occupied by sedges (80%), grasses (15%), and *Acrostichum aureum* (5%). A paddy field with associated *Heritiera littoralis* trees, *Barringtonia*, *Phoenix* palm trees and *Stenochlaena* sp. climber ferns surround the sampling site. This area also has some remnant mangrove trees and is sporadically flooded by river flows from December to April.

Stratigraphy and loss on ignition

The detailed stratigraphic descriptions of the three cores are given as ESM. The deepest sediments of BNR and CNR comprise organic matter and silt. Organic material including root fragments increase in the upper unit to the top of the core, where wood and bark fragments are also present. The boundaries between stratigraphic units in all three cores are transitional.

Organic carbon and carbonate content throughout three cores are low with 1-20% and 3-19%, respectively (Figures 2.4, 2.5, 2.6). ANR shows very low organic carbon content (1%) at the base within the sand layer where the highest values of carbonate content occur (11-19%) followed by increased organic carbon content (between 7-16%) throughout the core. Organic carbon content of BNR is between 7-20% in the lower units. However towards the top of the core at a depth of 65 cm there is an increase and a peak at 25 cm depth (20%) probably relating to the penetration of mangrove roots accompanied by decreased carbonate content. The carbonate curve is low throughout core BNR (3-10%), although pronounced peaks occur at depths of 205 cm and 385 cm. No shell fragments or sand were observed, so it is unclear why peaks of carbonate content have occurred. CNR also shows constant organic carbon content throughout the core with some peaks at 65 cm and 95 cm depth probably relating to increased root fragments included within the clay deposit from 35 to 115 cm depth. The carbonate content of CNR decreases towards the top of the core at a depth of 65 cm. The organic carbon content in the three cores does not show any distinct correlation to any dominant pollen taxa.

Chronology

Nine radiocarbon dates have been obtained from the three cores, one from core ANR, five from BNR and three from CNR (Table 2.1). A comparative age-depth relationship plot for the cores (Figure 2.7) shows a complex age-depth relationship using a linear interpolation of calibrated dates. It should be noted that the zero origin on all such graphs does not necessarily imply present day because of potential surface erosion. The calibrated radiocarbon dates indicate that the sediment deposits accumulated relatively continuously in the lower section of the cores, although the results from the upper part of core BNR (19 cm) and CNR (115 cm) are likely to represent at least one sedimentary hiatus. All dates presented in the text are calibrated according to Shcal04 curve (McCormac *et al.*, 2004), using the software OxCal v4.10 (Bronk-Ramsey, 2009) and quoted as the age range and median of calibrated dates.

Pollen analysis

11 angiosperms, one gymnosperm and five pteridophyte taxa were identified. Fossil pollen and spores are grouped into mangrove, back mangrove, terrestrial, herbaceous and pteridophytes. Mangrove and back mangrove are defined through field observation of modern ecological occurrences of mangrove taxa and from Watson's (1928) and Santisuk's (1983) inundation classes and are used to aid the interpretation of environmental conditions and sea level changes. Contemporary vegetation assemblages observed in the field revealed a distinct vertical and horizontal relationship with present sea level. The reconstruction of past sea level changes is therefore done by interpretation of the dominant mangrove taxa within the pollen record. Therefore, *Avicennia marina* dominates the environmental interpretation for ANR as it dominates the pollen assemblage at this location, and *Rhizophora mucronata* is used for interpretation as it dominates

the pollen assemblages in the coring sites BNR and CNR. The pollen zones of the three cores are described in Table 2.2.

Charcoal analysis

Charcoal abundance of the base of core CNR between the depths of 445 cm and 415 cm is relatively low and stable from 3-6 fragments mm^{-2} (Figure 2.8). From 385 cm to 305 cm, total charcoal accumulation increases (12-29 fragments mm^{-2}) particularly in the large charcoal class size of >60 µm. From 295 cm to 85 cm, the charcoal record is more variable (8-29 fragments mm^{-2}) with some peaks in the total charcoal accumulation. These peaks are related to the rise in both small and larger particles. There is a notable rise in the total charcoal accumulation from 75 cm to 5 cm, with an increase in both small and large particles (30-80 fragments mm^{-2}) with a clear peak of large particles (>60 µm) at 45 cm. Changes in total charcoal accumulation, especially in larger particles, agree well with the pollen zone boundaries of CNR.

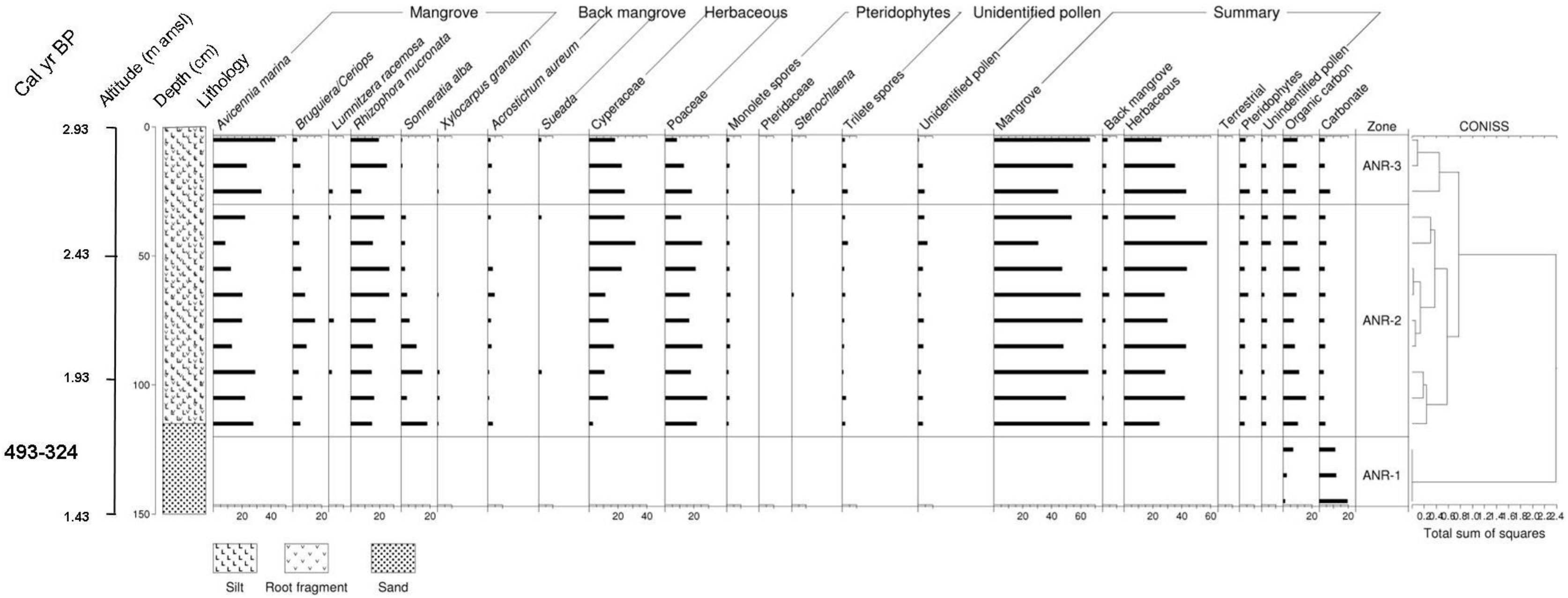

Figure 2.4 Pollen diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the seaward site of northern Rufiji Delta (ANR)

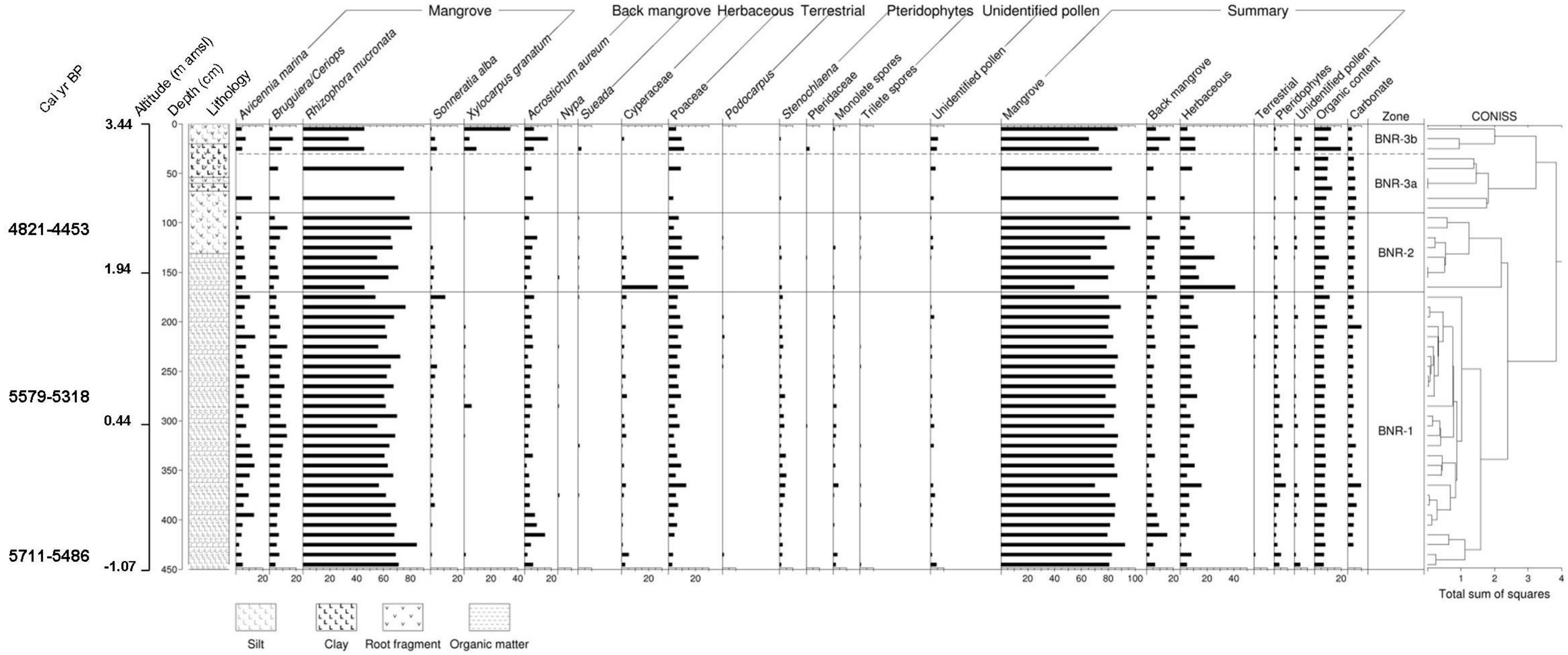

Figure 2.5 Pollen diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the central site of northern Rufiji Delta (BNR)

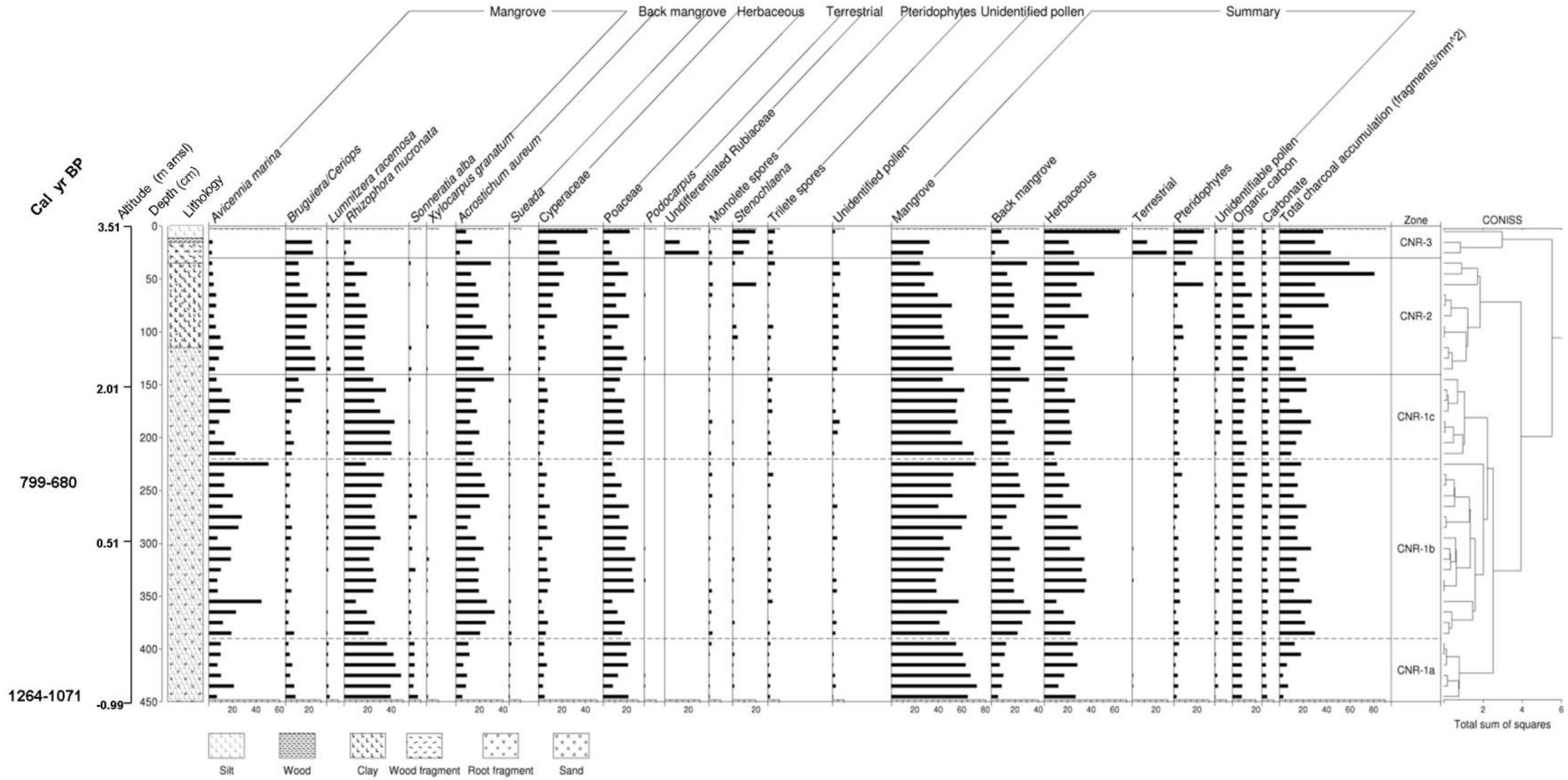

Figure 2.6 Pollen diagram showing percentage pollen frequency, organic carbon, carbonate profiles, and total charcoal accumulation from the landward site of northern Rufiji Delta (CNR)

Table 2.1. List of radiocarbon dates from northern Rufiji Delta including calibrated ages of Shcal04 curve (McCormac *et al.*, 2004) using the software OxCal v4.10 Bronk-Ramsey (2009).

Site	**Altitude amsl (m)**	**Depth (cm)**	**Code**	**$\delta^{13}C$**	**% Modern**	**^{14}C yr B.P.**	**(2σ) Calibrated age range yr B.P.**	**Calibrated age yr B.P.**	**Median of calibrated age yr B.P.**
ANR	1.65	128	Wk-26854	-25.7 ± 0.2	95.2 ± 0.2	392 ± 30	493-324	409 ± 85	400
BNR	3.25	19	UBA-15385	-22	119.12 ± 0.3	> A.D.1950			
BNR	2.98	46	UBA-15386			Failure to make graphite			
BNR	2.37	107	Wk-26855	-23.0 ± 0.2	59.5 ± 0.1	4167 ± 30	4821-4453	4637 ± 184	4637
BNR	0.64	280	Wk-26856	-23.1 ± 0.2	55.4 ± 0.1	4751 ± 30	5579-5318	5449 ± 131	5406
BNR	-0.99	443	Wk-26857	-22.4 ± 0.2	54.1 ± 0.1	4931 ± 30	5711-5486	5599 ± 113	5614
CNR	2.36	115	UBA-15387	-29.5	103.44 ± 0.3	> A.D 1950.			
CNR	1.09	242	Wk-26858	-23.1 ± 0.2	89.6 ± 0.2	884 ± 31	799-680	740 ± 60	747
CNR	-0.94	445	Wk-26859	-20.5 ± 0.2	85.1 ± 0.1	1292 ± 30	1264-1071	1168 ± 97	1173

Table 2.2. Pollen zone characteristics for the seaward site of northern Rufiji Delta (ANR), for the central site of northern Rufiji Delta (BNR) and for the landward site of northern Rufiji Delta.

Pollen zone	Pollen zone description	Environmental interpretation
ANR-3 2.93-2.63 m amsl depth 0-30 cm	Mangrove dominated by *Avicennia marina*, decline of herbs Mangrove: *A. marina* (23-43%), *Bruguiera/Ceriops* (1-6%), *Lumnitzera racemosa* (2.5%), *Rhizophora mucronata* (7-25%), *Sonneratia alba* (<1%) Back mangrove group (2-3%). Herbs (26-43%). Pteridophyte spores (4-7%). No terrestrial pollen	Mangroves recovered, as indicated by increased *A. marina* probably due to wetter conditions or increased sea level; increased inundation
ANR-2 2.63-1.78 m amsl depth 30-115 cm	Mangrove dominated by *A. marina*, then decrease while herbaceous plants increase toward the top Mangrove: *A. marina* (12-27%), *R. mucronata* (15-27%), *Bruguiera/Ceriops* (4-15%), *L. racemosa* (2%), *S. alba* (3-18%), *Xylocarpus granatum* (1-5%). Back mangrove (<3%). Herbs (25-57%). Pteridophyte spores (2-7%). No terrestrial pollen	Mangroves established probably due to wet conditions or increased sea level at the beginning inundated by medium high to all high tides indicated by the predominance of *A. marina*. Mangroves retreated seaward indicated by decreased *A. marina* and increased herbaceous vegetation probably due to drier conditions or lower sea level with less inundation
ANR-1 1.28 m amsl depth 115-150 cm	Very poor pollen and spore preservation	Not possible

Table 2.2. Pollen zone characteristics for the seaward site of northern Rufiji Delta (ANR), for the central site of northern Rufiji Delta (BNR) and for the landward site of northern Rufiji Delta (cont.).

Pollen zone	Pollen zone description	Environmental interpretation
BNR-3(a-b) 3.44-2.54 m amsl depth 0-90 cm	Mangrove increases at the beginning, declines at the top Mangrove: *R. mucronata* declines (30-75%) while *X. granatum* increases at the top (4-34%), *A. marina* (4-7%), *S. alba* (1-5%), *Bruguiera/Ceriops* (2-17%). Back mangrove increase towards the top (7-17% dominated by *Acrostichum* spores). Herbs increase (5-11%). Pteridophyte spores (<2%). No terrestrial pollen	Mangroves retreated seaward indicated by decreased *R. mucronata* and increased *X. granatum* and back mangrove probably due to drier conditions or lower sea level with less inundation
BNR-2 3.54-1.74 m amsl depth 90-170 cm	Mangrove declines at the beginning, gradually rises at the top, in contrast to herbs Mangrove: *R. mucronata* (46-81%). *A. marina* (2-11%), *Bruguiera/Ceriops* (3-13%), *S. alba* (<3%). Back mangrove low (0-10%). Herbs (3-41%). Pteridophyte spores low (<3%). Almost no terrestrial pollen	Mangroves retreated to seawards at the beginning, indicated by decreased *R. mucronata* and increased herbaceous vegetation, probably due to drier conditions or lower sea level at the beginning of this zone. Less inundation. Mangroves gradually increase again, indicated by increased *R. mucronata* and decreased herbaceous vegetation probably due to wetter conditions or increased sea level and inundation
BNR-1 1.74-(-1.01) m amsl depth 170-445 cm	Mangrove dominates with the majority of *R. mucronata* Mangrove: *R. mucronata* (54-85%), *A. marina* (2-14%), *Bruguiera/Ceriops* (4-13%), *S. alba* (1-11%). Back mangrove (1-15%). Herbs (1-16%). Pteridophyte spores (1-9%). Terrestrial pollen low (<1%)	Mangroves established, as indicated by the high occurrence of *R. mucronata* probably due to wet conditions or high sea level. Inundated by normal to medium high tides
CNR-3 3.51-3.21 m amsl depth 0-30 cm	Sudden reduction of *R. mucronata* at the top. Mangrove completely disappears, replaced by herbs Mangrove: *R. mucronata* (0-5%), *Bruguiera/Ceriops* (22-23%), *A. marina* (<3%), *S. alba* (<1%). Back mangrove (3-15%). Herbs (21-64%). Terrestrial assemblage: undiff. Rubiaceae (29%). Pteridophyte spores (16-26%)	Mangroves retreated seawards and were completely replaced by terrestrial taxa due to drier conditions or sea level regression. Inundation by high spring to highest astronomical tides

Table 2.2. Pollen zone characteristics for the seaward site of northern Rufiji Delta (ANR), for the central site of northern Rufiji Delta (BNR) and for the landward site of northern Rufiji Delta (cont.).

Pollen zone	Pollen zone description	Environmental interpretation
CNR-2 3.21-2.11 m amsl depth 30-140 cm	Mangrove gradually declines; *Ceriops/Bruguiera* dominates and rises, *R. mucronata* declines, herbs rise Mangrove: *Ceriops/Bruguiera* (11-26%), *A. marina* (3-12%), *L. racemosa* (1-3%) *R. mucronata* (8-19%), *S. alba* (<2%), *X. granatum* (<1%). Back mangrove (13-31%). Herbs (12-42%). Pteridophyte spores (1- 25%). No terrestrial pollen	Mangroves continued retreating to seawards indicated by decreased *R. mucronata* and increased *Bruguiera/Ceriops*, back mangrove and herbaceous vegetation probably due to drier conditions or continuing lower sea level with less inundation by normal to high spring tides
CNR-1c 2.11-1.31 m amsl depth 140-220 cm	Mangrove characterised by *R. mucronata*, rises at the beginning, declines at the top while back mangrove and herbs behave the opposite way. Mangrove: *R. mucronata* (25-42%), *A. marina* (5-22%), *Bruguiera/Ceriops* rises at the top (5-15%), *L. racemosa* (1-2%), *S. alba* (<2%), *X. granatum* (<1%). Back mangrove (12-31%). Herbs (8-26%). Pteridophyte spores (<3%). No terrestrial pollen	Mangroves migrated landward indicated by increased *R. mucronata* probably due to wetter conditions or higher sea level with more inundation at the beginning but mangroves retreated seaward indicated by decreased *R. mucronata* and increased *Bruguiera/Ceriops* and back mangrove at the top of the zone due to drier conditions or lower sea level with less inundation
CNR-1b 1.31-(-0.39) m amsl depth 220-390 cm	Mangrove characterised by *R. mucronata* decreases while back mangrove and herbaceous assemblage increase at the beginning. After that there are variations between mangrove, back mangrove and herbaceous plants until the top Mangrove: *R. mucronata* (10-34%). *Bruguiera/Ceriops* (1-7%), *L. racemosa* (<2%), *S. alba* (1-7%), *X. granatum* (<1%), *A. marina* (varying from 7 up to 50% at the top). Back mangrove (12-33%). Herbs (10-36%). Pteridophyte spores low (1-7%). Terrestrial pollen very low (<1%)	Mangroves retreated seawards indicated by decreased *R. mucronata* probably due to drier conditions or lower sea level with less inundation. Dynamic mangrove zones indicated by variations of *R. mucronata*, back mangrove and herbaceous taxa probably due to fluctuating sea level. Possible rise in sea level at the top indicated by an increase in *A. marina*
CNR-1a (-0.39)-(-0.94) m amsl depth 390-445 cm	Mangrove characterised by *R. mucronata* Mangrove: *R. mucronata* (36-48%), *A. marina* (7-21%), *Bruguiera/Ceriops* (3-8%), *L. racemosa* (1-2%), *S. alba* (4-8%), *X. granatum* (<1%). Back mangrove (6-12%). Herbs (12-29%). Peridophyte spores low (1-5%). Terrestrial pollen very low (<1%)	Mangroves established, indicated by the predominance of *R. mucronata*, probably due to wet conditions or increased sea level. Inundated by medium to normal high tides

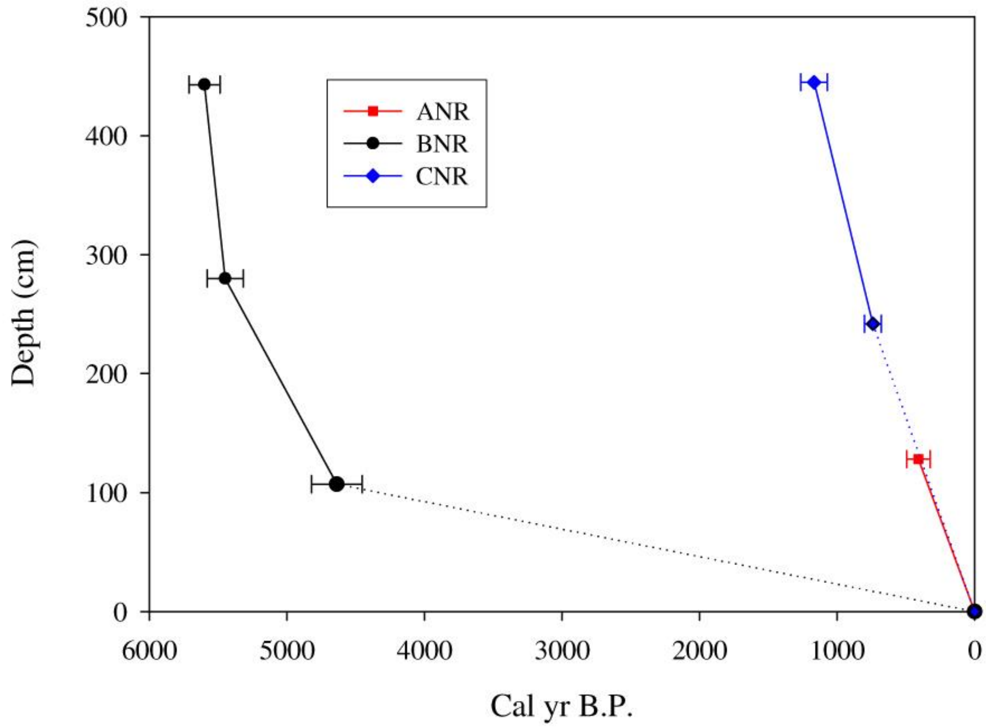

Figure 2.7 Age-depth relationship plot of three cores, seaward (ANR), central (BNR), and landward (CNR) using linear interpolation of calibrated ages. The solid line represents the relationship between age and depth. The dotted line represents an uncertain date age relationship and most likely containing sedimentary hiatuses. For the exact meaning of zero years (origin), see page 79.

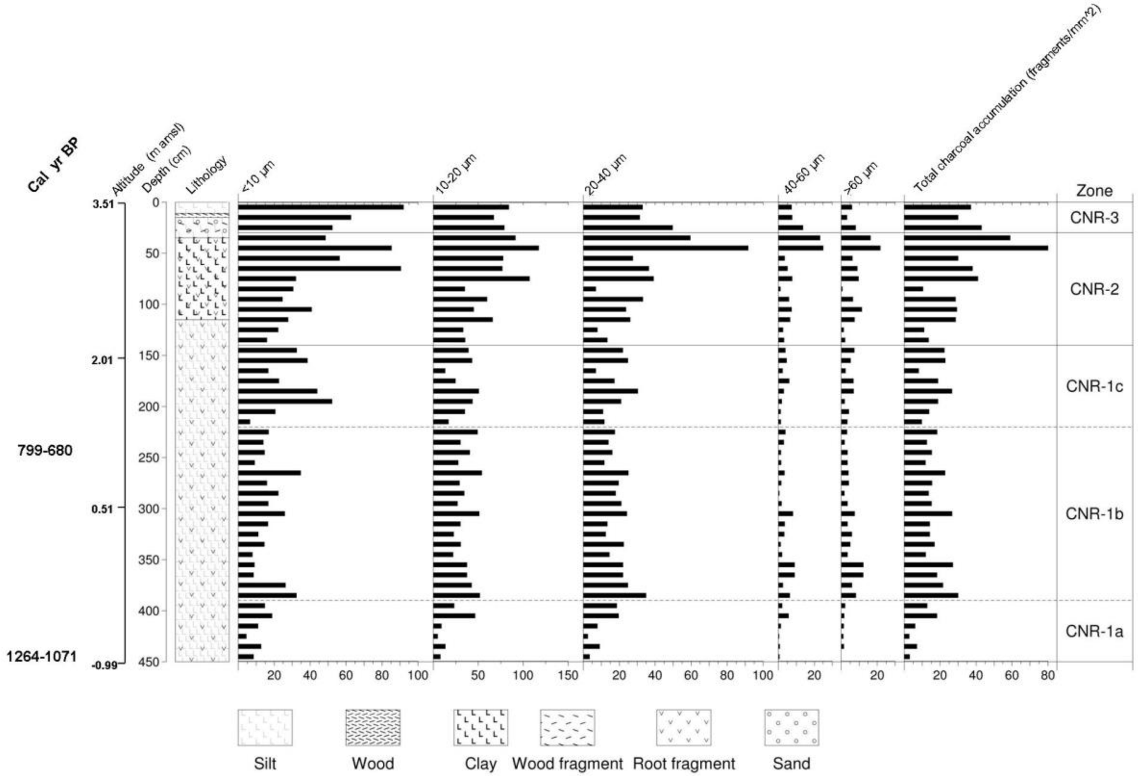

Figure 2.8. Charcoal diagram from the landward site of northern Rufiji Delta (CNR) representing pollen slide size class counts and the total charcoal accumulation standardised to number per calculated area of each sample slide. Zonations are based on pollen data

Interpretation and discussion

Reconstructed mangrove environments from the Rufiji Delta sediment cores represent a variety of mangrove communities which are influenced by a number of environmental variables. In addition to inundation frequency from sea water, mangrove community composition and distribution in the delta is also influenced by climate, via changes in rainfall-river discharge which transports freshwater and nutrient inputs from both upstream and estuarine sources, environmental and human activities. As these influences on community composition often operate in combination, we discuss the changes recorded under three headings; sea level, regional environmental changes and recent human impacts. The identification of causal factors to explain ecosystem changes is further hampered by chronological uncertainties in the age-depth relationships.

Stratigraphy and chronology

The radiocarbon chronology shows a complex age-depth relationship. Although this is not surprising for a deltaic mangrove system where there are numerous controls on sediment accumulation, erosion and re-deposition, it does present a number of caveats for interpreting the palaeoecological data. Rather than using the dates as specific points in time, we use them to divide the sedimentary data into broad time periods. The ages at depths from 443 to 107 cm provide results of mid-Holocene age. The dates from 19 cm BNR and 115 cm CNR record modern sediment, more recent than A.D. 1950 and, therefore, have probably been contaminated by younger carbon. There are age-depth discontinuities between 4821-4453 cal yr B.P. and the modern deposition in BNR and also between 799-680 cal yr B.P. and the modern deposition in CNR. The percent modern carbon of the two radiocarbon ages recorded as “modern” dates suggest that reworking by mechanical or biogeochemical processes may have occurred. These younger than anticipated carbon ages could have resulted from the contamination during the sampling procedure, although great care was taken in selecting sediments from the internal part of the core. ^{14}C contamination problems in depositional environments have been reported previously (Hammond *et al.*, 1991; Almond 1996; Toscano and Macintyre, 2003; Newham *et al.*, 2007), indicating that the source of contamination in peat and sediment samples was from the high rainfall and leaching environments which may in turn be responsible for the problems encountered within the estuarine mangrove environments in this study. The most likely causes of contamination result from roots penetrating the sediment column bringing young material down the sediment profile and/or causing percolation of humic acids through leaching (Hammond *et al.*, 1991) and/or bioturbation by fauna borrowing several decimetres into the mangrove peat sequences (Vandergoes and Prior, 2003). It is possible that these young carbon dates are as a consequence of a potential sedimentary hiatus above 4821-4453 cal yr B.P. at 107 cm. However, the other six radiocarbon dates are useful and provide the chronology indicating that mangrove communities recorded at the three sites represent a record of three different time periods: at the central site, representing the mid-Holocene prior to 5711-5486 cal yr B.P. until the present, the landward site representing the late-Holocene prior to 1264-1071 cal yr B.P. until present, and the seaward site representing the last millennium prior to 493-324 cal yr B.P. until the present.

There is likely to be at least one sedimentary hiatus in core BNR at some point between the radiocarbon date of 4821-4453 cal yr B.P. and the modern deposit, at the depth of 107 cm towards the top of the core. The likelihood of a hiatus is supported by a discontinuous stratigraphy, changing age-depth relationship and low pollen preservation in the sediments, although there is no remarkable change in organic carbon or carbonate content. The sedimentary break(s) could be represented by the discontinuous sedimentation of silt layers interrupted by the occurrence of thin clay layers. These could be due to tidal creek migration resulting in sedimentary erosion, re-deposition, and poor pollen preservation. Migrating tidal creeks are a common feature of the present environment. Estuarine mangrove systems are characterised by very dynamic sedimentary environments and can change over time as the rivers regularly migrate laterally. The hiatus(es) observed at the study sites may also result from several major floods which have been recorded relatively recently during the period 1917-1945 in the Rufiji Delta (Ochieng, 2002) and a large change in the course of the river Rufiji during the 1970s (Fisher *et al.*, 1994; Ochieng, 2002; Erftemeijert and Hamerlynck, 2005). More recently there was also extensive and prolonged flooding caused by the 1997-98 El Nińo event (Erftemeijert and Hamerlynck, 2005) that could have caused sedimentary erosion and which might explain some of these age-depth discontinuities.

The influence of sea level changes on mangrove dynamics

Analysis of BNR and CNR shows *Rhizophora. mucronata* pollen dominating while ANR is dominated by *Avicennia marina* pollen. The change in the dominant component of the major mangrove taxa is expected as these coring sites represent a 20 km horizontal distance across the Rufiji Delta. The different contemporary local vegetation types surrounding each coring site result from different mangrove environments. The dominant mangrove pollen in each core is therefore used as a proxy for inundation and sea level changes. According to vegetation observations during fieldwork used to develop the inundation classes (Figure 2.1), the dominance of *R. mucronata* trees represents mangrove communities which are inundated by normal to medium high tides, whereas that of *A. marina* trees represents mangroves which are inundated by medium to all high tides. Studies of recent marine sediments (Muller, 1959; Campo and Bengo, 2004) and surface sediments (Grindrod, 1985; Somboon, 1990) revealed that *Rhizophora* has localised pollen dispersal and is over-representated, while *Avicennia* is under-represented in relation to the abundance of the source plants in the mangrove forests. Despite these restrictions, numerous studies report that mangroves are a reliable proxy of sea level throughout the Quaternary (Ellison, 2005; Horton *et al.*, 2005; Vedel *et al.*, 2006; Engelhart *et al.*, 2007; Hait and Behling, 2009).

The dominance of *R. mucronata* pollen at the beginning of Zone BNR-1 suggests that mangroves reached their greatest extent, and sea level probably reached its highest, sometime around 5711-5486 cal yr B.P. (Figure 2.5). The timing of this is consistent with studies that indicate a sea level rise between 5080 and 4650 ^{14}C yr B.P. and supports the suggestion of a mid-Holocene sea level highstand in the southwest Indian Ocean (Ramsay, 1995; Ramsay and Cooper, 2002). However, this is in conflict with other studies from Mozambique (Jaritz *et al.*, 1977), the western Indian continental margin (Hashimi *et al.*, 1995) and South Africa (Compton, 2001) that indicate that sea level continued rising from the early Holocene and reached a mid-Holocene high level around 7000-6000 ^{14}C yr B.P. The very high sedimentation rate in core BNR between 5711-5486 and 5579-5318 cal yr B.P. (Figure 2.5) may have resulted from a high frequency of tidal inundation, possibly in response to a higher sea level during that time. The predominance of *R. mucronata* pollen among the other mangrove taxa also suggests that this area was located in a low intertidal environment which was flooded by medium to normal high tides, a further indication of a higher sea level relative to the present day. According to the contemporary distribution of *Xylocarpus granatum*, it is likely that there was a greater inundation frequency in this area than at the present day. High sea level characterised the area as shown by the steady predominance of *R. mucronata* pollen in association with silt and undifferentiated organic matter until after 5579-5318 cal yr B.P. and prior to 4821-4453 cal yr B.P. *R. mucronata* pollen subsequently decreased, combined with an increase in terrestrial grasses, suggesting less frequent inundation, possibly due to a slightly lower sea level that may have resulted in mangroves retreating seaward, allowing more fluvial terrestrial influences and the establishment of grasses and sedges. In addition, a decrease in sedimentation rate between 5579-5318 and 4821-4453 cal yr B.P. may also indicate a lower sea level during this period, although there is no robust evidence of lower sea level recorded in the southwest Indian Ocean at this time. After 4821-4453 cal yr B.P. (4167 ^{14}C yr B.P.) mangroves, represented by *R. mucronata* pollen, dominate again and could suggest increased inundation by sea level. This corresponds to the continuous sea level rise as suggested by Camoin *et al.*, (2004) and Rijsdijk *et al.*, (2011) after a mid-Holocene dry period, until the sea reached its present level around 3000 ^{14}C yr B.P. Interestingly, there are a few appearances of *Nypa* in the mid Holocene sequence (Figure 2.5) that cannot be over-interpreted and which may purely result from long-distant transport. *Nypa* was introduced into West Africa in the early 20th century from Singapore (Spalding *et al.*, 1997; Ukpong, 1997; Isebor *et al.*, 2001). It is believed that the origin of *Nypa* is from the pro-Atlantic region (Hutchings and Saenger, 1987; Spalding *et al.*, 1997) although recent studies indicate that *Nypa* is of Indo-Pacific origin (Isebor *et al.*, 2001; Mehrotra *et al.*, 2003).

Mangroves, represented by *R. mucronata* pollen, established at the higher elevations of the Rufiji Delta (CNR) by at least the late Holocene (1264-1071 cal yr B.P.) (Figure 2.6), suggesting that this area was influenced by tidal inundation. The prevalence of *R. mucronata* pollen indicates that this area was located in a low intertidal environment inundated by medium to normal high tides. This mangrove development may be related to a second late Holocene sea level highstand dated along South African coasts at 1300 cal yr B.P. (Compton, 2001) and 1610 ^{14}C yr B.P. (Ramsay, 1995). Comparison with the proportion of *R. mucronata* pollen in BNR, the lower values of predominant *R. mucronata* pollen and the higher proportion of herbaceous taxa probably suggest more influence of terrestrial input at the landward site from at least the late Holocene. There then followed a reduction in mangrove species and an increase in back-mangrove and terrestrial grasses indicative of less frequency of inundation that possibly allowed mangroves to retreat to seaward due to a lower sea level. There were some changes between mangroves, back-mangrove and terrestrial grasses possibly due to fluctuating sea level until prior to 799-680 cal yr B.P. Subsequently, there was a gradual change from mangroves characterised by *R. mucronata* pollen to terrestrial vegetation and the replacement of mangroves by herbaceous taxa. This could suggest that the frequency of sea level inundations was further reduced, probably as the sea level started to decline after about 799-680 cal yr B.P., allowing terrestrial vegetation to develop. Such an interpretation is in agreement with a study from Kenya indicating that sea level fell at about 500 ^{14}C B.P. (Åse, 1981).

The pollen record from ANR (seaward core) shows that mangroves occurred in this area at least from 493-324 cal yr B.P. with pollen from the dominant seaward taxon *Avicennia marina* accompanied by *Sonneratia alba* (Figure 2.4). *A. marina* and *S. alba* are normally found as a pioneer species of mangroves growing in exposed seaward areas. As *A. marina* trees dominate this seaward sampling site presently, it suggests that after 493-324 cal yr B.P., this area was similar to the present day; a low flat intertidal area close to present sea level and flooded during medium high tides. Some fluctuations occurred between mangroves and grasses up to the top of this core probably corresponding to a decrease in *Rhizophora mucronata* pollen and an increase in *Xylocarpus granatum* pollen in BNR during recent times that may be contemporary with a sea level regression recorded in the CNR core site.

Regional environmental change and mangrove response

The greatest occurrence of mangroves in the base of core BNR from 445 cm coincides with a relatively wet period in East Africa during the mid Holocene (Gasse *et al.*, 1989; Thompson *et al.*, 2002; Trauth *et al.*, 2003) and corresponds to a period of maximum monsoon intensity occurring across the southwest Indian Ocean region between 10,000 and 5000 ^{14}C yr B.P. (Overpeck *et al.*, 1996). Mangroves were present at this time in BNR, suggesting that wet conditions occurred until prior to 4640 cal yr B.P. when there was an increase in terrestrial herbaceous taxa, including grasses and sedges, and decrease in mangrove taxa that may reflect the influence of more terrestrial inputs possibly due to a drier climate. This period corresponds to regionally arid conditions across East Africa commencing around 4500-4100 ^{14}C yr B.P. (Hassan, 1997; Bonnefille and Chalie, 2000; Thompson *et al.*, 2002; Kiage and Liu, 2006; Rijsdijk *et al.*, 2011). Such a drought would have had an effect on the hydrological regimes across Africa (Gasse, 2000; Marchant and Hooghiemstra, 2004). For example, the diatom record from Lake Rukwa in Tanzania revealed that the maximum salinity in the lake occurred after 4400 to 3900 ^{14}C yr B.P., indicative of dry conditions (Haberyan, 1987). The present study may suggest such a dry period occurring along the Tanzanian coast prior to 4821-4453 cal yr B.P. (4167 ^{14}C yr B.P.) that could have resulted in a decrease of mangrove extent due to enhanced terrestrial conditions suitable for grasses and sedges to establish themselves.

Established mangroves at the higher elevations of the Rufiji Delta (CNR) suggest that this area was characterised by wet conditions at least until 1264-1071 cal yr B.P. The relatively low charcoal accumulations indicating few regional fires, possibly also support the proposed wet conditions. After 1264-1071 cal yr B.P. (from the depth of 385 cm) until 799-680 cal yr B.P., a reduction in the mangrove species assemblage and an increase in back-mangrove and terrestrial grasses indicate drier conditions that agree with increased charcoal accumulation, and particularly the presence of large particles, suggesting that fires occurred close to the site and more frequently. This period is concomitant with low lake level records from lake Tanganyika during 1250-1100 B.P. and 900-700 B.P. (Alin and Cohen, 2003). A climate reconstruction inferred from a pollen record from lake Masoko, southern Tanzania and Namelok swamp, southern Kenya, also suggest that arid conditions occurred from 1200 to 500 cal yr B.P. (Vincens *et al.*, 2003; Rucina *et al.*, 2010). After about 799-680 cal yr B.P., fringing mangrove taxa gradually changed to the upper intertidal mangrove taxa represented by *Bruguiera/Ceriops* pollen, and to terrestrial ferns and grasses corresponding to the more terrestrial vegetation that completely replaced the mangrove communities. Probably a change in climate may have been a contributory factor responsible for this transition and possibly relating to a dry phase recorded throughout East African lakes at the same time as the Medieval Warm Period (MWP) (Verschuren *et al.*, 2000; Alin and Cohen, 2003). Notably, a significant rise in the total charcoal accumulation towards the top of the core also indicates a change in fire regime, with a higher frequency of local fires possibly associated with drier conditions.

Recent human impacts

Herbaceous assemblages dominated by Cyperaceae at the top of the CNR core indicate that fresh water was significantly more influential than salt water in this area in more recent times and this probably relates to flooding of the river during 1917-1945 (Fisher *et al.*, 1994; Ochieng, 2002). Flooding of the river Rufiji has generally been considered to be one of the most important factors for rice growing (Shaghude *et al.*, 2004, 2008). The replacement of mangroves by inland plants and paddy fields clearly records an increase in human activities in the higher elevations of the Rufiji Delta during the last millennium.

The recent decrease of mangrove pollen in BNR and CNR, particularly that of *R. mucronata*, is probably also a consequence of the human activities associated with damming and harvesting of mangroves that would have affected downstream and coastal environments. Three dams have been built upstream on the river Rufiji which reduce fluvial inputs, nutrients and sediment reaching the coastal area (Duvial and Hamerlynck, 2007; Snoussi *et al.*, 2007), and resulting in cessation of mangrove development. Charcoal analysis from CNR clearly demonstrates an increase of charcoal accumulation, particularly the peaks in the particles larger than 60 µm at 45-35 cm representing fires close to the coring site, which could represent the burning of woody plants. This coincides with decreased mangrove taxa, particularly *R. mucronata* pollen, which then disappears towards the top of the core, demonstrating further evidence of human interaction on mangrove ecosystems. The use of mangroves is a significant component for the livelihoods of the WaRufiji people (Semesi, 1992; Mwalyosi, 1993; FAO, 2007; Snoussi *et al.*, 2007). Trading of mangrove poles for building and firewood from the Rufiji Delta to Zanzibar (Mainoya *et al.*, 1986), and Arab countries via wider Swahili trade routes (Horton and Middleton, 2000), has been recorded at least from the 9th century (Spalding *et al.*, 1997). In the 18th century A.D., Oman ruled Zanzibar, leading to rapid development and urbanisation (Havnevik, 1993; Kessy, 2003) and becoming the centre of trading on the East African coast. The mangrove pole trade flourished up to 1960 (Mainoya *et al.*, 1986) and most of the mangroves, particularly *Rhizophora*, *Ceriops* and *Brugiera*, are commercially cut for poles (Turpie, 2000; Shaghude *et al.*, 2004, 2008). Such an industry may account for the more recent decline in some of these taxa. Charcoal trading in Tanzania has been recorded from the 1970s onwards although it is likely to have been done long before that (Havnevik, 1993), and demand for firewood from mangroves is also increasing (Shaghude *et al.*, 2004, 2008). Moreover, export of rice from Rufiji to Zanzibar and Arab countries around the 19^{th} century (Havnevik, 1993) and the rapid population growth in Rufiji Delta in the late 20th century (Kulindwa *et al.*, 2000) may have led to the destruction of mangrove areas in some areas of Rufiji Delta as areas were cleared for rice cultivation (Spalding *et al.*, 1997; Taylor *et al.*, 2003).

Conclusions

The pollen records from the northern Rufiji Delta are the first evidence of Holocene mangrove dynamics along the East African coast. Although a challenging site to interpret with its dynamic sedimentary environment reflected by a complex age-depth relationship, the following conclusions have been reached:

1. Mangrove ecosystems have been established in this area from at least the mid Holocene suggesting a higher sea level and wetter climate than the present day. The predominance of *R. mucronata* pollen suggests that, during this time, the BNR core site was located in a low intertidal environment flooded by medium to normal high tides. This new record contributes to the body of evidence for a mid Holocene sea level highstand in the southwest Indian Ocean.

2. After 5410 cal yr B.P., and prior to 4640 cal yr B.P., an increase in terrestrial grasses and reduced mangrove presence suggests less frequent marine inundations, possibly due to a slightly lower sea level. This is contemporary with arid conditions across the East Africa region. Mangroves then retreated seaward and marine regression would have allowed terrestrial conditions to extend and grasses and sedges to establish.

3. Mangroves established at a higher elevation of the Rufiji Delta in the late Holocene. This area was located in a low intertidal environment inundated by high tides, probably correlating with the late Holocene sea level highstand.

4. Marked vegetation changes from fringing mangrove taxa to upper intertidal mangrove taxa, to terrestrial vegetation after around 750 cal yr B.P. resulting from a contribution of sea level regression, a dry climate and/or human impact. Paddy fields have now completely replaced mangrove communities reflecting increased human settlement and rice cultivation in this area.

5. The recent main decrease of mangroves, particularly *R. mucronata* pollen in BNR and CNR, together with the rapid increased charcoal content of CNR, suggests a combination of sea level regression and human activities during the last millennia including damming and harvesting of mangroves.

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ESM

Stratigraphic descriptions of the core ANR

Altitude amsl (m)	Depth (cm)	Sedimentary description
2.93 – 1.62	0-131	Silt containing frequent small root fragments
1.62 – 1.43	131-150	Fine sand containing some wood, bark fragments and leaves of herbaceous plants
1.43	150	Impenetrable

Stratigraphic descriptions of the core BNR

Altitude amsl (m)	Depth (cm)	Sedimentary description
3.44 – 3.24	0-20	Silt containing frequent small root fragments
3.24 – 2.90	20-54	Clay containing frequent small root fragments
2.90 – 2.84	54-60	Silt containing frequent small root fragments
2.84 – 2.76	60-68	Clay containing frequent small root fragments
2.76 – 2.13	68-131	Silt containing small root fragments
2.13 – (-1.06)	131-450	Undifferentiated organic silt containing small root fragments
-1.06	450	Impenetrable

Stratigraphic descriptions of the core CNR

Altitude amsl (m)	Depth (cm)	Sedimentary description
3.51 – 3.47	0-4	Dark brown top soil
3.47 – 3.40	4-11	Grey silt containing frequent small wood and bark fragments
3.40 – 3.36	11-15	Dark wood and bark fragments
3.36 – 3.17	15-35	Silt associated with red brown sand containing wood and bark fragments
3.17 – 2.36	35-115	Clay containing frequent small root fragments
2.36 – (-0.99)	115-450	Silt containing small root fragments
-0.99	450	Impenetrable

Chapter 3: Holocene mangrove dynamics in Makoba Bay, Zanzibar

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Abstract Pollen and charcoal analyses on sediment cores retrieved across an altitudinal transect in Makoba Bay, Zanzibar, Tanzania, set within a chronology provided by 11 radiocarbon dates, are used to reconstruct Holocene mangrove ecosystem dynamics. Using the changing ratio of the key mangrove taxa *Sonneratia*/(*Bruguiera/Ceriops*) (S/BC) relative changes in past sea level are inferred. The interpretation of the pollen record is guided by an initial assessment of modern pollen-vegetation and vegetation to environmental relationships. Mangrove communities in Makoba Bay are recorded from at least the early Holocene in what was a similar environment to the present day. Mangroves migrated landward, probably in relation to a sea level rise until the mid Holocene as the seaward and central core locations developed as a lower intertidal mangrove area. A phase of lower sea level occurred from the mid Holocene to ~ 1450-1550 cal yr B.P. characterised by the mangrove communities retreating seaward. After 1450-1550 cal yr B.P., sea level rose again and greater inundation frequency caused mangroves to shift landward, gradually falling until reaching the present sea level. The recent decrease of mangrove species, *Rhizophora mucronata*, may result from increasing anthropogenic influences in the mangrove ecosystems during the last centuries as supported by an increase in charcoal.

Keywords: coastal change, pollen analysis, vegetation-pollen index, charcoal analysis

Introduction

The East African coast situated in the Southwestern Indian Ocean (Woodroffe and Horton, 2005) lies in a "far-field" location and hence should provide a sensitive location in which to approximate eustatic sea level fluctuations. However, other mechanisms drive Holocene sea level changes in far-field locations such as hydro-isostasy (continental levering) and equatorial syphoning dependent on the width of the continental shelf (Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). Studies on the magnitude and timing of sea level changes within the Southwest Indian Ocean, using a range of different geomorphological proxies such as reef terrace and raised platforms, (Alexander, 1969; Jaritz *et al.*, 1977; Åse, 1981; Ramsay, 1995; Camoin *et al.*, 1997, 2004; Compton, 2001; Ramsay and Cooper, 2002; Muzuka *et al.*, 2004) are conflicting. Exacerbated by different isostatic histories at different locations, and marred by dating uncertainties, there remains considerable debate on the timing and duration of Holocene sea level fluctuations. Coastal vegetation dynamics in East Africa potentially offer an additional and untapped archive to unravel far-field sea level fluctuations; this potential is only starting to be realised with one palaeoecological study undertaken to-date within East Africa mangrove ecosystem (Punwong *et al.*, 2012).

Mangrove ecosystems comprise evergreen trees and shrubs that have physiological and morphological adaptations to grow in the intertidal zone between mean sea level and high water spring tide (Woodroffe and Grindrod, 1991; Blasco *et al.*, 1996; Ellison and Farnsworth, 2001; Ellison, 2008). Different mangrove species appear in zones that reflect inundation frequency, salinity and nutrient availability (Blasco *et al.*, 1996; Hogarth, 1999). Studies on mangrove ecosystem change, combined with an understanding of the present relationship of mangrove composition to the altitude of sea level, can be used to reconstruct sea level fluctuations. Mangrove ecosystems respond to changing sea level altitude by migrating landward or seaward with a rise or fall in sea level respectively (Figure 3.1). Mangrove pollen preserved in sediment cores can be used to reconstruct past mangrove dynamics (e.g. Cohen *et al.*, 2005; Horton *et al.*, 2005; Vedel *et al.*, 2006; Tossou *et al*., 2008; Hait and Behling, 2009) and used as a proxy for sea level reconstruction (Engelhart *et al*., 2007; Ellison, 1989; 2005; 2008). In addition to sea level, mangrove ecosystems are influenced by a range of other environmental factors particularly including climate, and anthropogenic activities (Field, 1995; Duke *et al.*, 1998; Alongi, 2008; Gilman *et al.*, 2008). Changes in any of these variables, or combination of variables, will result in changes in mangrove composition and distribution. For example, an increase in precipitation enhances freshwater runoff, fluvial sediment, nutrient inputs and reduces salinity which can result in increased growth rate and diversity of mangrove ecosystems (Nicholson and Flohn, 1980; Kjerfve, 1990; Duke *et al.*, 1998; Hughes *et al.*, 1998; Saintilan and Wilton, 2001; Alongi, 2008; Gilman *et al.*, 2008; Eslami-Andargoli *et al.*, 2009). Conversely, low duration and intensity of rainfall, combined with high evaporation rates, results in hypersaline conditions (Snedaker, 1995; Ellison, 2000; Gilman *et al.*, 2008; Mikhailov and Isupova, 2008) and will decrease mangrove growth rates and diversity (Field, 1995; Gilman *et al.*, 2008). Mangrove ecosystems are also sensitive to anthropogenic disturbance (Blasco *et al.*, 1996; Hogarth, 1999; Gilman *et al.*, 2008). Most mangrove degradation for example in Tanzania is caused by agricultural expansion i.e. rice fields and aquaculture (Spalding *et al*., 1997; 2010; Taylor *et al*., 2003). Mangroves in Zanzibar are used by local people for building poles, firewood, charcoal for domestic uses and for salt production by boiling sea water: many of these practives have been carried out for many centuries (Horton and Middleton, 2000; Ngoile and Shunula, 1992; Spalding *et al*., 1997). Although there is an increase in conservation and public awareness in Zanzibar on the broader benefits of a healthy of mangrove ecosystems, the over-exploitation is still a considerable concern (Shunula, 2002; Taylor *et al.*, 2003). As fire is a sensitive indicator of environmental response to arid climate and anthropogenic influences, one palaeoecological approach to investigate the driving forces behind the frequency and intensity of fire events over time is charcoal analysis (Conedera *et al.*, 2009; Daniau *et al.*, 2010). Furthermore, analysis of charcoal fragment size can indicate the distance from the source of the fire. Larger fragments imply the presence of a local fire, while smaller fragments derived from more remote locations may have been transported to the site by wind (Clark, 1988) or fluvial transport (Blackford, 2000).

The aim of this research is to reconstruct mangrove dynamics from Zanzibar by dating biostratigraphic changes recorded in pollen and charcoal fragments to investigate the response of mangroves to a range of environmental changes. Mangrove responses to sea level change are constrained through comparison to the relationship between contemporary vegetation assemblages and their frequency of inundation level. Combined with charcoal analysis, past fire and climatic regimes and anthropogenic activities, and how these impact on mangrove ecosystems, are also considered.

Study sites

Location

Zanzibar is a group of islands that includes the large inhabited island of Unguja and Pemba located in the Indian Ocean about 40 km off the coast of Tanzania. Unguja is a local name for Zanzibar and in this paper, we use the term Zanzibar for Unguja. Zanzibar is about 85 km long and 39 km wide with an area of 1,660 km^2 (Mustelin *et al*., 2009). The island is surrounded by fringing coral reefs with mangroves found along the western shores, particularly within embayments, and covering approximately 6,000 hectares (Francis and Brycesson, 2001). The study area is located in the northwest of Makoba Bay, about 25 km northwest of Zanzibar town (Figure 3.1). The study area is covered by a belt of dense mangroves varying from 100-700 m in width occurring in a north-south alignment with the majority of trees up to 4 m in height and some of the regeneration vegetation reaching heights of between 1 and 2 m. The area is characterised by shallow unconnected tidal creeks that have occasional freshwater input from terrestrial runoff even during the heavy rainy season and may therefore experience a temporary decrease in salinity (Mwandya *et al*., 2010). Makoba Bay is influenced by a tidal range of 2-4 m (Mwandya *et al*., 2010).

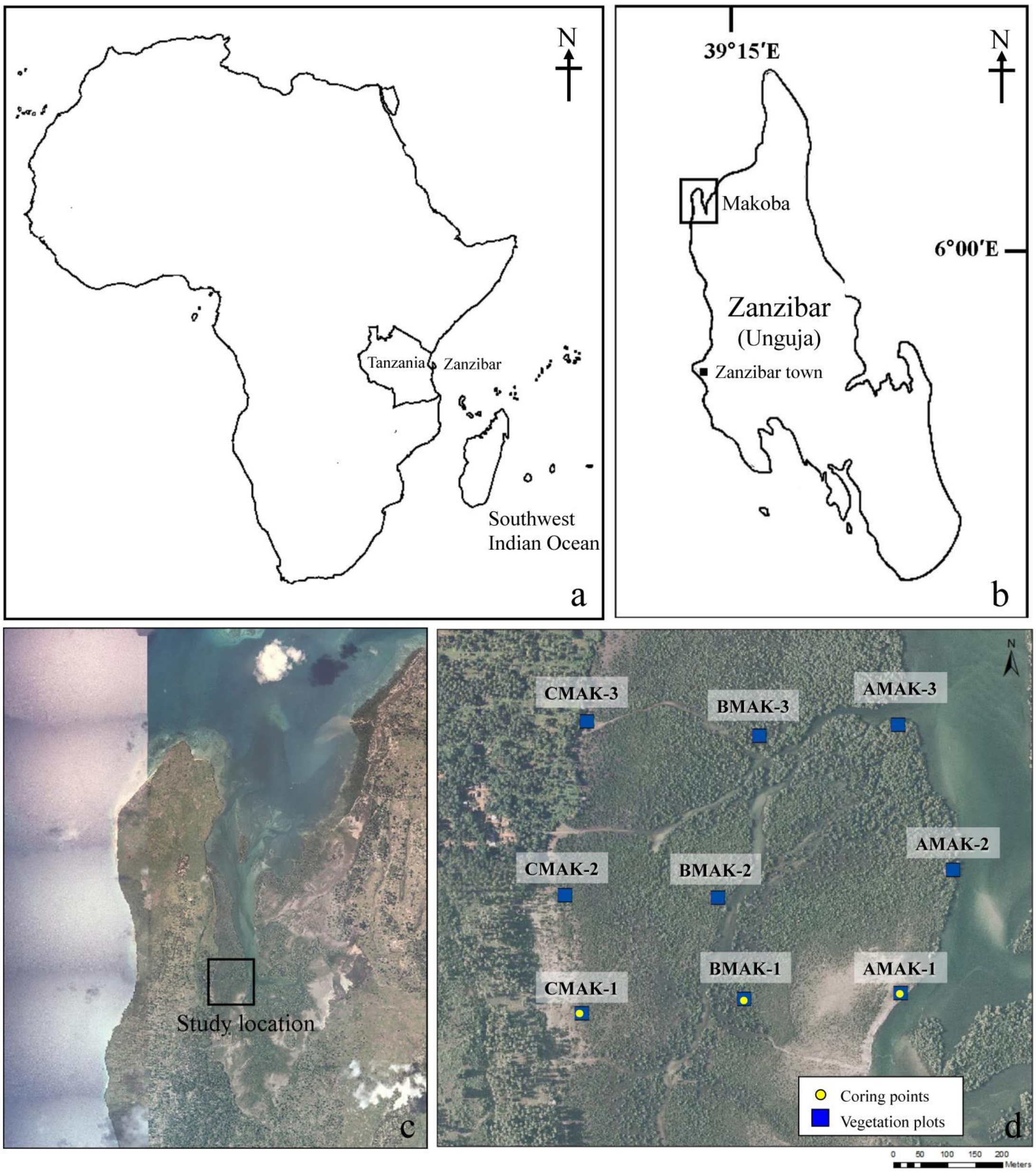

Figure 3.1. (a) Map of the Southwest Indian Ocean showing the location of sea level sites. (b-d) Map of Zanzibar showing the location of the study sites and where sedimentary cores and vegetation plots were taken.

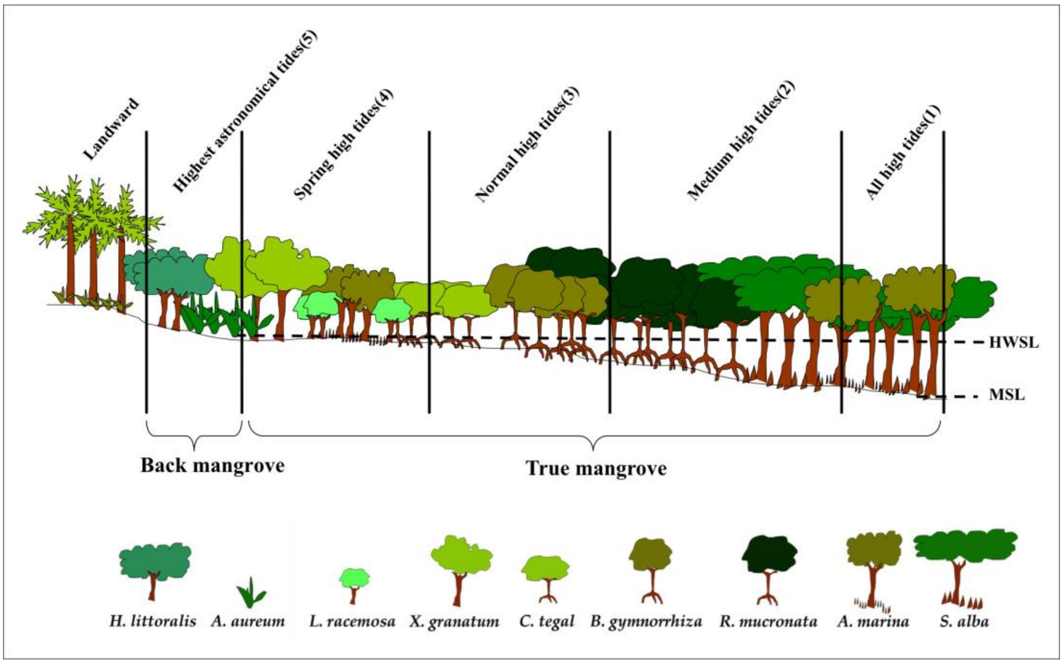

Figure 3.2. Summary cross section showing typical mangrove zonation in Zanzibar developed from Watson's (1928) and Santisuk's (1983) inundation classes and field observations. Numbers inferred to Watson's inundation classes as given in Table 3.1.

Geology and geomorphology

Zanzibar is located on the continental shelf and was connected to the mainland when sea level was 30-40 m below present mean sea level. Sea level transgressions during interglacial periods such on the Eemian (114-130 ka) caused Zanzibar to become an island (Ingrams, 1931; Arthurton *et al*., 1999) with the last connection to the mainland probably occurring around the last glacial period, prior to 10-15 ka B.P. (Hamilton, 1982; Camoin *et al*., 2004). Most of Zanzibar consists of Pleistocene reef limestone with alluvial deposits in some areas (Schlüter, 1997; Arthurton *et al*., 1999). Zanzibar is covered by quartz sand (Arthurton *et al*., 1999) and influenced by a semi-diurnal tide, ranging from 2 m on neap tide to 4 m on spring tide (Mwandya *et al*., 2010). The shores form 1-3 km intertidal platforms and support mangrove ecosystems in sheltered bays (Arthurton *et al*., 1999).

Climate and vegetation

The climate within Zanzibar is largely controlled by the north and south migration of the Inter-tropical Convergence Zone (ITCZ). The northeast monsoon dominates from November to March while the southeast monsoon prevails from April to October (Horrill *et al*., 2000). When the monsoon patterns change, Zanzibar experiences increased rates of precipitation with heavy rains from March to May and short rains from October to December (Machiwa and Hallberg, 1995; Knopp *et al.,* 2008; Moynihan, 2010; Mwandya *et al*., 2010). Sea surface temperature variation in the Indian Ocean also influences the rainfall pattern (Saji *et al*., 1999; Behera *et al*., 2003; Marchant *et al*., 2007). The mean annual rainfall is about 1500-1800 mm yr^{-1} (Knopp *et al.*, 2008) and the temperature range is narrow throughout the year at about 27-30 ºC (Machiwa and Hallberg, 1995).

The East African coast possesses highly saline, anaerobic sediments, acidic soils, and unstable substrates resulting in relatively low mangrove diversity (Wang *et al.,* 2003). There are ten species of mangrove found in Zanzibar although not all species are found in every mangrove forest (Shunula, 2002; Francis and Bryceson, 2001). From the field-based observations in this study at three coastal sites, eight species of mangrove are found that form a distinct vegetation zonation. A zonation of the Zanzibar mangrove ecosystems has been developed based on a combination of Watson's (1928) and Santisuk's (1983) inundation classes and fieldwork observations (Figure 3.2). The mangrove ecological distributions and response to tidal inundation regimes (Tables 3.1, 3.2) (Figure 3.2) is used as an aid in interpreting ecosystem and environmental changes throughout the fossil record.

Table 3.1. The zonation of mangrove species typically found in Zanzibar.

Speices	Position on the environmental gradient
Sonneratia alba J. Smith	*S. alba* occurs within a soft mud or silt on open coasts (Gallin *et al*., 1990; Taylor *et al*., 2003). It is commonly found as a pioneer of the exposed area along outer seaward mangroves and forms a thick belt of mangrove margin flooded by every tide (Chapman, 1976; Tomlinson, 1986; Taylor *et al.*, 2003). This species prefers growing under tide influence. The distribution range of *S. alba* is limited by the influence of freshwater runoff and found down stream where salinity is close to sea water (35‰) and constant during wet and dry season. (Duke, 1992)
Avicennia marina (Forsk.) Vierh.	*A. marina* demonstrates bimodal distribution (Mattijs *et al.*, 1999; Duke *et al.*, 1998) regarding its tolerance to sea water inundation and wide range of salinity (2-90‰) (Chapman, 1986; Duke, 1992; Smith, 1992). *A. marina* is commonly found on firm sandy soils. It is commonly found in the most landward belt to the exposed seaward fringes as a primary colonist associated with *S. alba* (Chapman, 1986; Taylor *et al.*, 2003) or also extends along almost the entire length of the estuary (Duke, 1992). *A. marina* growing at the landward areas is smaller than the seaward individual which is large when fully grown (Chapman, 1986; Mattijs *et al.*, 1990). This is due to the great difference in salinity between these two zones. At the landward zone which is flooded at the highest spring tides salinity concentrations in soil become very high probably up to 2-3 times of that sea water (Chapman, 1986; Mattijs *et al.*, 1990), and it is not well developed (Macnae and Kalk, 1962; Mattijs *et al.*, 1990).
Rhizophora mucronata Lam.	*R. mucronata* is a primary colonist occurring in large homogeneous stands on river mouths and creeks (Chapman, 1976; Taylor *et al.*, 2003). It usually grows in the area that tends to be wet, muddy, and in silty sediments in the tidal zone flooded daily by tides (Tomlinson, 1986). This species is also found upstream where some neap high waters may not cover the ground (Chapman, 1976). It occasionally may be found as a pioneer on open beaches flooded by all the tides (Macnae and Kalk, 1962).

Table 3.1. The zonation of mangrove species typically found in Zanzibar (cont.).

Speices	**Position on the environmental gradient**
Bruguiera gymnorrhiza (L.) Lamk.	*B. gymnorrhiza* is typically a plant of the middle mangrove community, extending into the transition of landward communities. It may be found on the exposed shores where the mangrove belt is thin (Tomlinson, 1976). It can be found as an independent belt between *R. mucronata* and the landward fringe where the rainfall is high whilst occuring between *R. mucronata* and *C. tegal* in more arid areas (Chapman, 1976). This species is recognised as tolerant of low ranges of salinity (Ball *et al.*, 1988) and can be found in the area where is salinity is lower (15-20 ‰) (Chapman, 1976)
Ceriops tagal (Perr.) C. B. Robinson	*C. tegal* is typically a plant of the upper intertidal mangrove (Tomlinson, 1986). This species is less capable of withstanding strong waves and currents due to its weaker root system. It appears in upper intertidal and dry areas where salt water occasionally inundates and high soil salinity is produced by evaporation (Matthijs, 1999; Tayler *et al*, 2003). *C. tegal* is considered as a highly salt tolerant plant (Ball *et al.*, 1988).
Lumnitzera racemosa Wild.	*L. racemosa* is a characteristic of landward mangrove communities and can also be found at the upper landward mangrove (Tomlinson, 1986; Gallin, 1990; Su *et al.*, 2006). It is tolerant of high salinity soil up to 90‰ (Smith, 1992). This species is also associated with *C.tegal* and *A. marina* in dry areas (Gallin, 1990).
Xylocarpus granatum Koenig.	*X. granatum* commonly occurs in landward fringes of mangrove which are occasionally inundated by exceptional or equinoctial tides and there is a greater freshwater influence (Taylor *et al.*, 2003; He *et al.*, 2007). This species prefers growing in non-saline soils (Clough, 1992).

Table 3.1. The zonation of mangrove species typically found in Zanzibar (cont.).

Speices	**Position on the environmental gradient**
Heritiera littoralis (Dryand.) Air.	*H. littoralis* is found on river banks and considered a constituent of the back mangrove which is flooded by spring or equinoctial high tides (Tomlinson, 1986; Taylor *et al.*, 2003; Wang, 2010) and may occupy the forest fringe. This species is intolerant to salinity and prefers growing in non-saline soils (Clough, 1992). Consequently, it grows in habitats with low salinity and does not occur in exposed areas and is thus limited to areas away from the sea. The substrate is firmer compared to those on which other mangrove species are found (Tomlinson, 1986, Clough, 1999; Semesi, 2001).
Acrostichum aureum Linnaeus	This fern is a typical constituent of back mangroves and associated with brackish conditions. It is opportunistic in disturbed areas where the mangrove has fallen (Chapman, 1976; Tomlinson, 1986). This fern dominates in the understory of back mangrove areas with relatively high rainfall and frequent desalinization of the upper soil layers (Medina *et al.*, 1990). It is not restricted to mangrove habitats and can survive without saline conditions (Tomlinson, 1986; Wang, 2010).

Table 3.2. Watson's (1928) inundation classes.

Inundation class	Area flooded by	Times flooded per month	
		From	To
1	All high tides	56	62
2	Medium high tides	45	56
3	Normal high tides	20	45
4	Spring high tide	2	20
5	Highest astronomical tides	-	2

Material and methods

Fieldwork and sampling

Three sediment cores (AMAK-1 (05º56'20.3"S, 039º12'19.2"E) seaward, BMAK-1 (05º56'20.7"S, 039º12'10.1"E) central, and CMAK-1 (05º56'22.3"S, 039º11'59.6"E) landward were extracted during July 2009 from the northwest of Makoba Bay along a transect perpendicular to the coastline (Figures 3.1, 3.3). The AMAK-1 core site is located 0.6 m above mean sea level on a long intertidal coastline about 5 m from the bay at the tip of the creek and therefore has the least marine influence due to the altitude (Figure 3.3). The BMAK-1 core site is in the middle of the transect about 300 m away from AMAK-1 and 0.45 m above mean sea level (amsl) in an area influenced by tidal inundation from the creeks when bank-full. The CMAK-1 core site is located at the landward margin of the mangrove ecosystem approximately 200 m away from the influence of tidal creeks, and about 1.51 m above mean sea level. The CMAK-1 core site is backed by a steep ancient coral terrace approximately 4 m in height along the mangrove landward area in north-south alignment which delimits the eastern extent of mangrove area. The characteristics of sediments were described using a modified version of the Tröels-Smith (1955) classification (Kershaw, 1997).

Vegetation plots

To study the plant and structural composition at different levels of inundation, vegetation in nine 20 m^2 nested quadrats were established from which surface sediment samples were collected. Altitudinal heights above mean sea level were obtained using a differential GPS (model Leica TCRA Total Station) and leveled relative to the Ministry of Lands and Environment Benchmark (Zanzibar). Three quadrats were located at each core sampling point (AMAK-1, BMAK-1, CMAK-1) in addition two quadrats were placed approximately 250 m apart at seaward location (AMAK-2, AMAK-3), the mid tide section (BMAK-2, BMAK-3) and the landward region (CMAK-2, CMAK-3) (Figure 3.1). The trunk diameter of the trees relates to their age and height. From the field observations, the diameter of the trees was categorised into shrub size, small tree size and large tree size as 0-4 cm, 4-9 cm, and >9 cm DBH respectively. Within the 5 m^2 subplot species with a diameter of 0-4 cm were recorded; in the 10 m^2 subplot, trees with a diameter between 4 cm and 9 cm were recorded; in the 20 m^2 plot, all trees with a diameter over 9 cm were recorded. Although there are no specific measurements on pollen production we can expect larger mangrove trees to produce more pollen, and a multiplication of 1, 4, 16 (relating to the three different area size of the subplot for 0-4 cm, 4-9 cm, and >9 cm diameter trees respectively) is applied and used to calculate total plant percentages. Modern mangrove specimens were identified and anthers to be used for pollen identification collected under the supervision of a botanist (William Kindeketa) who participated in the field based vegetation survey along the Makoba Bay.

Palaeoecological analysis

2 cm^3 of sediment was extracted at intervals of 10 cm along the length of each core for pollen analysis and for measurements of the organic matter (OM) and carbonate (CO_3) content by loss on ignition (LOI) at 550 ºC and 950 ºC, respectively following procedures outlined by Heiri *et al.* (2001). Pollen and spores from sediment cores and surface samples were extracted using the acetolysis method (Erdtman, 1969; Faegri and Iversen, 1989). Sample residues were stored in silicone oil. More than 94% of pollen and spores were identified by comparison with pollen from extant mangrove specimens and modern mangrove references (Thanikaimoni, 1987; Punwong, 2008). *Bruguiera gymnorhiza* and *Ceriops tegal* were grouped together as *Bruguiera/Ceriops* type because they could not be distinguished under light microscopy (Grindrod, 1985). The pollen content of some samples was very sparse and therefore insufficient to achieve a count of 200 grains. To determine the optimal grain count, pollen and spores in 5 samples from the each site were counted and the number of taxa recorded for every 20 grains up to count of 200 grains. After 80 grains the number of new taxa did not increase (Figure 3.4). At least 150 pollen grains were counted for each level after establishing that this number was sufficient to identify any new taxa; this total count also conforms to other mangrove studies (e.g. Ellison, 1989). The pollen data are represented as percentage pollen frequency diagrams and are zoned using stratigraphically constrained cluster analysis, CONISS, based on sum

of pollen and spores within the graphics software TILIA2 and TILIA*Graph (Grimm, 1991).

Pollen-slide charcoal analysis was conducted to reconstruct fire history using size class of microscopic charcoal modified from Tinner and Hu (2003) and Rucina *et al*. (2009). The charcoal counts for each size class are presented as the total number of fragments enumerated within a complete slide. The total charcoal content is expressed for each size class and totalled by summing the multiples of the mean length of each size class with the quantity of fragments per calculated area of each sample slide.

Statistical analysis

To determine the relationship between pollen assemblages and vegetation composition, statistical analyses were undertaken. These included three indices devised by Davis (1984): association index (A), under-representation index (U), over-representation index (O), to identify those pollen types that accurately reflect source plants according to the following formulae:

$A = B_0/(P_0+P_1+B_0)$,

$O = P_0/(P_0+B_0)$,

$U = P_1/(P_1+B_0)$.

B_0 is the number of samples where the pollen type and associated plant taxon are both present, P_0 is the number of samples where the pollen type is present but the associated plant taxon is absent from the quadrat, and P_1 is the number of samples where the pollen type is absent but the associated plant taxon is present within the quadrat. Correlation Coefficients (CC) are used to describe the correlation between pollen percentages and plant percentages from nine vegetation quadrats.

Chronology

11 bulk sediment samples containing organic matter were selected for AMS dating and submitted to Radiocarbon Dating Laboratories at the CHRONO Centre, Queen’s University Belfast, UK. Range-finder dates were analysed at the start of the laboratory work with targeted dating taking place once analytical work

had been completed to date biostratigraphical changes. The dates were calibrated to calendar years using the southern hemisphere calibration of Shcal04 curve (McCormac *et al.*, 2004) and the software OxCal v4.10 Bronk-Ramsey (2009).

Results

Stratigraphy and loss on ignition

Detailed stratigraphic descriptions of the three sample cores are shown in Supplementary tables 1. The basal unit is a grey silt unit containing some shell fragments which is overlain by a peat unit containing woody root fragments and fine sand in AMAK-1 and BMAK-1. Sand is found in the uppermost unit of all three cores. The boundaries between stratigraphic units in all three cores are transitional.

Organic carbon content and carbonate content throughout the three cores vary between 1 and 29% and 0.5 to 7%, respectively (Figures 3.5, 3.6, 3.7). AMAK-1 has very low organic carbon content (1-4%) from the base with increased content (6-21%) in the overlying peat unit followed by decline (5%) at the core top. The carbonate content of AMAK-1 is relatively high at the base and corresponds to the occurrence of shell fragments. The organic carbon content of BMAK-1 varies from 10-23% in the lower units composed of silt frequent organic matter (325-395 cm) and declines at 125 cm coincident with a sand layer. However, towards the top of core BMAK-1 (at 115 cm and 45-55 cm) the organic content increases in the peat layer. The carbonate curves recorded low percentages throughout core BMAK-1 (1-7%) with relatively high carbonate content between 205 cm and 345 cm corresponding to shell fragments. CMAK-1 also shows very low and constant organic carbon content (2-10%) throughout the core with small peaks at 55 cm and 85 cm depths. Carbonate curves remain uniformly low throughout core CMAK-1 (0.5-3%). The organic carbon content in the three cores does not show any distinct correlation to any dominant pollen taxa spectra.

Chronology

11 radiocarbon dates have been obtained from the sites; two from core AMAK-1, six from BMAK-1 and three from CMAK-1 (Table 3.3, Figure 3.3).

All radiocarbon dates are on bulk material selected from different stratigraphic components and to date with seemly biostratigraphic changes. The basal date of BMAK-1 representing an early Holocene (8025-7872 cal yr B.P.) from 396 cm and is supported by the date of 7735-7582 cal yr B.P. from 320 cm in BMAK-1. The date of 5892-5659 cal yr B.P. from core AMAK-1 at 213 cm represents the mid Holocene and was selected to date a biostratigraphic change of pollen composition and a stratigraphic change of silt with fine sand, undifferentiated organic material and some shell fragments to silt with fine sand and small root fragments without shells. The radiocarbon results from core BMAK-1 (96 and 195 cm) and CMAK-1 (107 and 172 cm) show a complex age-depth relationship (Figure 3.8). The date at the deeper column (195 cm of BMAK-1) gives relatively a young age while the date at the upper column (96 cm of BMAK-1) is relatively told. Three dates on core CMAK-1 date the base of sequence (172 cm), a stratigraphic change (107 cm) and a sample between these two reversal dates (130 cm). Possible reworking of mangrove sediments may have occurred through root penetration introducing younger carbon at lower depths and/or causing percolation of humic acids through leaching (Hammond *et al.*, 1991) into the mangrove sequences and mixing older sediments in the upper column. This is not surprising as radiocarbon contamination is common in the high rainfall and leaching depositional environments (Almond, 1996; Toscano and Macintyre, 2003; Newnham *et al*., 2007). A relatively continuous accumulation rate, no abrupt change in stratigraphy, and similar pollen compositions in cores AMAK-1 and BMAK-1 suggest reliable dates of 1525-1385 cal yr B.P. (AMAK-1) and 1692-1408 cal yr B.P. and 1477-1305 cal yr B.P. (BMAK-1). The sedimentation rates of AMAK-1 and BMAK-1 show similar trends in the lower part with relatively low sediment accumulation rates of 0.20-0.21 mm cal. yr^{-1} (98-213 cm of AMAK-1; 158-320 cm of BMAK-1) and in the uppermost part (0-98 cm of AMAK-1; 0-106 cm of BMAK-1) with 0.67 - 0.76 mm cal. yr^{-1}. Therefore, seven radiocarbon dates are used to provide a chronological framework to interpret the palaeoecological data. Given the chronological uncertainities and numerous controls on sediment accumulation, erosion and re-deposition that commonly occur within a mangrove system we err on the side of caution and interpret the palaeoenvironmental data as a series of time bands rather than using the dates as specific points in time.

Modern vegetation to pollen relationship

Seven angiosperm and one Pteridophyte taxa from the sediment cores and surface samples were identified from their pollen. To aid in the interpretation of environmental conditions and sea level changes, fossil pollen and spores were grouped into mangrove, back mangrove, terrestrial, herbaceous and Pteridophyte ecological categories. Allocation of mangrove and back mangrove species were defined through field observation of modern ecological occurrences of mangrove taxa and from Watson's (1928) and Santisuk's (1983) inundation classes and the altitudinal range of mangrove areas are between -1.6 and 1.5 m amsl. To determine the association between the presence of the plant in the nine vegetation plots and its pollen in surface samples from Makoba, indices of association (A); either under- (U) or over-representation (O) and correlation coefficients (CC) for the taxa were calculated (Table 3.4). *Bruguiera/Ceriops* and *Rhizophora mucronata* show significant correlation between pollen percentages and plant percentages; these pollen types having a good agreement between the dominance in pollen spectra and the local vegetation. The correlation is significant between pollen and plant percentages for *Avicennia marina* and *Sonneratia alba* indicating that there is a moderate correlation between representivity in pollen spectra and the local vegetation. *Acrostichum aureum*, Cyperaceae, Poaceae and monolete spores do not accurately represent the presence of their parent plants in the local vegetation.

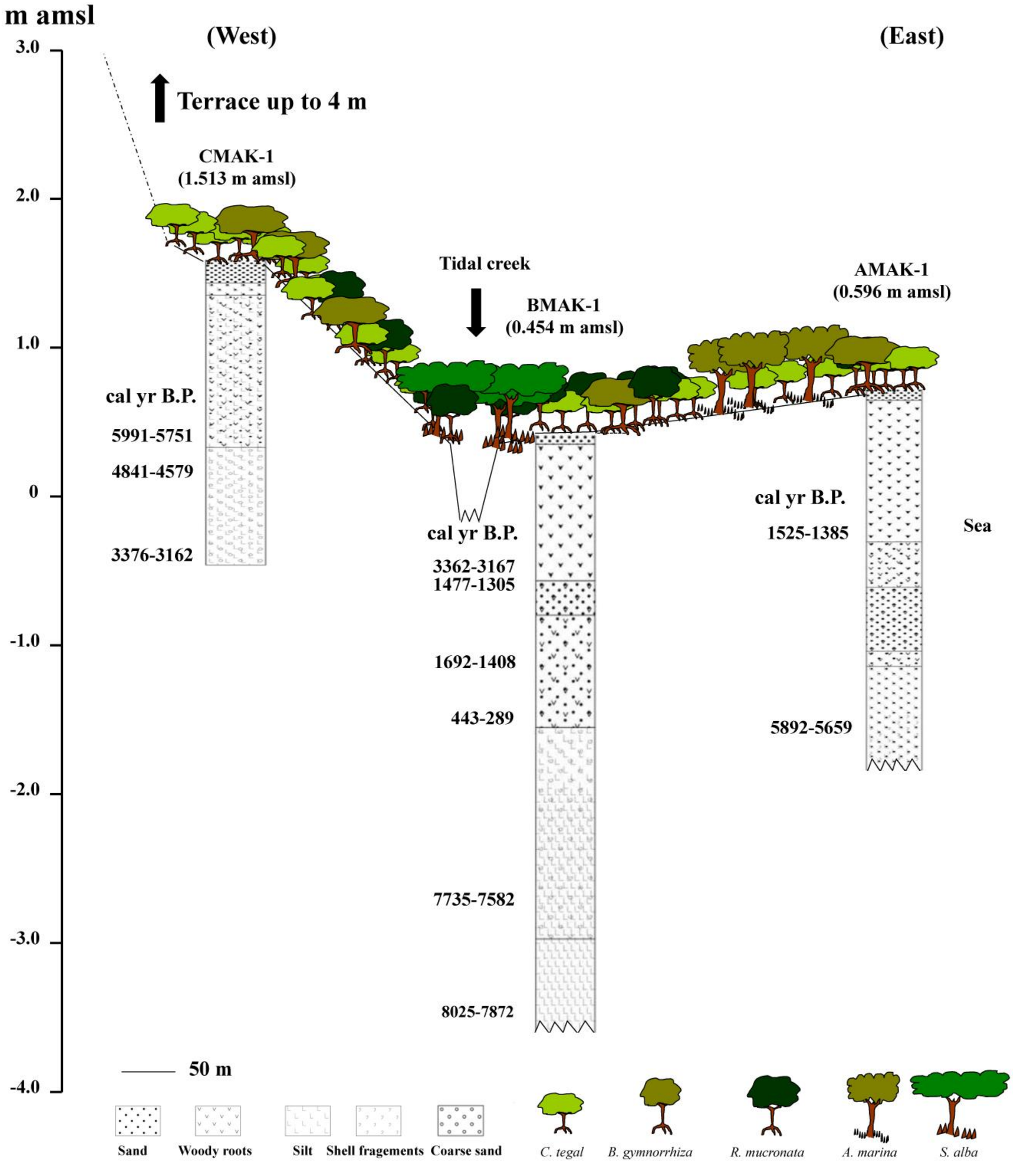

Figure 3.3. Stratigraphic profiles of cores AMAK-1, BMAK-1 and CMAK-1 core sites and mangrove vegetation along a transect from the Makoba Bay showing location of transect (amsl = above mean sea level).

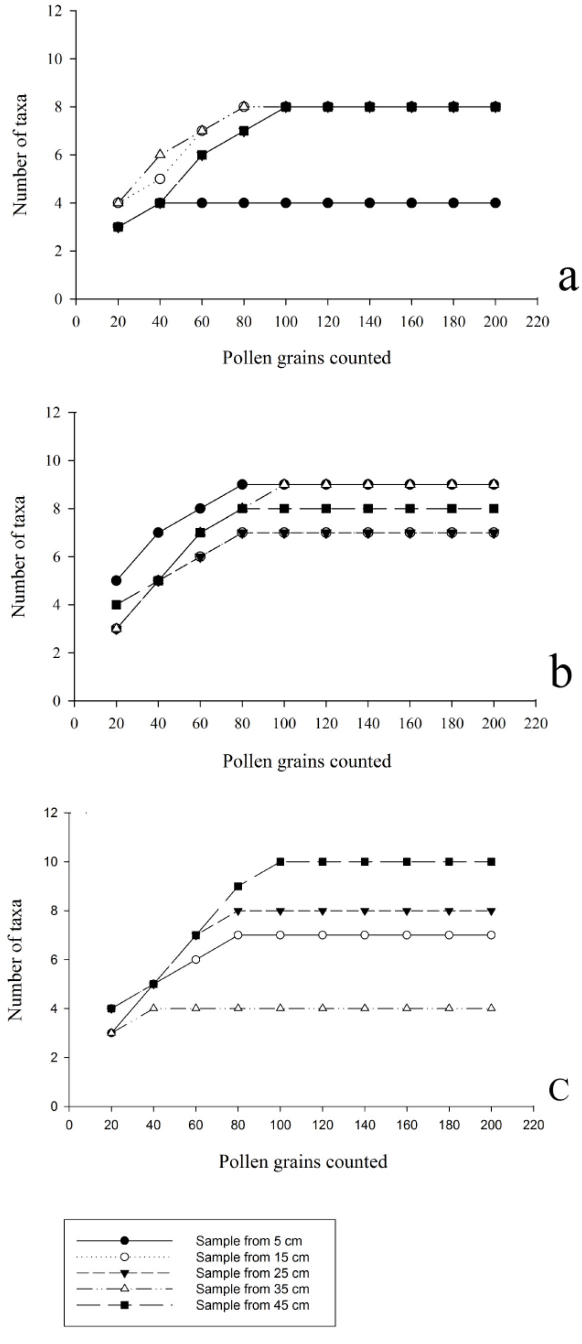

Figure 3.4. Graph showing the number of taxa against pollen grains counted from (a) AMAK-1, (b) BMAK-1 and (c) CMAK-1.

Table 3.3. List of radiocarbon dates from Makoba including calibrated ages determined using the Shcal09 curve (McCormac *et al*., 2004) and OxCal v4.10 (Bronk-Ramsey, 2009).

Site	**Altitude amsl (m)**	**Depth (cm)**	**Code**	**$\delta^{13}C$**	**^{14}C yr B.P.**	**(2σ)Cal yr B.P.**	**(2σ)Cal yr B.P.**	**Type of sediment**
AMAK-1	-0.38	98	UBA-15378	-28.6	1615 ± 24	1385 – 1525	1455 ± 70	Peat, sand, woody plant roots
AMAK-1	-1.53	213	UBA-15379	-27.3	5078 ± 26	5659 – 5892	5776 ± 117	Silt, small organic material, shell fragments
BMAK-1	-0.51	96	UBA-15380	-26.6	3111 ± 24	3167 – 3362	3265 ± 98	Peat, sand, woody plant roots
BMAK-1	-0.61	106	UBA-19415	-30.0	1543 + 25	1305 – 1477	1391 ± 86	Sand, woody plant roots
BMAK-1	-1.13	158	UBA-16631	-33.0	1695 ± 50	1408 – 1692	1550 ± 142	Sand, silt, woody plant roots
BMAK-1	-1.50	195	UBA-15381	-28.0	309 ± 23	289 – 443	366 ± 77	Silt, sand, woody plant roots, small shell fragments
BMAK-1	-2.75	320	UBA-19416	-25.4	6878 ± 36	7582 – 7735	7659 ± 77	Silt, sand, woody plant roots, small shell fragments
BMAK-1	-3.51	396	UBA-15382	-28.9	7202 ± 30	7872 – 8025	7949 ± 77	Silt, undifferentiated organic material
CMAK-1	0.44	107	UBA-15383	-26.1	5200 ± 35	5751 – 5991	5871 ± 120	Silt, coarse sand,woody plant roots.
CMAK-1	0.21	130	UBA-16632	-23.8	4239 ± 37	4579 – 4841	4710 ± 131	Silt, coarse sand,woody plant roots.
CMAK-1	-0.21	172	UBA-15384	-28.8	3117 ± 35	3162 – 3376	3269 ± 107	Silt, coarse sand,woody plant roots.

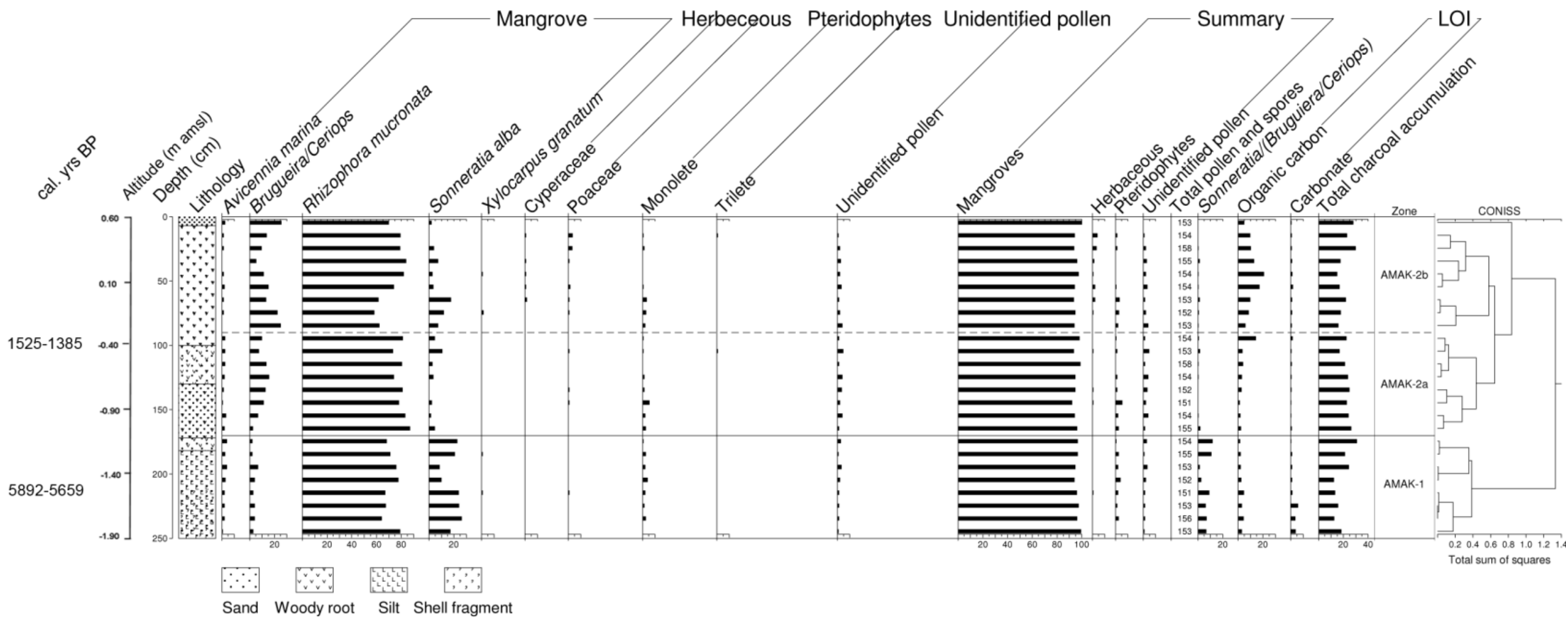

Figure 3.5. Percentage pollen frequency assemblage, organic carbon, carbonate, and total charcoal content profiles from the seaward core (AMAK-1)

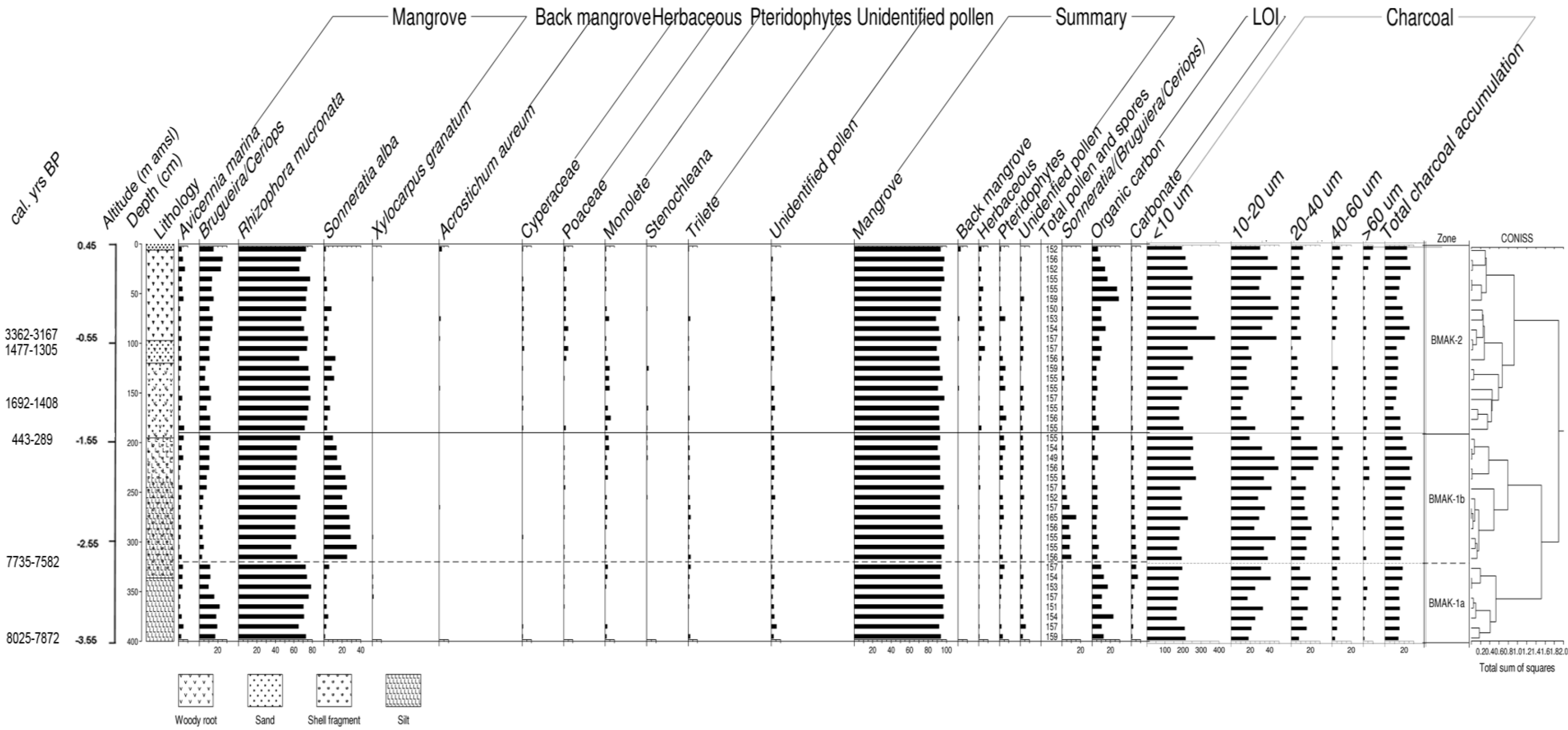

Figure 3.6. Percentage pollen frequency assemblage, organic carbon, carbonate, and charcoal frequency profiles representing size class counts and the total charcoal content standardised to number per calculated area of each sample slide from the central core (BMAK-1)

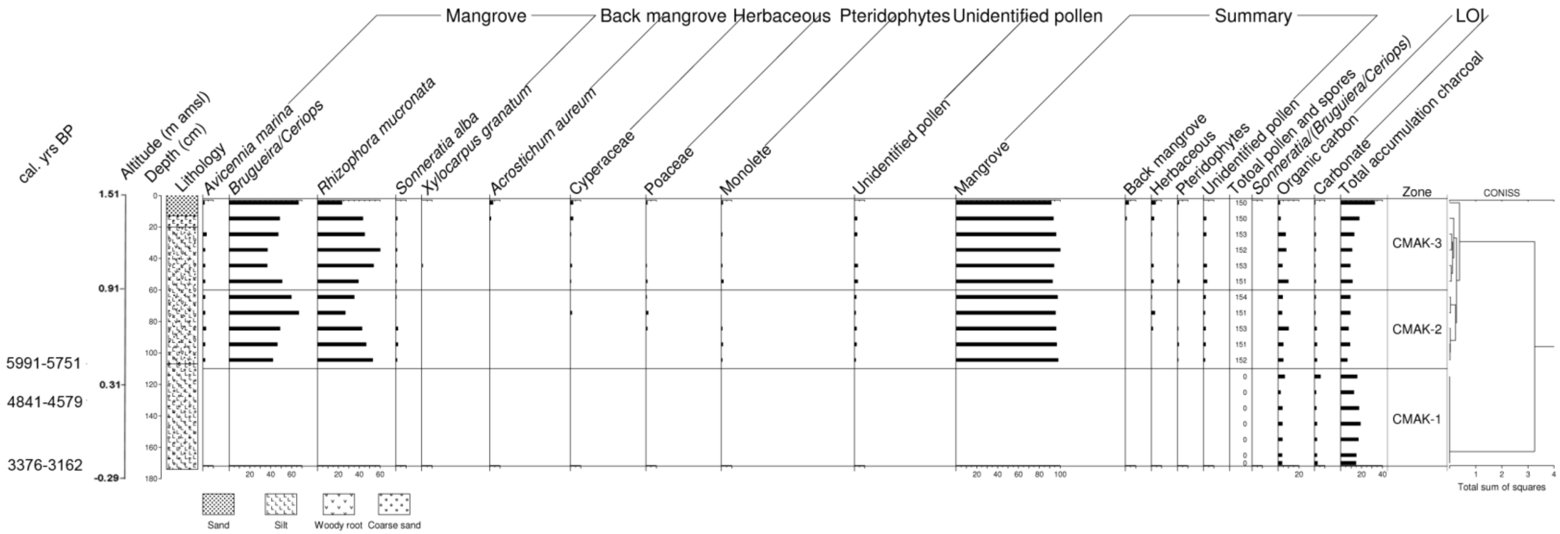

Figure 3.7. Percentage pollen frequency assemblage, organic carbon, carbonate, and total charcoal content profiles from the landward core (CMAK-1)

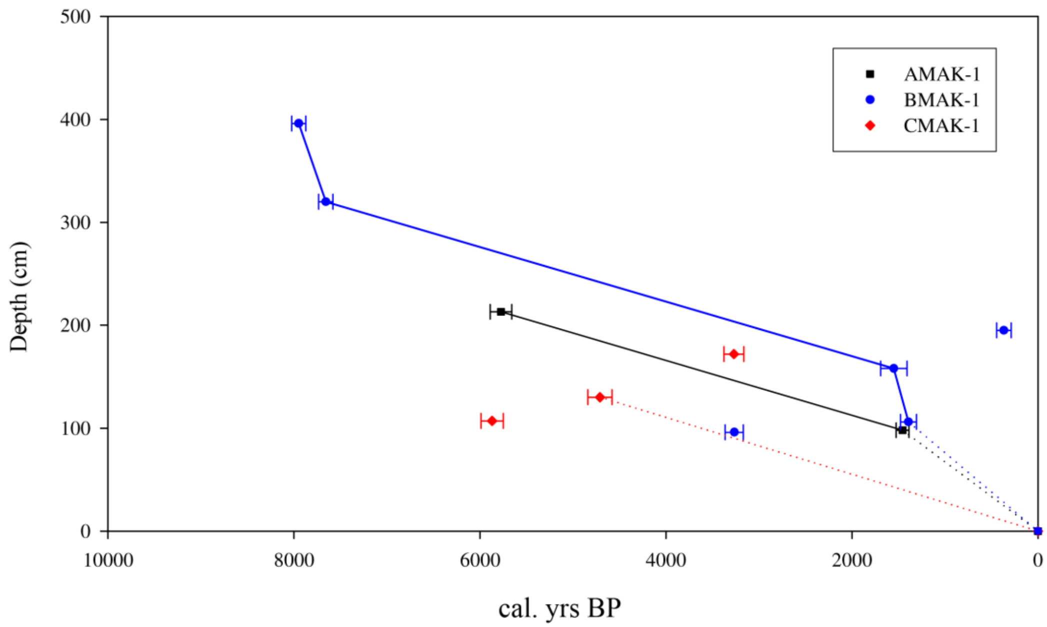

Figure 3.8. Age-depth relationship plot from the three cores using linear interpolation. The solid line represents the relationship between age and depth. The dotted line represents an uncertain age-depth relationship. For the exact meaning of zero years (origin), see page 79.

Pollen stratigraphy and application of modern vegetation relationships

The pollen zones are described in Supplementary table 2. Interestingly, there are some remarkable changes between the percentages of *Bruguiera/Ceriops* and *Sonneratia alba* pollen throughout cores AMAK-1 and BMAK-1. These two pollen types originate from different contemporary mangrove habitats and have different tolerances to sea level inundation (Table 3.1). Therefore, the pollen in the mangrove ecosystem can be reconstructed using changes in the relative proportions of *Sonneratia*/(*Bruguiera/Ceriops*) (S/BC) pollen and contemporary distribution from each vegetation plot with respect to mean sea level to characterise the inundation regime of the mangrove ecosystems. *Sonneratia*/(*Bruguiera/Ceriops*) ratios from the nine present day assemblages (Figure 3.9, Table 3.5) show a relationship between pollen proportion and inundation with respect to altitude. The calculated proportion of *Sonneratia*/(*Bruguiera*/*Ceriops*) is 0 for the mangrove assemblages at the highest altitudes inundated infrequently during a month, 0.2 to 1.3 for the mangrove assemblages at altitudes inundated several times during a month and 5.4 to 22.8 for the mangrove assemblages at altitudes inundated daily. Thus, an increase in the ratio of S/BC indicates an increase in the sea level altitude.

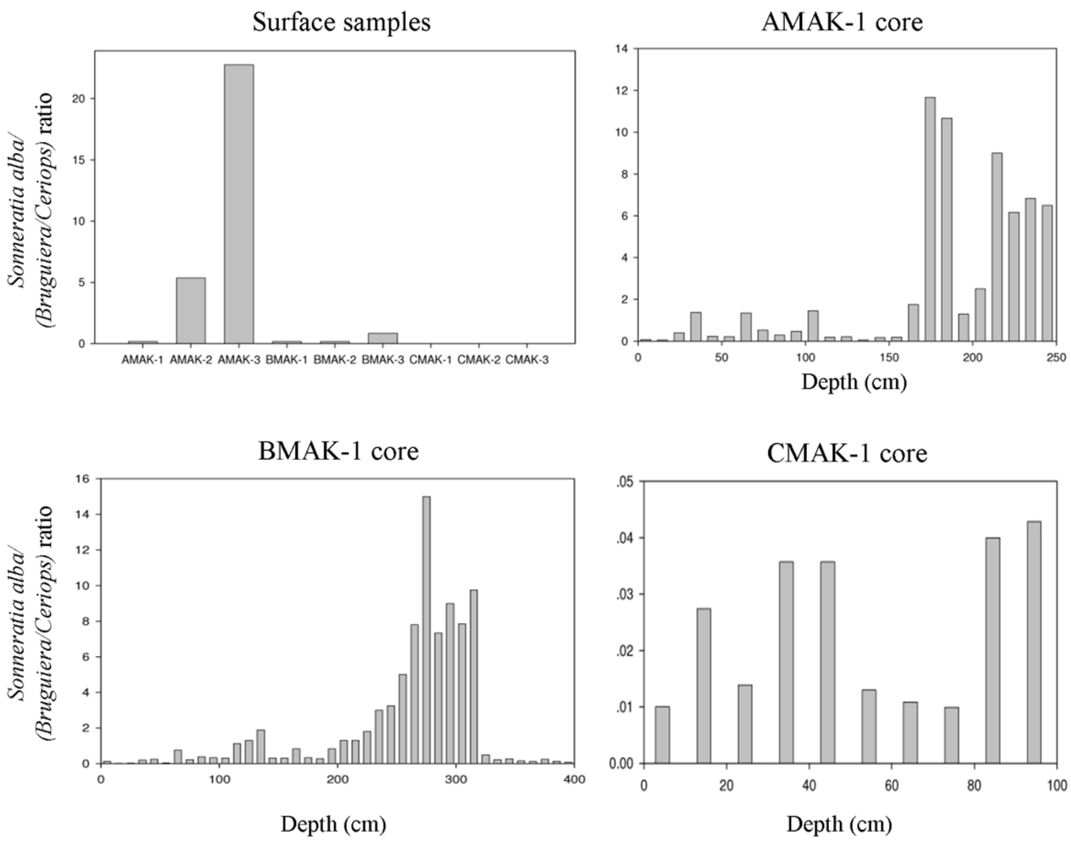

Figure 3.9. Graphs showing relationship between *S. alba* and (*Bruguiera/Ceriops*) pollen from surface samples of vegetation plots and sediment samples of the three cores.

Charcoal analysis

The charcoal content of the three cores varies from 6 to 32 fragments mm^{-2}. Total charcoal content of core AMAK-1 was relatively low (12-18 fragments mm^{-2}) prior to 5892-5659 cal yr B.P. (Figure 3.5) and then increased after this period (15-31 fragments mm^{-2}) until 1525-1385 cal yr B.P. Total charcoal content decreased and then increased from the depth of 25 cm towards the core top. Total charcoal content from 8025-7872 cal yr B.P. was relatively low until 1477-1305 cal yr B.P. when charcoal content increased with some peaks prior to 1692-1408 cal yr B.P. relating to the rise in all charcoal class sizes (Figure 3.6). After 1477-1305 cal yr B.P., the charcoal frequency rose towards the core top, particularly the number of large charcoal class size particles (> 40 µm). Total charcoal content of core CMAK-1 (Figure 3.7) was low after 4841-4579 cal yr B.P. and increased from 15 cm towards the core top with a clear peak of large particles (> 60 µm). Changes in total charcoal content, especially an increase in larger particles, is synchronous in the top of all three cores.

Table 3.4. Indices of association (A), under-representation (U), over-representation (O), and correlation coefficients (CC) between pollen percentages and plant percentages. **. Correlation is significant at the 0.01 level (2-tailed distribution).

Pollen type	B_0	P_0	P_1	A	U	O	CC
Present in both vegetation and pollen assemblages							
Avicennia marina	2	4	0	0.33	0	0.67	0.944**(0.0001)
Brugueira/Ceriops	6	3	0	0.67	0	0.33	0.862**(0.003)
Rhizophora mucronata	5	4	0	0.56	0	0.44	0.802**(0.009)
Sonneratia alba	2	4	0	0.33	0	0.67	0.967**(0.00002)
Only present in pollen assemblages							
Acrostichum aureum	0	2	0	0	0	1	
Poaceae	0	6	0	0	0	1	
Cyperaceae	0	3	0	0	0	1	
Monolete	0	4	0	0	0	1	

Table 3.5. Vegetation plots showing plant percentages, surface pollen percentages, *S. alba*/(*Bruguiera*/*Ceriops*) (S/BC) ratios of surface samples and inundation with reference to Watson's (1928) and Santisuk's (1983) classes.

Plot	Altitude amsl (m)	Plant percentages (%)	Pollen percentages (%) of surface samples	S/BC ratio of surface samples	Inundation frequency during a month
AMAK-1	0.596	*C. tegal* (95.31), *R. mucronata* (4.69)	*A. marina* (5.9), *Bruguiera/Ceriops* (32), *R. mucronata* (56.9), *S. alba* (5.2),	0.2	Several times
AMAK-2	-1.113	*A. marina* (48.39), *R. mucronata* (38.71), *S. alba* (12.9)	*A. marina* (17.3), *Bruguiera/Ceriops* (4), *R. mucronata* (57.3), *S. alba* (21.3)	5.4	Daily
AMAK-3	-1.567	*A. marina* (14.89), *S. alba* (85.11)	*A. marina* (12.7), *Bruguiera/Ceriops* (2.7), *R. mucronata* (22), *S. alba* (60.7), Monolete (2)	22.8	Daily
BMAK-1	0.454	*C. tegal* (43.14), *R. mucronata* (56.86)	*A. marina* (2.6), *Bruguiera/Ceriops* (21.1), *R. mucronata* (69.7), *S. alba* (3.3), Poaceae (2), Cyperaceae (1.3)	0.2	Several times
BMAK-2	-0.016	*B. gymnorrhiza* + *C. tegal* (70.9), *R. mucronata* (29.1)	*A. marina* (1.3), *Bruguiera/Ceriops* (21.1), *R. mucronata* (73.7), *S. alba* (3.3), Poaceae (0.7)	0.2	Several times
BMAK-3	-0.523	*R. mucronata* (100)	*A. marina* (1.3), *Bruguiera/Ceriops* (4.6), *R. mucronata* (87.5), *S. alba* (3.9), Poaceae (0.7), Monolete (2)	1.3	Several times
CMAK-1	1.513	*C. tegal* (100)	*Bruguiera/Ceriops* (66.5), *R. mucronata* (28.7), *S. alba* (0), Poaceae (1.8), Cyperaceae (1.8), Monolete (1)	0	Infrequently
CMAK-2	1.545	*C. tegal* (100)	*Bruguiera/Ceriops* (76.3), *R. mucronata* (19.7), *S. alba* (0), *Acrostichum aureum* (2.6), Poaceae (1.3)	0	Infrequently
CMAK-3	1.04	*B. gymnorrhiza* + *C. tegal* (100)	*Bruguiera/Ceriops* (61.8), *R. mucronata* (28.3), *S. alba* (0), *Acrostichum aureum* (1.3), Poaceae (2.6), Cyperaceae (2.6), Monolete (2)	0	Infrequently

Interpretation and discussion

The multi-proxy sediment analyses set within a radiocarbon chronology from Makoba Bay provide an insight into past ecosystems and environmental changes during the Holocene. The sea level changes are reconstructed using the pollen, vegetation and LOI analyses and the charcoal analysis provide evidence of climate and anthropogenic influences.

Mangrove dynamics and sea level changes

In complex sedimentary mangrove environments, local environmental conditions including wind, tides, hydrology and bioturbation will all influence pollen-vegetation relationships. It is vital to understand how pollen assemblages reflect the parent vegetation to develop on informed interpretation of palaeoecological sequences and the ensuing environmental reconstruction. The indices of associations for pollen types and correlation coefficients show that *Bruguiera/Ceriops* and *Rhizophora mucronata* represent their source plants very well. *R. mucronata* trees can dominate throughout a mangrove area and are considered to be very prolific pollen producers as they are a wind-pollinated species (Muller, 1959; Tomlinson, 1986; Somboon, 1990; Campo and Bengo, 2004). Although *Bruguiera gymnorhiza* and *Ceriops tegal* pollen cannot be distinguished under light microscopy, they occupy a similar mangrove habitat in the upper intertidal zone (Chapman, 1976; Tomlinson, 1986), and hence have a comparable ecological interpretative value. *B. gymnorhiza* and *C. tegal* pollen are smaller in size and have a similar structure to *Rhizophora* but are thought to produce less amounts of pollen as they are bird- and insect-pollinated. The relationship of *Bruguiera/Ceriops* and *R. mucronata* trees to their pollen in the Makoba Bay mangroves appears to be closely associated. The indices of association of *Avicennia marina* and *Sonneratia alba* suggest these taxa are over represented but the correlation coefficients suggest that the percentage of *S. alba* and *A. marina* pollen are in proportion to the percentage of the source plants in the surface plots. This discrepancy can be explained by their contemporary seaward distribution. *S. alba* and *A. marina* pollen can disperse moderately widely in surface assemblages although they are present in relatively low quantities in the areas where they do not exist; tidal inundation mixing the surface pollen from the surrounding area. Hence, *A. marina* and *S. alba* pollen moderately reflect their source plants. *Acrostichum aureum*, Cyperaceae, Poaceae and monolete spores are present in low quantities within surface pollen assemblages and are most likely to originate from the elevated areas near the study site, being subsequently transported by wind or water. The contemporary mangrove pollen records, combined with an assessment of the vegetation, show that fossil mangrove pollen can be used to reliably reconstruct coastal ecosystem dynamics.

The pollen diagrams from all three Makoba cores show the mangrove assemblages dominating (>88%) indicating that this area has been influenced by sea water with the history of mangrove development extending different times (Figure 3.3). Mangroves occurred at least 2.5 m below present day altitude (1.9 m below mean sea level) at about 5800 cal yr B.P. in AMAK-1, at least 4 m below present day altitude (3.65 m below mean sea level) at about 8000 cal yr B.P. in BMAK-1, and at least 1.05 m below present day altitude (0.46 m above mean sea level) after about 4700 cal yr B.P. in CMAK-1 suggesting that Makoba Bay has been covered by mangroves for the last 8000 years. By combining all three cores, and using contemporary vegetation and surface pollen spectra relationships, particularly the ratio of *S. alba* and *Bruguiera*/*Ceriops* to reconstruct changes in sea level, the following sea level interpretation has been developed.

From ~8000 to ~7700 cal yr B.P.

An early Holocene sea level rise has been documented along the coasts of the Mayotte foreslopes, Mauritius and Réunion Island (Colonna *et al*., 1996; Camoin *et al*., 1997; 2004; Zinke, 2000; Zinke *et al*., 2003). The high occurrence of *R. mucronata*, accompanied by other mangrove species (*A. marina*, *Bruguiera/Ceriops*, *S. alba* and *X. granatum*), in sub-zone BMAK-1a (Figure 3.6) suggests that Makoba Bay also underwent sea level rise and intertidal area may have formed supporting mangrove development at least about 8000 cal yr B.P. Interestingly, the S/BC ratios in this zone are constant at around 0.2 indicating that this area had a ecosystem composition contemporaneous to the present day location of AMAK-1, BMAK-1 and BMAK-2 (Figure 3.1, Table 3.5) and was inundated several times during a month. The sedimentation rate in this zone is relatively quick (2.6 mm yr^{-1}), combined with silt deposition and high organic carbon content; this probably indicates a rapid rate of sea level rise as recorded from Mauritius, Réunion and Mayotte from about 11,000 to 7500 cal yr B.P. (Colonna *et al*., 1996; Camoin *et al*., 1997).

From ~7700 to mid Holocene

Higher *S. alba* percentages from 7700 cal yr B.P., an increase in average S/BC ratios in zones BMAK-1b (5.6) and AMAK-1 (6.8), the appearance of shell fragments, higher carbonate content from the core base to 213 cm, combined with similar sedimentation rates suggest that these two coring sites experienced similar environmental conditions. Zone AMAK-1 and sub-zone BMAK-1b also show S/BC ratios similar to the present day and AMAK-2 (Table 3.5). The modern vegetation analogue for AMAK-2 suggests the mangroves experienced increased inundation frequency from several times during a month to daily from 7700 cal yr B.P. at BMAK-1 and prior to 5800 cal yr B.P. at AMAK-1. Such a landward shift of mangrove zonation indicates a relative rise in sea level from around 7700 to 5800 cal yr B.P. coincident with the deposition of marine shells. This marine transgression transformed the area of AMAK-1 and BMAK-1 to a lower intertidal mangrove area with the coastline retreating landwards. This could probably be a continuation of the sea level rise recorded in the early Holocene (Colonna *et al*., 1996; Camoin *et al*., 1997), or a different mid-Holocene highstand (Ramsay 1995; Ramsay and Cooper, 2002). Indeed, the timing of this transgression is consistent with studies on the Mayotte foreslope in the Comoro Islands (Camoin *et al*., 1997; 2004) indicating the rate of sea level rise fell to around 1-1.5 mm yr^{-1} after the rapid early Holocene sea level rise dated about 7500 cal yr B.P. Other studies from Mozambique, Western India and South Africa indicate that sea level continued rising from the early Holocene and reached a mid-Holocene highstand around 7400-7200 cal yr B.P. (Jaritz *et al.*, 1977; Compton, 2001). Although, some studies indicate sea level rise occurred a little later, between 5900-5600 and 5300-4900 cal yr B.P., they still support a mid-Holocene sea level highstand across the Southwest Indian Ocean (Ramsay, 1995; Ramsay and Cooper, 2002). Such a mid-Holocene sea level rise in Makoba Bay possibly attained the higher altitude about the CMAK-1 core site resulting in mangrove establishment. The sediments deposited in CMAK-1 core between 174 and 105 cm are characterised by grey silt containing coarse sand with very poor preservation of pollen grains although most of them are mangrove taxa (Figure 3.7). The palynological record from 105 cm upwards show that the ratios of S/BC throughout the core are very close to 0 suggesting this area may have been occupied by the upper intertidal mangrove after around 4580 – 4840 cal yr B.P. and would be inundated infrequently throughout this period up to the present day. According to the stratigraphy, sea level flooded this area before 4580 – 4840 cal yr B.P. changing the area from bedrock to a tidal flat that would be subsequently suitable for mangrove establishment. Such a rise in sea level would also result in Makoba Bay becoming more constricted due to coastal squeeze against the ancient coral terrace.

From mid-Holocene to present

After the mid Holocene (from sub-zone boundaries AMAK-2a and AMAK-2b), a lower sea level is recorded by a shift of mangrove communities seawards reflected in the decrease of the average S/BC ratio in sub-zone AMAK-2a (0.57). It should be noted that zone BMAK-2 contains a similar age determination (1550 cal yr B.P.) to zone AMAK-2a, a similar average S/BC ratio (0.48), stratigraphy of the seaward core and lower sedimentation rate (0.26 mm yr^{-1}); such cross-core similarity further supports this interpretation. This period corresponds to regional drought phases across tropical Africa that started around 4500-4100 ^{14}C yr B.P. (Hassan, 1997; Bonnefille and Chalie, 2000; Thompson *et al.*, 2002; Stager *et al.*, 2003; Kiage and Liu, 2006; Rijsdijk *et al.*, 2011). This mid-Holocene drought would have influenced hydrological regimes (Gasse, 2000; Marchant and Hooghiemstra, 2004) possibly caused by a lower sea level. Less inundation frequency, and the lower sedimentation rates of these two cores, may be correlated to a decreased rate of sea level rise recorded from volcanic islands in the Southwest Indian Ocean (Camoin *et al.*, 1997; 2004) commencing after around 5000 cal yr B.P. In addition, sea level fall was probably caused by continental levering occurring at the continental margin locations after 6000 cal yr B.P. (Milne and Mitrovica, 2008) After the mid Holocene the changing S/BC ratios in sub-zone AMAK-2b indicate a slower rate of sea level rise until about 1550 to 1450 cal yr B.P. Sea level continued rising, as suggested by higher S/BC ratios from sub-zone AMAK-2b and zone BMAK-2 and increased inundation frequency compared to the present day environment. Mangroves retreated landwards until 65 cm in cores AMAK-1 and BMAK-1 reflecting the late-Holocene highstand (Ramsay, 1995; Compton, 2001; Ramsay and Cooper, 2002). Following this period, the gradual decline of S/BC ratios, combined with an increase in terrestrial grasses and sedges indicate sea level gradually fell until the present sea level was attained. The high organic content suggests a build-up of mangrove peat from *R. mucronata* and *Bruguiera*/*Ceriops* which formed during a fall in sea level. This is coincident with a study from Kenya that indicates that sea level dropped around 500 years ago (Åse, 1981).

Impacts of environmental changes and anthropogenic influences on the mangrove ecosystems of Makoba

From ~8000 to mid Holocene

Charcoal deposition from sub-zone BMAK-1a indicates that fire regimes have been a feature within the mangrove ecosystems surrounding Makoba for at least the last 8000 cal yr B.P. Relatively low charcoal content at the base of the core may correspond to a decreased incidence of fire frequency as documented across Africa of~8,000 cal yr B.P. (Power *et al.*, 2008) possibly induced by relatively humid conditions. This is likely to be coincident with the early Holocene African humid period (Thomson *et al*., 2002) and an early Holocene maximum monsoon intensity prevalent in the Southwest Indian Ocean region (Overpeck *et al*., 1996). The total charcoal content is consistently low in sub-zone BMAK-1b and zone AMAK-1 prior to about 5800 cal yr B.P. suggesting humid conditions probably relating to a Mid-Holocene humid phase (Stager *et al*., 2003).

From mid Holocene to present

From about 5800 cal yr B.P., the charcoal content increases and is likely to be congruent with the top of sub-zone BMAK-1b (particularly the rise in large particles) and zone CMAK-1 indicating greater fire frequency close to Makoba Bay and drier conditions probably corresponding to regional mid-Holocene drought (Stager *et al.*, 2003). The peak in total charcoal content from sub-zone AMAK-2a and AMAK-2b boundary is also possibly linked to a period of regionally arid conditions around 4500-4100 ^{14}C yr B.P. recorded across East Africa (Hassan, 1997; Bonnefille and Chalie, 2000; Thompson *et al.,* 2002; Stager *et al*., 2003; Kiage and Liu, 2006; Rijsdijk *et al.*, 2011). After this period to the present, variable fire frequency is indicated by the fluctuating charcoal records. From about 1400 cal yr B.P., the increase in charcoal content may relate to drier conditions as recorded from Lake Tanganyika (Alin and Cohen, 2003), Lake Masoko, southern Tanzania (Vincens *et al.*, 2003) and Namelok Swamp, southern Kenya (Rucina *et al*., 2010) and thus relating to a desiccation phase recorded throughout East Africa from 1200 to 500 cal yr B.P. Associated with an appearance of grasses and sedges and the loss of woody tree cover; this phase may reflect early human settlement in Zanzibar that commenced from the last millennium B.C. to the first millenium A.D. (2950 to 950 cal yr B.P.) (Chami, 2001; Juma, 2004). Soon after this period, the charcoal content decreases suggesting a decline in the regional fire frequency and wetter conditions. This period is probably related to the Little Ice Age when easternmost areas of East Africa experienced a period of wet conditions (Verschuren *et al.*, 2000; Russell *et al.*, 2007). The recent increase in charcoal, particularly in the large size particles, recorded in all three cores, demonstrates a greater fire frequency close to Makoba Bay. This is coincident with decreased mangrove taxa, particularly *R. mucronata*, that is further evidence of increased anthropogenic influences; possibly coincident with the urbanisation of Zanzibar was developed from around A.D. 1500 (450 cal yr B.P.) as the Portuguese colonised the island (Horton and Clark, 1985; Nimaga, 2011). Harvesting of mangrove for poles, charcoal and firewood trading has increased as Zanzibar developed (Masoud, 1991; Shunula, 2002; National Bureau of Statistics, 2006) resulting in mangrove ecosystems becoming seriously threatened due to over-exploitation (Shunula, 2002). This threat, although focused on the resource provision from mangrove ecosystems, is also impacting on the ability to provide a buffer to mitigate against coastal erosion and salinisation of freshwater supplies to the island inhabitants.

Conclusions

The relationship of indices between mangrove pollen in surface samples and present vegetation provide an aid to the interpretation of fossil mangrove pollen records from Makoba Bay, Zanzibar.

1. Mangrove dynamics/sea level relationships are reconstructed using changes in the proportions of *Sonneratia*/*(Bruguiera/Ceriops*) (S/BC) from vegetation plots with respect to mean sea level to characterise the inundation of mangrove assemblages.

2. Mangrove ecosystems established in Makoba Bay from at least the early Holocene. This is evidence for a rapid early-Holocene sea level rise as mangroves migrated landward. The S/BC ratios suggest the mangrove environment experienced higher inundation frequency due to a mid Holocene sea level rise and the mangroves in Makoba became constricted against the ancient coral terrace.

3. A lower sea level is inferred after the mid Holocene by the decrease in S/BC ratios resulting in mangroves migrating seaward. An increase in charcoal content at this time is contemporaneous with arid conditions across the East Africa region. From about 1400 cal yr B.P., the increase in charcoal is likely to relate to drier conditions,. After 1450-1550 cal yr B.P., sea level rose as mangroves shifted landward to a late-Holocene highstand after which sea level gradually fell until the present day.

4. The recent increase in charcoal, in combination with decreased mangrove taxa, particularly *R. mucronata*, provide evidence on the impact of anthropogenic activities within mangrove ecosystems in Zanzibar.

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Supplementary table 1 Stratigraphic description of cores AMAK-1, BMAK-1 and CMAK-1.

Sites	Altitude amsl (m)	Depth (cm)	Sedimentary description
AMAK-1	0.60 – 0.53	0-7	Dark brown sand containing some small root fragments
	0.53 – (-0.40)	7-100	Peat containing fragments of woody plant roots and some wood and bark fragments with fine brown sand
	(-0.40) – (-0.70)	100-130	Grey sand with peat containing small fragments of woody plant root
	(-0.70) – (-1.12)	130-172	Grey sand with frequent small fragments of root and some wood and bark fragments
	(-1.12) – (-1.22)	172-182	Sand with peat containing small fragments of woody plant root
	(-1.22) – (-1.53)	182-213	Grey silt with fine sand and small root fragments
	(-1.53) – (-1.90)	213-250	Grey silt with fine sand containing some small organic material and shell fragments
	-1.9	250	Impenetrable
BMAK-1	0.45 – 0.39	0-6	Dark brown sand
	0.39– (-0.52)	6-97	Peat containing small fragments of woody plant roots and some wood and bark fragments with fine brown sand
	(-0.52) – (-0.75)	97-120	Brown sand with frequent small fragments of woody plant roots
	(-0.75) – (-1.50)	120-195	Grey sand with grey silt containing frequent small fragments of woody plant roots
	(-1.50) – (-1.91)	195-236	Grey silt with fine sand containing some small fragments of woody plant roots and some small shell fragments
	(-1.91) – (-2.91)	236-336	Grey silt with fine sand containing frequent small root fragments and some small shell fragments
	(-2.91) – (-3.55)	336-400	Grey silt with some undifferentiated organic material
	-3.55	400	Impenetrable
CMAK-1	1.51 – 1.38	0-13	Light brown fine sand
	1.38 – 1.31	13-20	Brown silt with fine sand
	1.31 – 0.44	20-107	Grey silt with fine sand containing frequent small fragments of root
	0.44 – (-0.23)	107-174	Grey silt with coarse sand and frequent small fragments of woody plant roots.
	-0.23	174	Bedrock

Supplementary table 2 Description of pollen diagrams showing pollen zone characteristics for the three core sites of Makoba (AMAK-1, BMAK-1, CMAK-1).

Sites	Pollen zone	Pollen zone description	Environmental interpretation
AMAK-1	AMAK-2b (altitude 0.60-(-0.30) m amsl, depth 0-90cm)	Mangrove dominates. *R. mucronata* declined at the beginning of this zone, then increased and declined while *Bruguiera/Ceriops* increased at the top of this zone. Mangrove (94-99%): *R. mucronata* (44-84%), low *A. marina* (<2%), *Bruguiera/Ceriops* (5-49%), *S. alba* (0-12%), *X. granatum (<1%)*. Herbaceous taxa increased at the top (1-4%). Low peridophyte spores (0-4%).	Mangroves retreated seaward probably lower sea level and less inundation frequency
	AMAK-2a (altitude (-0.30)-(-1.10) m amsl, depth 90-170cm)	Mangrove dominates although *S. alba* declined while *R. mucronata* and *Bruguiera/Ceriops* increased. Mangrove (92-99%): *R. mucronata (*73-87%), *A.marina* (1-3%), *Bruguiera/Ceriops* (3-16%), *S. alba* (0-5%). Very low herbaceous taxa (<1%). Low peridophyte spores (0-5%).	Mangroves retreated seaward probably lower sea level and less inundation frequency
	AMAK-1 (altitude (-1.10)- (-1.90) m amsl; depth 170-250 cm)	Mangrove dominates characterised by *R. mucronata* accompanied by *S. alba*. Mangrove (94-99%): *R. mucronata* (64-80%), *A. marina* (1-4%), *Bruguiera/Ceriops* (2-7%), *S. alba* (9-26%) , *X. granatum* (<1%). Very low herbaceous taxa (<1%). Low peridophyte spores (0-4%).	Mangroves established probably increased sea level inundated daily
BMAK-1	BMAK-2 (altitude 0.45-(-1.45) m amsl, depth 0-190cm)	Mangrove dominates. *S. alba* decreased at the beginning of the zone. *Bruguiera/Ceriops* increased at the top of the zone. Mangrove (94-97%): *R. mucronata* (65-77%), *A. marina* (2-7%), *Bruguiera/Ceriops* (6-25%), *S. alba* (1-12%), *X. granatum (<1%)*. Back mangrove appeared at the top of the zone (1-3%). Herbaceous taxa increased at the top (0-6%). Pteridophyte spores (0-7%).	Mangroves retreated seaward probably lower sea level and less inundation frequency
	BMAK-1b (altitude (-1.45)-(-2.75) m amsl, depth 190-320cm)	Mangrove dominates. *S. alba* increased and *Bruguiera/Ceriops* declined at the beginning of the zone. Mangrove (88-97%): *R. mucronata* (57-67%), *A. marina* (1-5%), *Bruguiera/Ceriops* (2-12%), *S. alba* (10-36%), *X. granatum* (<1%). Very low back mangrove (<1%). Very low herbaceous taxa (<1%). Low peridophyte spores (1-5%).	Mangroves shifted landward probably increased sea level inundated daily
	BMAK-1a (altitude (-2.75)-(-3.55) m amsl; depth 320-400 cm)	Mangrove dominates characterised by *R. mucronata* accompanied by *Bruguiera/Ceriops.* Mangrove (92-97%): *R. mucronata* (65-73%), *A. marina* (1-5%), *Bruguiera/Ceriops* (9-22%), *S. alba* (1-6%) , *X. granatum* (<1%). Very low herbaceous taxa (<1%). Low peridophyte spores (1-5%).	Mangroves established inundated several times during a month

Supplementary table 2 Description of pollen diagrams showing pollen zone characteristics for the three core sites of Makoba (AMAK-1, BMAK-1, CMAK-1) (cont.)

Sites	Pollen zone	Pollen zone description	Environmental interpretation
CMAK-1	CMAK-3 (altitude 1.51-1.01 m amsl, depth 0-50 cm)	Mangrove dominates. *R. mucronata* increased while *Bruguiera/Ceriops* declined at the beginning of this zone. In the middle of this zone *R. mucronata* declined while *Bruguiera/Ceriops* increased and back mangrove appears at the top of the zone. Mangrove (93-100%): *R. mucronata* (23-60%), low *A. marina* (<3%), *Bruguiera/Ceriops* (40-67%), very low *S. alba* (<1%) and *X. granatum* (<1%). Herbaceous taxa increased at the top (0-3%). Low peridophyte spores (0-3%).	Mangroves recovered, probably higher sea level at the beginning of this zone indicating increased inundation frequency. Mangrove then gradually retreated seaward probably due to lower sea level and less inundation frequency to the present day.
	CMAK-2 (altitude 1.01-0.46 m amsl, depth 50-105cm)	Mangrove dominates characterised by *Bruguiera/Ceriops* which increased while *R. mucronata* declined at the top of the zone. Mangrove (95-98%): *R. mucronata (27*-53%), *A. marina* (2-3%), *Bruguiera/Ceriops (42-70%)*, *S. alba* (1-2%). Very low herbaceous taxa (<2%). Low peridophyte spores (1-3%).	Mangroves established, inundated infrequency during a month. Less inundation to the top of this zone probably due to lower sea level.
	CMAK-1(altitude 0.46-(0.23) m amsl, depth 105-174cm)	Low pollen and spore preservation.	Not possible.

Chapter 4: Holocene mangrove dynamics from Unguja Ukuu, Zanzibar

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Abstract Sediment, pollen and charcoal data, set within a radiocarbon chronological framework, from Unguja Ukuu, Zanzibar are used to reconstruct mangrove ecosystem dynamics during the Holocene. Changes in mangrove ecosystem composition were driven by a combination of sea level and environmental changes, anthropogenic interaction and geomorphological activity. The high occurrence of *Rhizophora mucronata*, accompanied by other mangrove species, suggests that the headland of Unguja Ukuu supported a mangrove community from about 7000 cal yr B.P. During the mid Holocene, mangroves migrated landward, probably in response to a sea level highstand. After the mid Holocene a short term decrease in *Sonneratia alba*, with an increase in more terrestrial mangrove species, the appearance of Poaceae and increase in the quantity of charcoal all indicate a lower sea level and relatively dry environmental conditions. This is likely to be coincident with the appearance of the earliest habitation of Zanzibar. The increase in *S. alba* pollen until prior to 530 cal yr B.P. is likely to reflect a sea level rise. The increase in charcoal after about 1400 cal yr B.P. is likely to relate to drier conditions and may reflect early human settlement at Unguja Ukuu. A recent decrease in *R. mucronata*, combined with an increase in *S. alba*, is likely to result from sea level rise and decreased moisture availability. Recent human-ecosystem interactions are characterised by a reduction in mangrove extent, possibly associated with the mangrove pole trade and rising fuelwood consumption in Zanzibar, particularly from around 530 cal yr B.P.

Keywords: pollen, charcoal, sea level, human impact, Tanzania

Introduction

Mangroves are tropical ecosystems consisting of evergreen trees and shrubs that are physiologically and morphologically adapted to exist in the intertidal zone between mean sea level and high water spring level (Woodroffe and Grindrod, 1991; Blasco *et al.*, 1996; Ellison and Farnsworth, 2001; Ellison 2008). Mangrove ecosystem composition is sensitive to changes in sea level, climate and anthropogenic disturbance (Blasco *et al.,* 1996; Hogarth, 1999; Gilman *et al.*, 2008); responding by migrating landward or seaward with a rise or fall in sea level respectively (Figure 4.1). Mangroves provide a range of services and materials needed to support livelihoods e.g. timber for poles, fences, houses, boats, fish traps and are an important source of fuel (charcoal and firewood) (Masoud, 1991; Thevenon *et al.,* 2003; Omodei *et al.,* 2004; FAO, 2007). Although mangroves in Zanzibar were listed as protected in 1968 (Semesi, 1998), and public awareness for conservation of the mangrove ecosystems has increased (Shunula, 2002), there is still considerable concern for the sustainable utilization and management of these ecosystems.

Stratigraphic, pollen, charcoal and loss on ignition analyses, set within a radiocarbon dated chronological framework, are used to reconstruct mangrove dynamics. Mangrove zonation can be related to sea level fluctuations by comparison with the contemporary vegetation assemblages and their sea level inundation relationships. These relationships are used to reconstruct Holocene sea level fluctuations and coastal changes at Unguja Ukuu, the former capital of Zanzibar. Charcoal analysis is used to reconstruct past fire regimes, infer climatic conditions, and possible inter-connections between ecosystem and societal developments.

Study site

Environmental setting

Zanzibar is a group of islands lying to the east of mainland Tanzania and consisting of two major islands, Unguja, colloquially called Zanzibar, and Pemba.

Zanzibar is located in the Southwest Indian Ocean about 40 km from the mainland separated by the Zanzibar channel (Figure 4.2). Zanzibar is about 85 km long and 39 km wide with an area of 1,660 km^2 (Mustelin *et al*., 2009) and surrounded by fringing coral reefs with approximately 6,000 hectares of mangroves found along the western shores (Francis and Bryceson, 2001). Most of Zanzibar consists of Pleistocene reef limestone covered by quartz sand (Schlüter, 1997; Arthurton *et al*., 1999). Zanzibar is influenced by a semi-diurnal tide, ranging from 3 m on neap tide to 5 m on spring tide (Shunula, 2002). The rainfall pattern within Zanzibar is largely controlled by the biannual migration of the Inter-tropical Convergence Zone (ITCZ) with the northeast and southeast monsoon bringing the heaviest rains from March to May and lesser rains from October to December (Machiwa and Hallberg, 1995; Knopp, 2008; Moynihan, 2010; Mwandya *et al*., 2010). The Indian Ocean Dipole, an episodic movement of warm water pools across the Indian Ocean, is another climatic driver that influences rainfall pattern (Saji *et al*., 1999; Behera *et al*., 2003; Marchant *et al*., 2006). The mean annual rainfall is about 1500-1800 mm yr^{-1} (Knopp, 2008) and the average temperature range is about 23-30 ºC (Machiwa and Hallberg, 1995; Juma, 2004).

Although there are ten species of mangrove found on Zanzibar (Shunula, 2002; Francis and Bryceson, 2001), field-based observations at three coastal sites found eight species of mangrove commonly forming a distinct vegetation zonation (Figure 4.1). *Avicennia marina* and *Sonneratia alba* are found at the outer edges of mangrove community; although *A. marina* shows a bimodal distribution also being found at landward locations. *Rhizophora mucronata* and *Bruguiera gymnorrhiza* form a thick belt in the inner mangrove. *Ceriops tegal* and *Lumnitzera racemosa* appear in the upper intertidal and dry areas. *Xylocarpus granatum* occurs in landward fringes where environmental conditions are less saline. *Acrostichum aureum* appears in a transition zone to freshwater swamp. The zonation of the Zanzibar mangrove ecosystems has been developed based on a combination of Watson's (1928) and Santisuk's (1983) inundation classes which have been developed as mangrove ecological distributions with regards to their appearance and response to tidal inundation regimes (Table 4.1) and fieldwork observations (Punwong *et al.*, submitted) and is used to interpret ecosystem and environmental changes through the fossil record (Figure 4.1).

The study area is located in the mangrove area of the east Makime headland of Unguja Ukuu (Juma, 2004) about 25 km south of Zanzibar town (Figure 4.2). The study area is covered by a belt of dense mangroves approximately 75-120 m in width and approximately 1 km in length occurring in a north-south alignment with the majority of trees reaching heights of between 1 and 2 m. The site is restricted to the south by the sea, to the west by a 3 m sand ridge high aligned in a north-south direction, and to the north by the villages of Unguja Ukuu and a creek bank in front of the mangrove area with a narrow sandy beach. The study area is influenced by tidal cycles and experiences minimal freshwater input from terrestrial runoff even during heavy rains season.

Table 4.1. Watson's (1928) inundation classes.

Inundation class	Area flooded by	Times flooded per month	
		From	To
1	All high tides	56	62
2	Medium high tides	45	56
3	Normal high tides	20	45
4	Spring high tide	2	20
5	Highest astronomical tides	-	2

Historical context

The timing of habitation on Zanzibar is highly controversial with studies suggesting settlement from the Neolithic period (Ingrams, 1931) to the 1st millennium BC (McIntyre and McIntyre, 2009). Dates on shell beads, potsherds, domesticated chicken and cat bones suggest that Zanzibar may have been inhabited from East Africa, around the third millennium BC (4000 ^{14}C B.P.) with a settled hunting-fishing community establish around the last millennium BC (Chami, 2001). The first archaeological evidence of settlement was recorded from Unguja Ukuu, the former capital of Zanzibar (Horton and Clark, 1985) and dates to around A.D. 500. By A.D. 500-750, a settlement of around 4 hectares existed and expanded to about 15-18 hectares by around A.D. 900 (Horton and Clark, 1985, Juma, 2004). Evidence from the early site includes mud-timber buildings, pottery, iron workings and other craft materials for domestic use and trading although there was no evidence of agricultural crops (Juma, 2004). There are also many ruins in Unguja Ukuu, emphasizing its past use as a major settlement and trade port (Horton and Clark, 1985). Trade connecting the town with other sites on the mainland, islands and the wider Swahili coast of East Africa has contributed to the development of Unguja Ukuu (Horton and Clark, 1985; Juma, 2004). Unguja Ukuu collapsed, probably due to the civil war, after around A.D. 900 (Juma, 2004). The number of archaeological sites increased along the coasts of Zanzibar from A.D. 1100 to 1400, especially on the western side of the island due to the increase in international contacts and the expansion of early Islamic communities as recorded by pottery, stone buildings, tombs and mosques (Horton and Clark, 1985; Kessy, 2003; Juma, 2004). Unguja Ukuu was re-occupied as an Islamic settlement around A.D. 1450-1600, as recorded by the stone buildings and tombs (Juma, 2004). The Portuguese presence on Zanzibar from the 15 century A.D. developed a trade community around Zanzibar Town (Kessy, 2003; McIntyrn and McIntyrn 2009). In the 18th century, Zanzibar was ruled by Oman leading to the rapid development and urbanisation of Zanzibar Town (Kessy, 2003; McIntyrn and McIntyrn 2009) which became the centre of trading, particularly in slaves and ivory, on the East African coast and then the capital of Oman. Zanzibar was a British protectorate from 1890, and obtained independence in 1963.

Material and methods

Fieldwork and sampling

Four sediment cores (A-UU-1 (07º47'22''S, 039º23'59''E), B-UU-1 (07º51'25''S, 039º20'26''E), C-UU-1 (07º54'07''S, 039º15'04''E) and C-UU-4 (07º54'07''S, 039º15'04''E)) were collected along a transect perpendicular to the coastline from seaward, mid shore, landward and an area approximately 300 m to the north of C-UU-1 respectively (Figure 4.2). A peat auger was used to test the stratigraphy and a 50 cm long, 5 cm diameter Russian corer used to extract sample cores from overlapping adjacent boreholes. The characteristics of sediments were described using a modified version of the Tröels-Smith (1955) classification (Kershaw, 1997). The sample cores were extruded into P.V.C. pipes, wrapped in aluminum foil and plastic sheeting and then labelled and packaged for transportation to the University of York where they were stored at -18 ºC.

Vegetation plots

Vegetation in nine 20 m^2 nested quadrats was recorded to study the plant and structural composition at different altitudes and levels of tidal inundation. Tree diameter was noted and surface sediment samples were collected to study the relationship between pollen assemblages and vegetation composition. Modern mangrove specimens and anthers to be used for pollen identification were also collected from the vegetation survey plots. Altitudinal heights in each quadrat were obtained using a differential GPS (δGPS model Leica TCRA Total Station) and leveled to the Ministry for Lands and Environment Benchmark (Zanzibar). To establish the relationship between modern mangrove assemblages and present altitude of the sea three vegetation quadrats are located at each core site (A-UU-1, B-UU-1, C-UU-1), two approximately 300 m apart in seaward (A-UU-2, A-UU-2), one in the mid-tide section (B-UU-2, B-UU-3) and one in the landward area (C-UU-2, C-UU-3) (Figure 4.1). The results from the δGPS were then used to map the altitudinal gradient for the species distribution using Inverse Distance Weighting within ArcGIS software. The relationship of the present day mangrove species distribution along different altitudinal gradients is used to reconstruct past sea level fluctuations through the fossil pollen records (Punwong *et al.*, submitted).

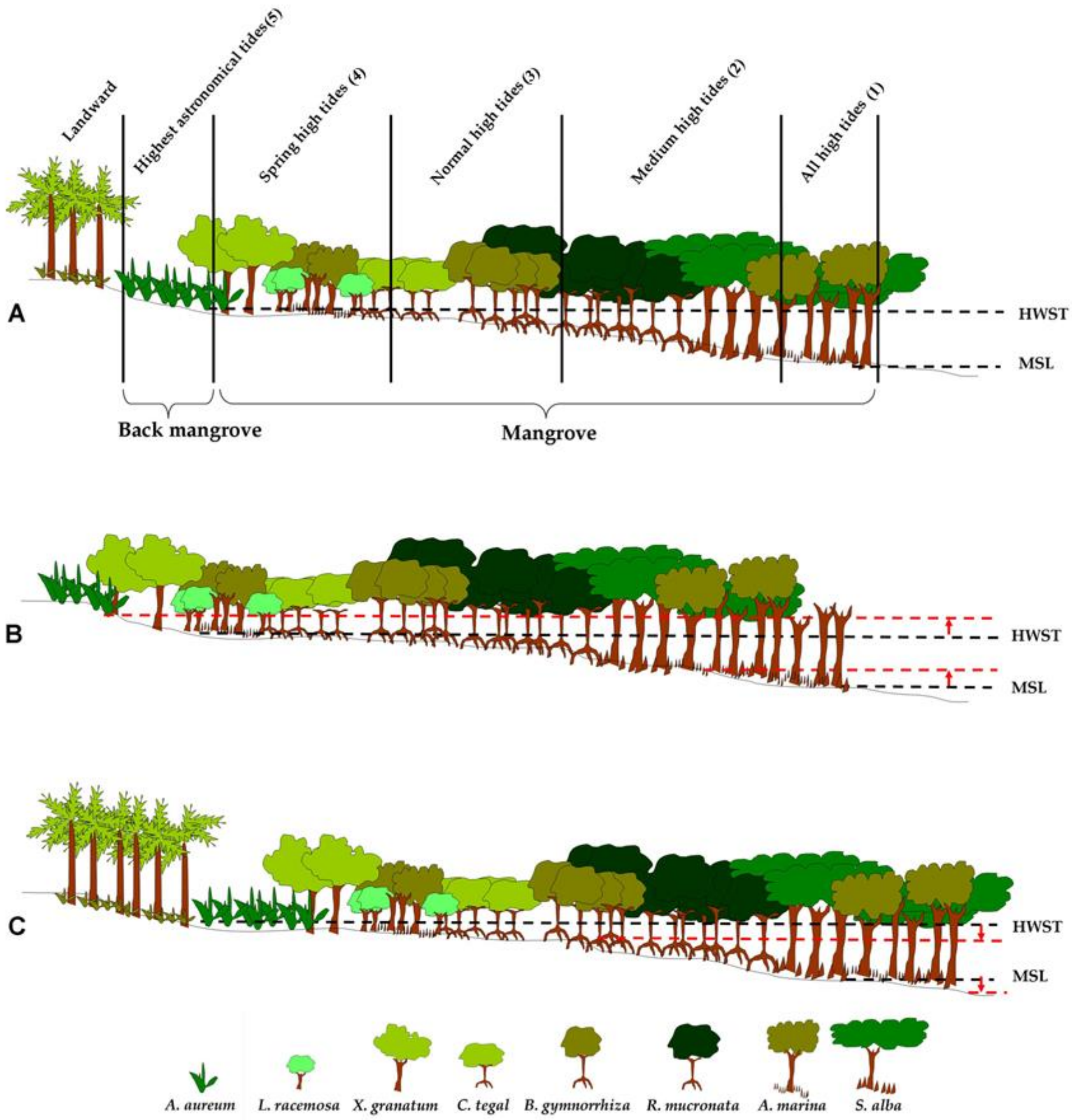


Figure 4.1. Summary cross section showing typical mangrove zonation in Zanzibar developed from Watson's (1928) and Santisuk's (1983) inundation classes and field observations. Numbers inferring inundation Watson's (1928) classes.

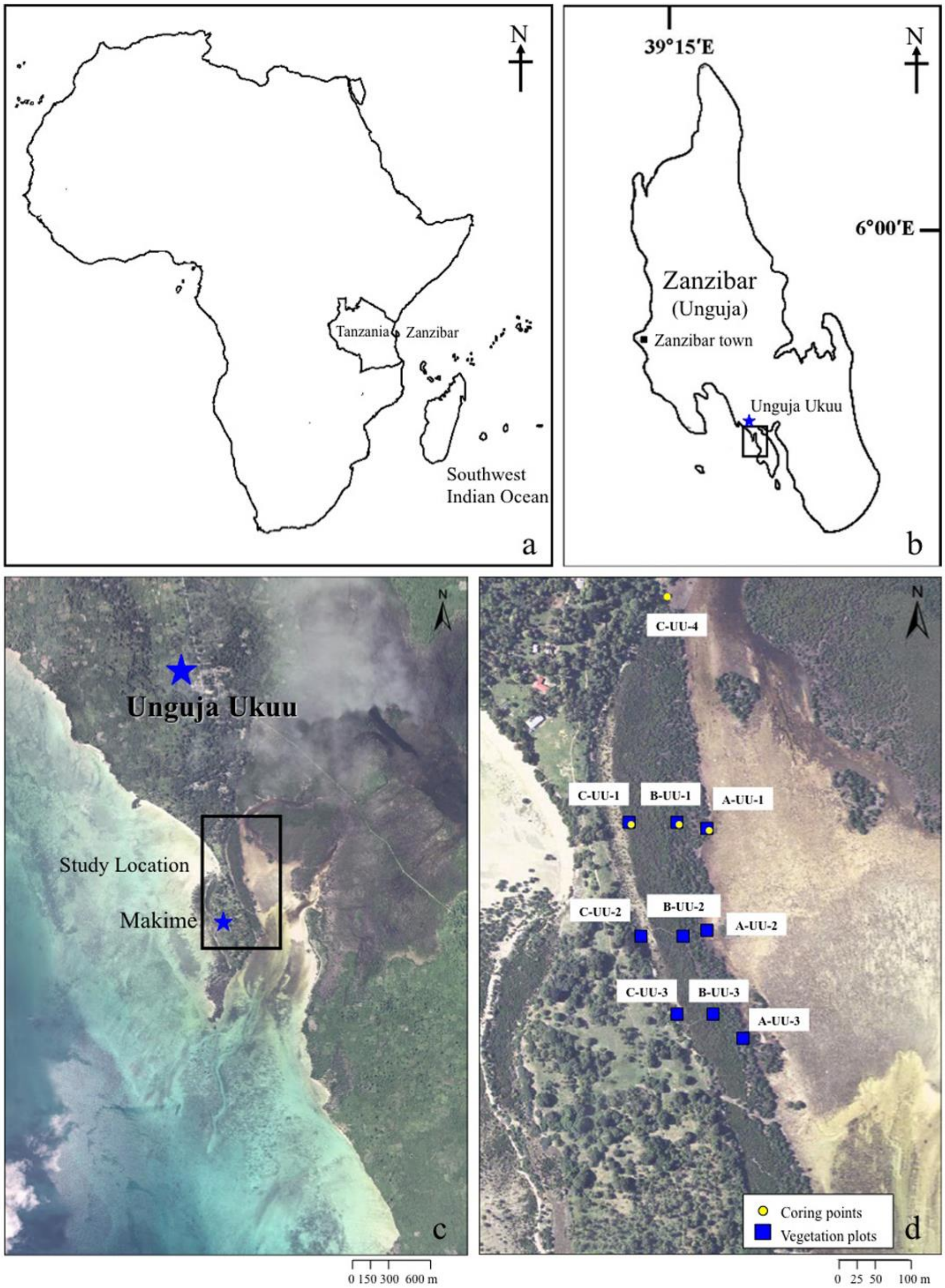


Figure 4.2. Map of Zanzibar showing the location of Unguja Ukuu. Inset d. shows where sedimentary cores were taken and the vegetation plots located.

Palaeoecological analysis

2 cm^3 of sediment was sub-sampled at intervals of 10 cm along the length of each core for pollen analysis and measurement of organic matter (OM) and calcium carbonate ($CaCO_3$) content by loss on ignition (LOI) at 550 ºC and 950 ºC respectively following procedures outlined by Heiri *et al.* (2001). Pollen and spores from sediment cores and surface samples were extracted using the acetolysis method (Erdtman, 1969; Faegri and Iversen, 1989). Sample residues were stored in silicone oil. More than 95% of pollen and spores were identified by comparison with pollen from extant mangrove specimens collected and identified from the study areas and modern mangrove references (Thanikaimoni, 1987; Punwong, 2008) and most of the unidentified grains comprise separate taxa. *Bruguiera gymnorhiza* and *Ceriops tegal* were grouped together as *Bruguiera/Ceriops* type because they could not be distinguished under light microscopy (Grindrod, 1985). The pollen content of some samples was very sparse and therefore insufficient to achieve a count of 200 grains. To determine the optimal grain count, pollen and spores in 5 samples from the each site were counted and the number of taxa recorded for every 20 grains up to count of 200 grains. After 80 grains the number of new taxa did not increase; therefore at least 150 pollen grains were counted for each level. This pollen count also conforms to other palaeoecological studies in mangrove environments (e.g. Ellison, 1989). The pollen data are represented as percentage pollen frequency diagrams and are zoned using stratigraphically constrained cluster analysis, CONISS, based on sum of pollen and spores within the graphics software TILIA2 and TILIA*Graph (Grimm, 1991).

The pollen assemblages and chronologies from the B-UU-1 and C-UU-4 core sites showed that there was a potential record of human impacts and therefore charcoal analysis was also undertaken on these cores. Pollen-slide charcoal analysis was conducted using size class of microscopic charcoal modified from Tinner and Hu (2003) and Rucina *et al*. (2009). The charcoal counts for each size class are presented as the total number of fragments enumerated within a complete slide. The total charcoal accumulation is expressed for each size class and totalled by summing the multiples of the mean length of each size class with the quantity of fragments per calculated area of each sample slide.

Statistical analysis

Statistical analyses were undertaken in order to understand the relationship between the pollen assemblages and vegetation composition and the reliability of using the proxy of mangrove pollen assemblages to reconstruct past environments and sea level changes. These included three indices devised by Davis (1984): association index (A), under-representation index (U), over-representation index (O), to identify how accurately the pollen grains reflect source plants. Correlation coefficients (CC) are used to describe the correlation between surface pollen percentages and plant percentages from nine vegetation quadrats.

Chronology

Six bulk sediment samples, identified from notable biostratigraphical changes, were selected for AMS dating and submitted to Radiocarbon Dating Laboratories at the CHRONO Centre, Queen's University Belfast, UK. The dates were calibrated to calendar years with the southern hemisphere calibration of Shcal04 curve (McCormac *et al.*, 2004) using the software OxCal v4.10 (Bronk-Ramsey, 2009).

Results

Stratigraphy and loss on ignition

The basal unit of all sediment cores is grey sand and silt overlain by a peat with woody root fragments except in C-UU-4 where a silt unit is present. Some small shell fragments are also found in A-UU-1 and B-UU-1. Peat layers with sand and small fragments of woody plant roots alternate with organic sand layers throughout the sediment column in all four cores. Sand containing small fragments of woody plant root forms the top unit of B-UU-1, C-UU-1, and C-UU-

4 while silt characterises the top unit of A-UU-1. The boundaries between stratigraphic units in all four cores are transitional (Figures 4.3, 4.4, 4.5 and 4.6).

Organic carbon and carbonate content throughout the four cores varies between 2 and 33% and 0.5-18%, respectively (Figures 4.3, 4.4, 4.5 and 4.6). A-UU-1 has relatively low organic carbon content from the base to 85 cm (5-9%) and some peaks between 75-65 cm and 35-25 cm (9-27 and 17-28 % respectively) towards the top followed by a decline to 10% at the top of the core. Carbonate content of A-UU-1 is relatively high from the base to 85 cm and from 15 cm to the core top (12-18% and 8-9% respectively) corresponding to the occurrence of shell fragments. Organic carbon content of B-UU-1 from the base to 55 cm is relatively low (3-8%) but then increases towards the top of the core corresponding to the presence of organic material. Carbonate levels recorded low percentages throughout core B-UU-1 (1-3%) although levels increased at the base corresponding to the occurrence of shell fragments. The organic carbon content of C-UU-1 varies from 2 to 28 % throughout the core with peaks between 55 to 45 cm and 15 cm. Carbonate concentrations remain uniformly low throughout core C-UU-1 (1-3%). The organic carbon content of C-UU-4 is relatively high (22-31%) from the base to 185 cm but then decreases towards the core top with high values at 125 cm and 15 cm. The carbonate content is homogeneously low throughout core C-UU-4 (1-3%). The variations in organic carbon content in the four cores do not show any distinct correlation with any dominant pollen taxa or litho-stratigraphy.

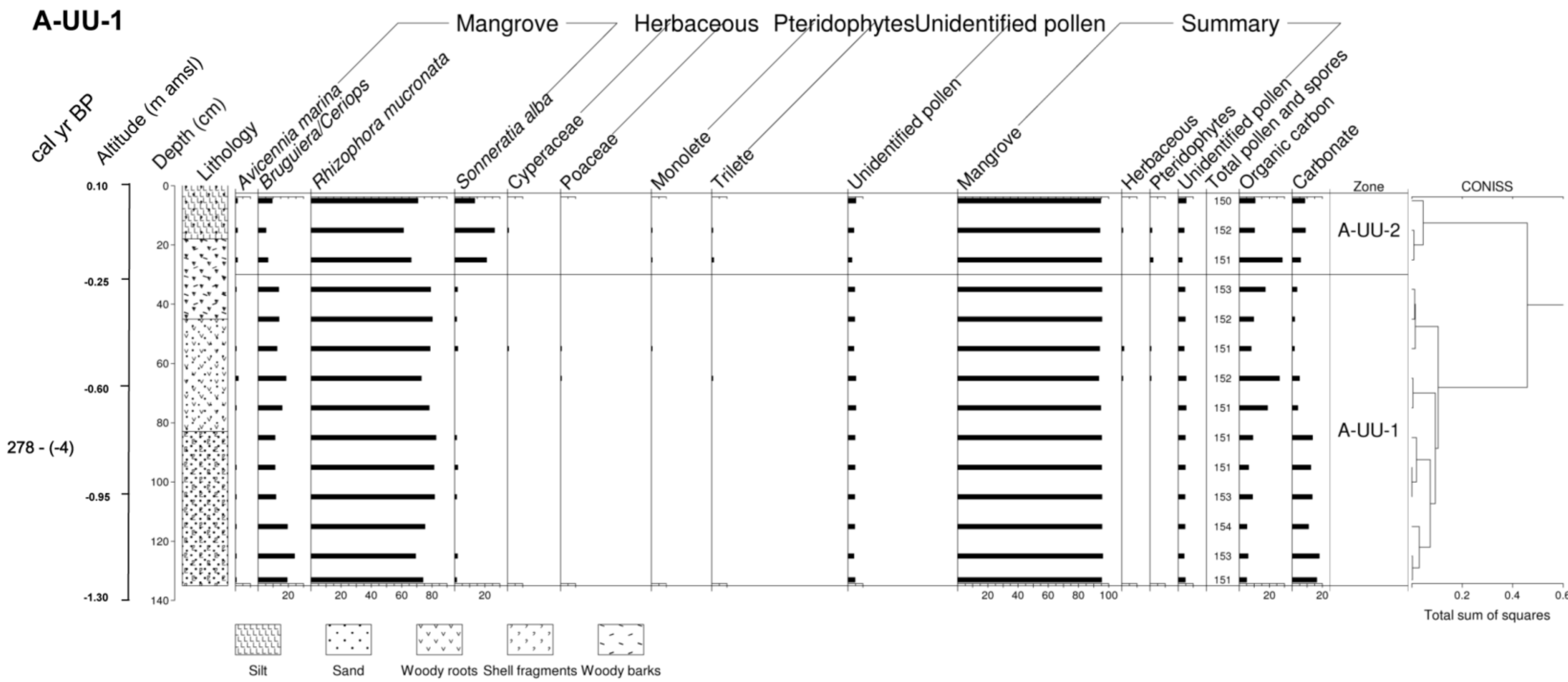


Figure 4.3. Percentage pollen frequency, organic carbon and carbonate profiles from A-UU-1.

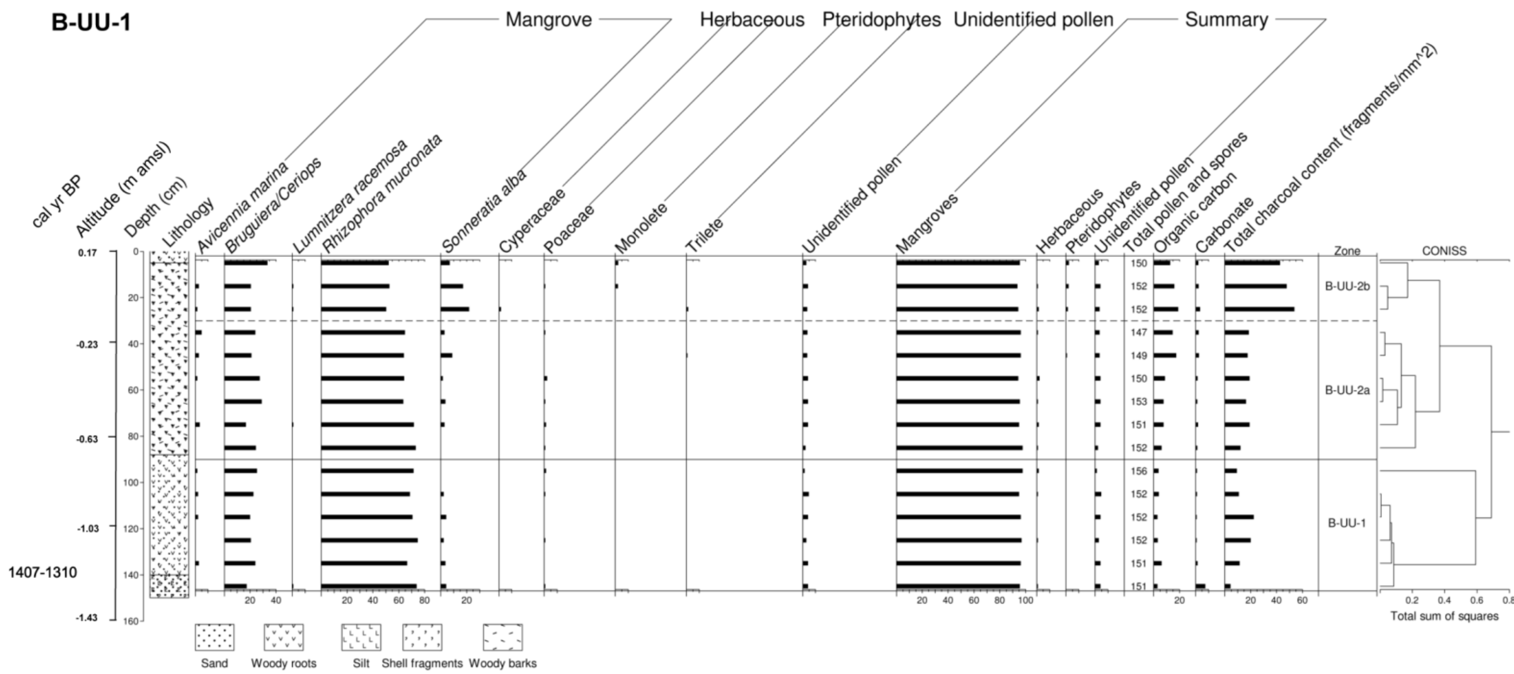


Figure 4.4. Percentage pollen frequency, organic carbon, carbonate and total charcoal content profiles from B-UU-1.

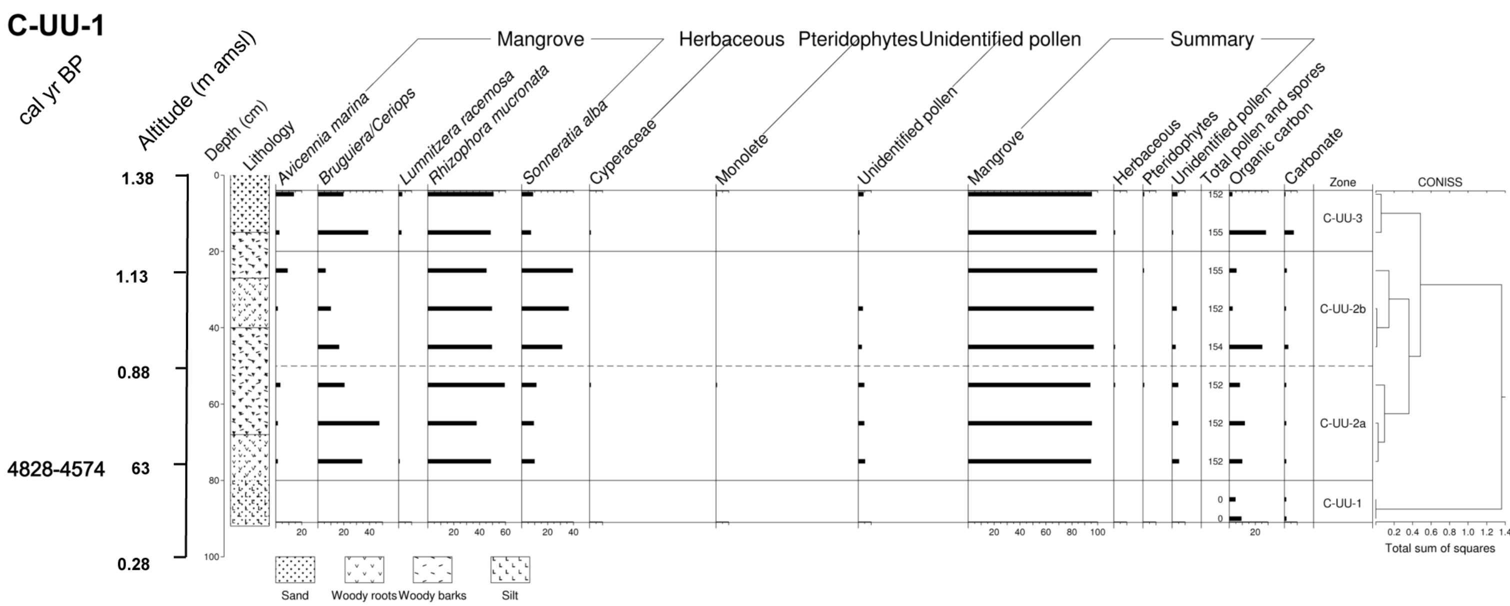


Figure 4.5. Percentage pollen frequency, organic carbon and carbonate profiles from C-UU-1.

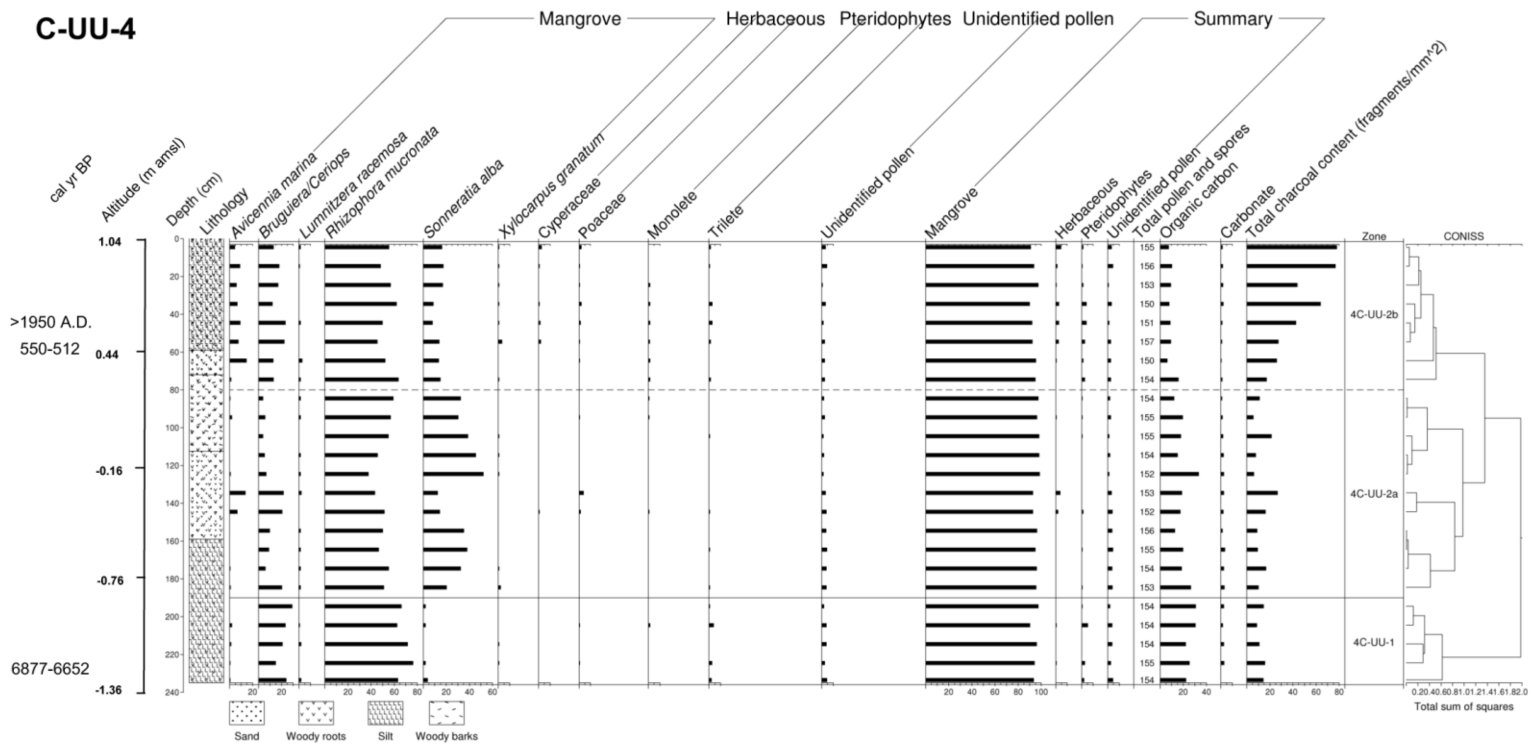


Figure 4.6. Percentage pollen frequency, organic carbon, carbonate and total charcoal content profiles from C-UU-4.

Table 4.2. List of radiocarbon dates from Unguja Ukuu including calibrated ages with Shcal09 curve (McCormac et al., 2004) using OxCal v4.10 (Bronk-Ramsey, 2009).

Site	Altitude amsl (m)	Depth (cm)	Code	$\delta^{13}C$	% Modern	^{14}C yr B.P.	(2σ) Calibrated age range yr B.P.	(2σ) cal yr B.P.
A-UU-1	-0.81	91	UBA-16626	-26.2	97.9 ± 0.3	169 ± 22	278-(-4)	137 ± 141
B-UU-1	-1.21	138	UBA-16627	-32.2	82.6 ± 0.2	1534 ± 23	1407-1310	1359 ± 48
C-UU-1	0.6	78	UBA-16628	-31	59.2 ± 0.2	4211 ± 25	4828-4574	4701 ± 127
C-UU-4	0.62	42	UBA-19485	-25.7	104.7 ± 0.4	>A.D. 1950		
C-UU-4	0.42	62	UBA-16629	-25.5	93.3 ± 0.2	560 ± 19	550-512	531 ± 19
C-UU-4	-1.26	230	UBA-16630	-26.4	47.5 ± 0.02	5973 ± 36	6877-6652	6765 ± 112

Chronology

Six radiocarbon dates have been obtained from the cores; one each from cores A-UU-1, B-UU-1, C-UU-1 and three from C-UU-4 (Table 4.2, Figure 4.7). The radiocarbon result from core C-UU-4 (42 cm) records modern age deposition (more recent than A.D. 1950) and has probably been contaminated by younger carbon.

Modern vegetation to pollen relationship

Eight angiosperm pollen taxa from the sediment cores and surface samples were identified. To aid in the interpretation of environmental conditions and sea level changes, fossil pollen and spores were grouped into mangrove, terrestrial, herbaceous and pteridophyte ecological categories. Changes in the pollen assemblages are shown in Table 4.3. To determine the association between the presence of plants in the nine vegetation plots and its pollen in surface samples from Unguja Ukuu, indices of association (A), either under- (U) or over-representation (O) and correlation coefficients (CC) for the taxa were calculated (Davis, 1984) (Table 4.4). *Bruguiera/Ceriops* and *Rhizophora mucronata* show significant correlation between pollen percentages and plant percentages and a good agreement between the dominance in pollen spectra and the local vegetation. The correlation is significant between pollen and plant percentages for *Avicennia marina* and *Sonneratia alba* indicating that there is a moderate correlation between representivity in pollen spectra and the local vegetation. Poaceae do not accurately represent the presence of their parent plants in the local vegetation.

Spatial analysis results using Inverse Distance Weighting of plant percentages obtained from nine quadrats represented in species abundance maps against the altitudinal gradient (Figure 4.8) support the field observations of modern ecological occurrences of mangrove taxa using Watson's (1928) and Santisuk's (1983) inundation classes. *A. marina* and *L. racemosa* were found only in landward sites (Figure 4.8a, 4.8c), *B. gymnorrhiza*/*C. tegal* was dominant in the middle mangrove areas and increased landwards (Figure 4.8b). *R. mucronata* was present in the middle mangrove areas and increased seawards (Figure 4.8d). *S. alba* was abundant in the seaward locations (Figure 4.8e). Contemporary vegetation assemblages observed in the field revealed a distinct horizontal relationship relative to present sea level. The reconstruction of palaeo sea level changes is determined through interpretation of the dominant mangrove taxa within the pollen record. *R. mucronata* is used as a proxy for interpretation of sea level as it dominates the pollen assemblages in all four coring sites and is combined with changes in other associated mangrove taxa including *Bruguiera/Ceriops* and *S. alba.* According to field observation of modern ecological occurrences, spatial analysis (Figure 4.8) and Watson's (1928) and Santisuk's (1983) inundation classes (Figure 4.1), *Bruguiera/Ceriops*, *R. mucronata* and *S. alba* originate from different contemporary mangrove habitats and have different tolerances to sea level inundation frequency. Therefore, sea level can be reconstructed using the changes in these three mangrove taxa as an increase in *S. alba* and *R. mucronata* will represent an increase in sea level while an increase in *Bruguiera/Ceriops* will represent a decrease in sea level as recorded in the biostratigraphic records shown in Figure 4.7.

Charcoal analysis

Total charcoal abundance from the base of core B-UU-1 after around 1407-1310 cal yr B.P. (Figure 4.9) to 35 cm is relatively low with some peaks in all charcoal class sizes between 125 and 115 cm. From 25 cm towards the top of B-UU-1 core, clear peaks in both small and large particles are observed. Total charcoal content is relatively low from the base of core C-UU-4 to 75 cm after about 6877-6652 cal yr B.P. and prior to about 550-512 cal yr B.P. with some peaks in particles < 20 µm at 135 cm and 105 cm and the appearance of the larger particles (40-60 µm) at 135 cm (Figure 4.10). From 65 cm towards the top of the core (or after 550-512 cal yr B.P. to the present) total charcoal content increases in all class sizes and particularly in the large charcoal size class > 60 µm from 25 cm towards the top. Changes in total charcoal content, especially in larger particles, are highly congruent with the pollen zone boundaries of B-UU-1 and C-UU-4 cores.

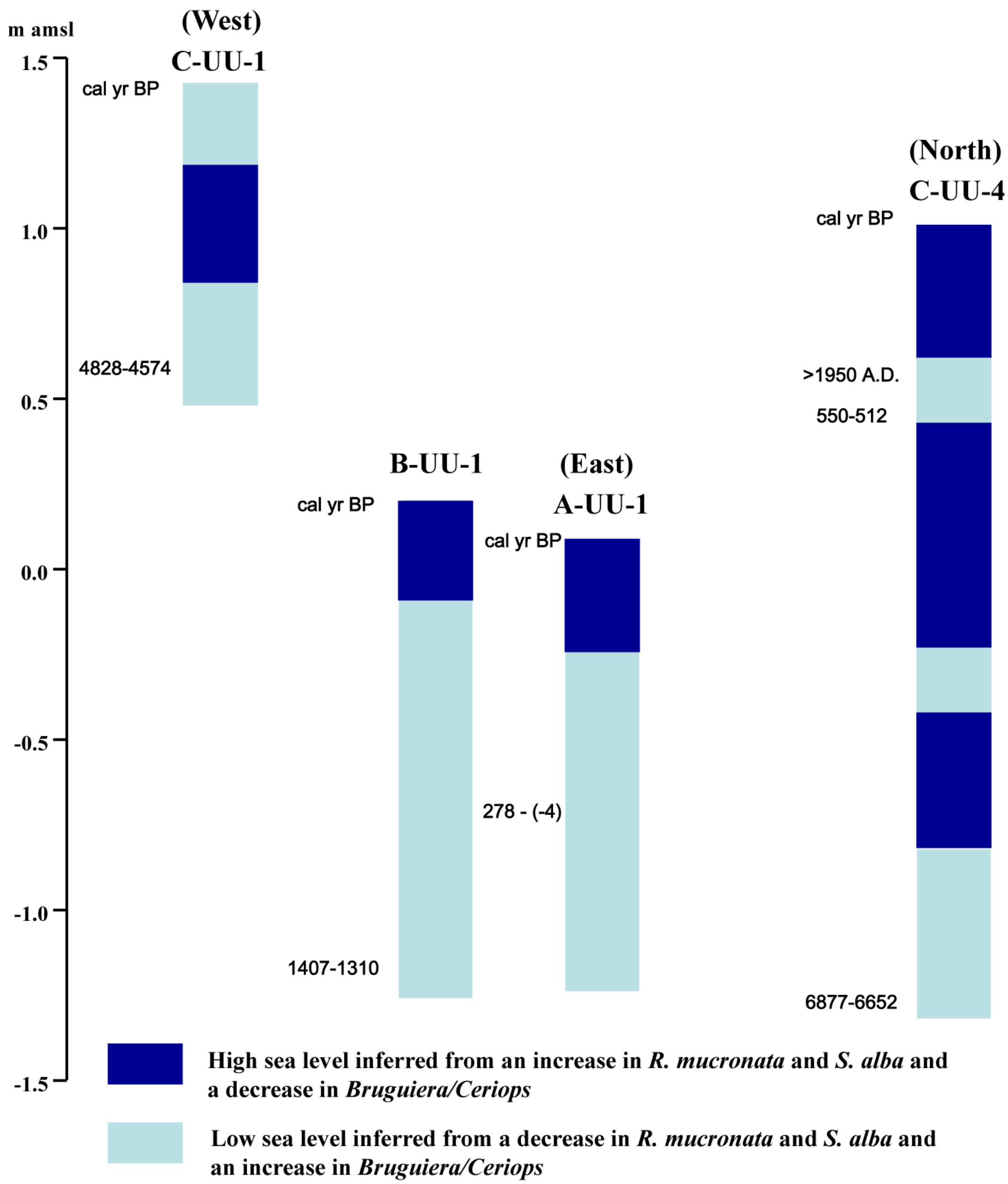
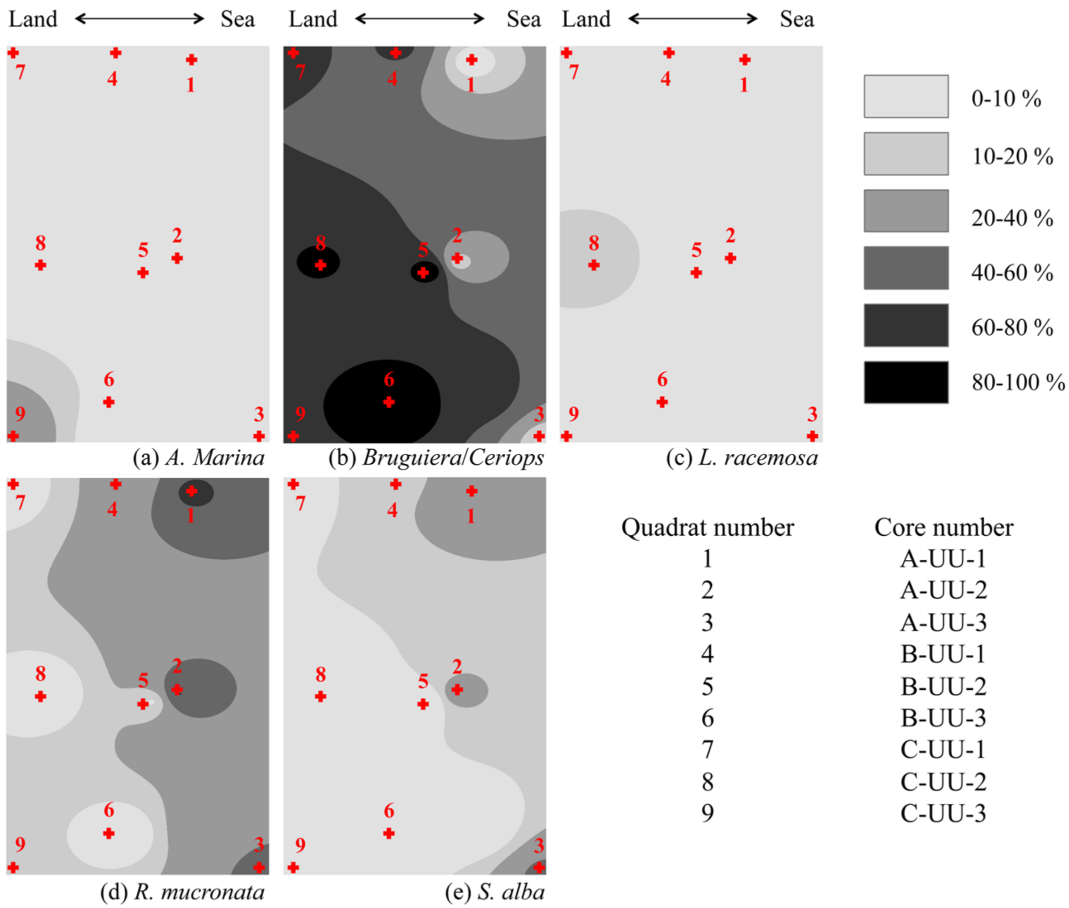


Figure 4.7. Biostratigraphy of A-UU-1, B-UU-1, C-UU-1 and C-UU-4 from the Unguja Ukuu showing sea level inferred from changes in R. mucronata, S. alba and Bruguiera/Ceriops through the fossil records (amsl = above mean sea level).



Quadrat number	Core number
1	A-UU-1
2	A-UU-2
3	A-UU-3
4	B-UU-1
5	B-UU-2
6	B-UU-3
7	C-UU-1
8	C-UU-2
9	C-UU-3

Figure 4.8. Species plots from nine quadrats sampled along altitudinal gradients at Unguja Ukuu. Shading represents plant percentage.

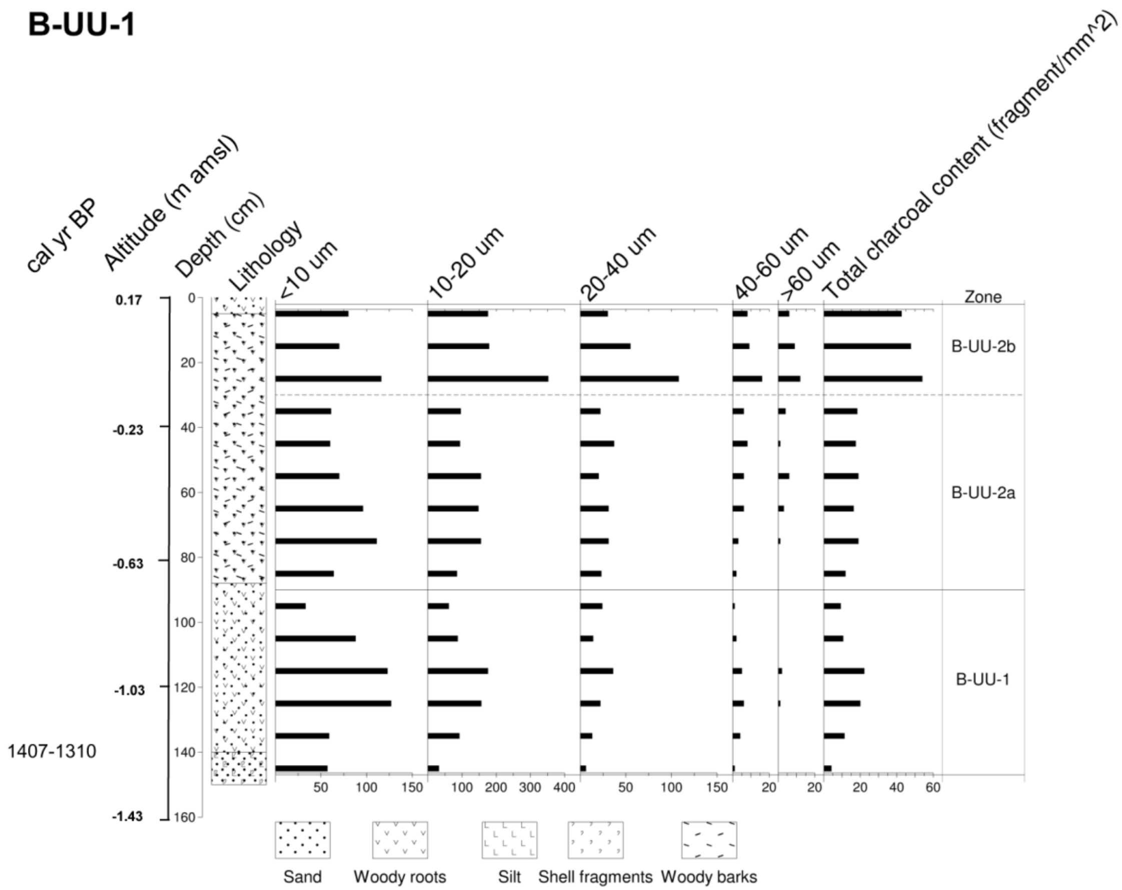


Figure 4.9. Charcoal diagram from B-UU-1 representing pollen-slide size class counts and the total charcoal content standardised to number per calculated area of each sample slide. Zonations are based on the pollen data.

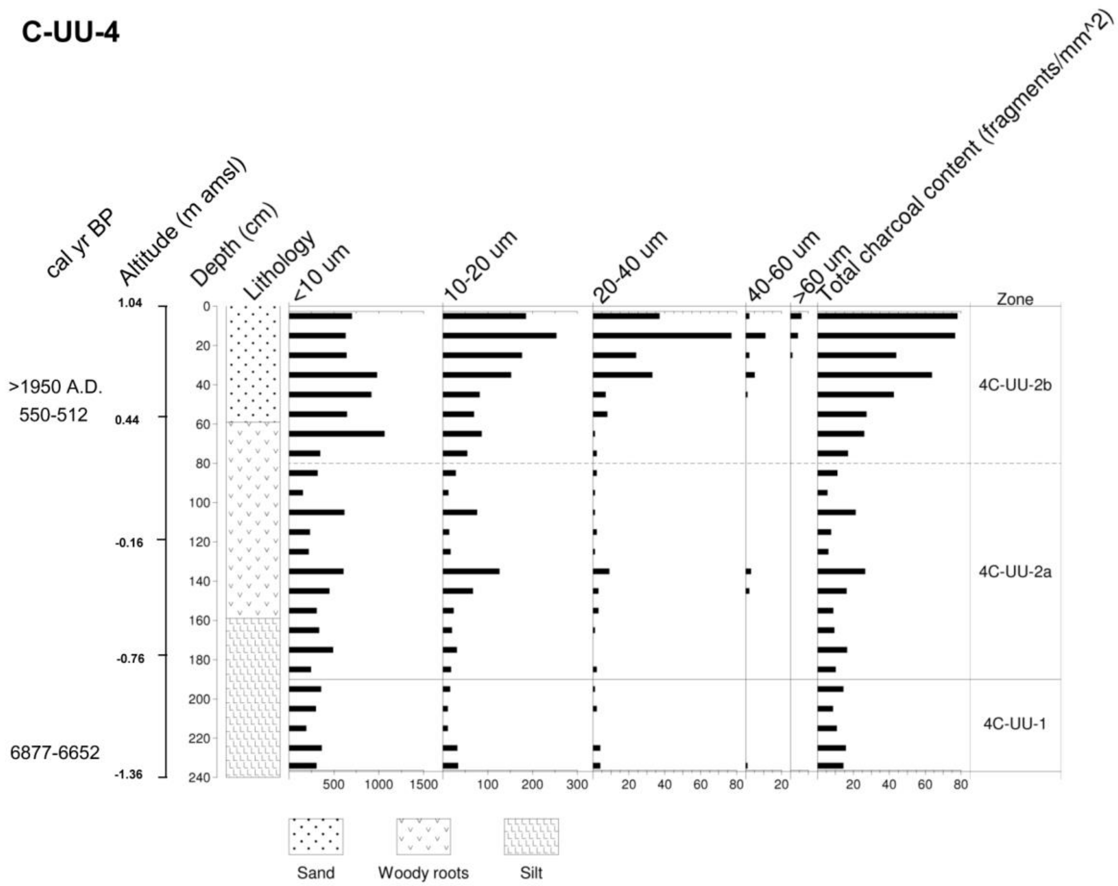


Figure 4.10 Charcoal diagram from C-UU-4 representing pollen-slide size class counts and the total charcoal accumulation standardised to number per calculated area of each sample slide. Zonations are based on the pollen data.

Table 4.3. Description of pollen diagrams showing pollen zone characteristics for the four core sites of Unguja Ukuu (A-UU-1, B-UU-1, C-UU-1, C-UU-4).

Site	Pollen zone	Pollen zone description	Environmental interpretation
A-UU-1	A-UU-2 (altitude 0.10- (-0.20) m amsl, depth 0-30cm)	Mangrove dominates (94-95%). *R. mucronata* decreases (61-71%) while *S. alba* dramatically increases (13-26%) at the beginning of this zone.	Mangroves retreated landward probably sea level rise and increased inundation.
	A-UU-1 (altitude (-0.20) - (-1.25) m amsl, depth 30-135cm)	Mangrove dominates (94-96%) characterised by *R. mucronata* (69-83%) accompanied by *Bruguiera/Ceriops* (11-24%).	Mangroves established and inundated by the sea
B-UU-1	B-UU-2b (altitude 0.17- (-0.13) m amsl, depth 0-30cm)	Mangrove dominates (93-95%). *R. mucronata* decreases (50-53%). *S. alba* dramatically increases (7-22%) and *Bruguiera/Ceriops* declines (20-33%) at the beginning of the zone and then increases at the top.	Mangroves retreated landward probably increased sea level and increased inundation.
	B-UU-2a (altitude (-0.13) - (-0.73) m amsl, depth 30-90cm)	Mangrove dominates (94-97%). *R. mucronata* decreases towards the top of the zone (65-77%).	Mangroves moved seaward probably lower sea level and less inundation.
	B-UU-1 (altitude (-0.73) - (-1.33) m amsl; depth 90-150 cm)	Mangrove dominates (95-97%) characterised by *R. mucronata* (66-74%) accompanied by *Bruguiera/Ceriops* (17-25%).	Mangroves established and inundated by the sea

Table 4.3. Description of pollen diagrams showing pollen zone characteristics for the four core sites of Unguja Ukuu (A-UU-1, B-UU-1, C-UU-1, C-UU-4) (cont.).

Site	Pollen zone	Pollen zone description	Environmental interpretation
C-UU-1	C-UU-3 (altitude 1.38-1.18 m amsl, depth 0-20cm)	Mangrove dominates (95-98%). *R. mucronata* (48-51%). *S. alba* decreases (7-9%) while *Bruguiera/Ceriops* (6-25%) increases. *A. marina* increases at the top (3-14%).	Mangroves moved seaward probably lower sea level and less inundation.
	C-UU-2b (altitude 1.18-0.88 m amsl, depth 20-50cm)	Mangrove dominates (97-99%). *R. mucronata* (45-49%). *S. alba* dramatically increases (10-36%) and *Bruguiera/Ceriops* declines (6-16%). *A. marina* increases at the top (0-9%).	Mangroves retreated landward probably increased sea level and increased inundation.
	C-UU-2a (altitude (-0.88-0.08 m amsl; depth 50-80 cm)	Mangrove dominates (94-95%) characterised by *R. mucronata* (37-60%) accompanied by *Bruguiera/Ceriops* (20-47%).	Mangroves established and inundated by the sea
	C-UU-1 (altitude 0.08-(-0.02) m amsl; depth 80-90 cm)	Very low pollen and spore preservation.	
C-UU-4	4C-UU-2b (altitude 1.04-0.24 m amsl, depth 0-80cm)	Mangrove dominates (90-97%). *R. mucronata* increases (45-64%) *S. alba* decreases (1-12%) while *Bruguiera/Ceriops* increases(4-23%). *A. marina* increased (2-15%).	Mangroves shifted seaward probably lower sea level and less inundation.
	4C-UU-2a (altitude 0.24-(-0.86) m amsl, depth 80-190cm)	Mangrove dominates (93-99%). *R. mucronata* decreases (37-57%). *S. alba* dramatically increases (12-52%) and *Bruguiera/Ceriops* declines (4-22%).	Mangroves shifted landward probably increased sea level and increased inundation.
	4C-UU-1 (altitude (-0.86)-(-1.31) m amsl; depth 190-235 cm)	Mangrove dominates (90-97%) characterised by *R. mucronata* (62-76%) accompanied by *Bruguiera/Ceriops* (15-29%).	Mangroves established and inundated by the sea

Table 4.4. Indices of association (A), under-representation (U), over-representation (O), and correlation coefficients (CC) between pollen percentages and plant percentages. **. Correlation is significant at the 0.01 level (2-tailed distribution).

Pollen type	B_0	P_0	P_1	A	U	O	CC
Present in both vegetation and pollen assemblages							
Avicennia marina	1	8	0	0.11	0	0.89	0.993**(9×10^{-8})
Brugueira/Ceriops	9	0	0	1	0	0	0.986**(10^{-6})
Lumnitzera racemosa	1	3	0	0.25	0	0.75	0.990**(4×10^{-7})
Rhizophora mucronata	6	3	0	0.67	0	0.33	0.950**(9×10^{-4})
Sonneratia alba	4	3	0	0.57	0	0.43	0.963**(3×10^{-8})
Only present in pollen assemblages							
Poaceae	0	3	0	0	0	1	

Interpretation and discussion

Understanding the relationship between contemporary vegetation and pollen representation is a prerequisite for interpreting any fossil pollen record (Davis, 1984). The pollen indices and correlation coefficients indicate *Bruguiera/Ceriops* and *Rhizophora mucronata* pollen represent their source plant very well (Table 4.4). Pollen from *Avicennia marina* and *Sonneratia alba* over-represent their parent plants moderately. Poaceae are still present in small quantities within surface pollen assemblages and are most likely to have come from the elevated areas near the study site. Hence, the constrained indices of association and correlation between mangrove pollen deposition and actual vegetation allow past environments and sea level changes to be reconstructed.

Mangrove communities from Unguja Ukuu are influenced by a number of environmental variables. In addition to sea level, changes in mangrove community composition will also be driven by climate, geomorphological setting and anthropogenic activity. These variables often operate in combination so attributing “cause and effect” relationships is more challenging than traditional palaeo archives. The suite of pollen, charcoal and LOI from multiple cores is used to reconstruct mangrove ecosystems, and attribute possible driving factor(s) to explain ecosystem changes. The character of current contemporary mangrove ecosystems and their tidal relationships are also used to guide the interpretation.

The radiocarbon chronology shows a modern date (42 cm of C-UU-4) that has probably been contaminated by younger carbon. Possible reworking of mangrove sediments by root penetration causes introduction of younger carbon and reworking and/or percolation of humic acids caused by leaching (Hammond *et al*., 1991) and/or bioturbation within the mangrove peat sequences (Vandergoes and Prior, 2003). The other five dates are comparable in age to those obtained from a second study site in the northwest of Zanzibar supporting the chronology of Unguja Ukuu (Punwong *et al.*, submitted). This shows a similar chronology and pollen record from the early Holocene (about 8000 cal yr B.P.) to the present. Therefore, these five dates provide a useful chronological context that allow us to interpret the palaeoenvironmental data as a series of time bands.

Early mangrove establishment: around 7000 cal yr B.P. to mid Holocene

Although there is a complex age-depth relationship, the sedimentary sequences show that Unguja Ukuu has been influenced by the sea and supported mangrove ecosystems from at least the mid Holocene period. C-UU-1 and C-UU-4 record mangrove development at landward sites prior to 4828-4574 cal yr B.P. and 6877-6652 cal yr B.P. respectively suggesting that Unguja Ukuu has been covered by mangroves for the last 7000 years and during the earliest part of the record was characterised by a higher sea level. Combining these two landward cores, and applying understanding of the present vegetation distribution (Figure 4.8), the following sea level interpretation has been developed (Figure 4.7).

The high occurrence of *R. mucronata* in subzone 4C-UU-1 (Figure 4.6) suggests that the headland of Unguja Ukuu was influenced by a sea level rise that allowed mangrove development from at least around 6770 cal yr B.P. Silt deposition and the high organic carbon content probably indicates sediment brought on land by marine processes and the high organic carbon content probably reflects the establishment of the mangrove ecosystem until the boundary of zone 4C-UU-1 and subzone 4C-UU-2a. It is likely that mangroves were already established during the mid Holocene and were related to a sea level rise; this has been recorded from other sites across the Southwest Indian Ocean (Jaritz *et al.*, 1977; Hashimi *et al*., 1995; Colonna *et al*., 1996; Camoin *et al*., 1997; 2004; Compton, 2001, Punwong *et al.*, 2012). Charcoal presence in subzone 4C-UU-1 indicates fires have occurred within the ecosystems surrounding Unguja Ukuu for at least the last 7000 cal yr B.P. Zanzibar was not inhabited until about 4000 ^{14}C yr B.P. ago (Chami, 2001), hence the charcoal would have originated from natural fire events. The high occurrence of *R. mucronata,* which grows in areas inundated by the sea (Tomlinson, 1986), and the low level of charcoal may reflect early Holocene humid conditions in Africa (Thompson *et al*., 2002) and an early Holocene maximum monsoon prevailing in the Southwest Indian Ocean region (Overpeck *et al*., 1996).

The stratigraphy and chronology, along with the low altitude of A-UU-1 and B-UU-1 and the higher altitude of C-UU-1 and C-UU-4 (Figure 4.7), make interpretation of sea level changes difficult. A-UU-1 and B-UU-1 appear to represent recent marine deposition but at the same altitude in C-UU-4 (about 250 m away from A-UU-1 and B-UU-1), the mid Holocene sea level change is represented. It is likely that the geomorphology of the area has been quite dynamic during the Holocene with sedimentary erosion and/or estuarine migration along the shore. A-UU-1 and B-UU-1 sites may have been located on sand bars before the mid Holocene and the sand bars may have migrated and/or eroded during the mid Holocene sea level rise (Ramsay, 1995; Ramsay and Cooper, 2002). The upper unit of the present day mangrove ecosystem is bounded by a sand bar extending to a sand beach found on Unguja Ukuu (Figure 4.1).

Mid Holocene until late Holocene (prior to 530 cal yr B.P.)

During the mid Holocene a decrease in *R. mucronata* and a dramatic increase in *S. alba* at the beginning of zone 4C-UU-2 occurred. *S. alba* is commonly found in an outer seaward position flooded by every tide (Figure 4.8d) (Watson, 1928; Santisuk, 1983; Punwong *et al.*, 2012; submitted). The recorded increase in *S. alba* suggests the mangrove environment experienced a higher inundation frequency due to a relative rise in sea level and a shift of mangrove landward allowing C-UU-4 to become a lower intertidal mangrove area. The timing of this transgression is consistent with a mid Holocene sea level highstand recorded in the Southwest Indian Ocean (Ramsay, 1995; Ramsay and Cooper, 2002). Such a mid Holocene sea level rise resulted in mangrove establishment at C-UU-1 where *R. mucronata* dominated after around 4570-4830 cal yr B.P. (Figures 4.5, 4.7). The charcoal accumulation continued to be relatively low indicating infrequent, natural fires suggesting moist environmental conditions prevailed, as inferred for the East African mainland (Stager *et al*., 2003). A short term dramatic decrease in *S. alba*, along with an increase in upper intertidal mangrove species such as *Bruguiera*/*Ceriops* and *A. marina*, as well as the appearance of Poaceae, in the middle of zone 4C-UU-2 indicate that the frequency of sea level inundations was further reduced and a lower sea level causing mangrove communities to retreat seawards occurred. This period may be coeval to the tropical Africa mid Holocene drought phase occurring at around 4500-4100 ^{14}C B.P. (Hassan, 1997; Bonnefille and Chalie, 2000; Thompson *et al.*, 2002; Stager *et al*., 2003; Kiage and Liu, 2006; Rijsdijk *et al.*, 2011) that would have influenced all hydrological regimes (Gasse, 2000; Marchant and Hooghiemstra, 2004) due to a lower sea level. Increased charcoal content (particularly in the larger particles) also indicates a greater fire frequency close to Unguja Ukuu and possibly indicates drier environmental conditions. However, ecological interpretation of these changes in Unguja Ukuu is complicated as the earliest habitation of the area is likely to have occurred from around 4000 ^{14}C yr B.P. as recorded at Machaga cave, 5 km distant from Unguja Ukuu (Chami, 2001).

A rise in *S. alba* and a decrease in *Bruguiera*/*Ceriops* indicate another period of increased inundation frequency occurred causing mangroves to retreat landwards until prior to 550-512 cal yr B.P. This rise in relative sea level may correlate to the late Holocene highstand recorded from the southern African coasts (Ramsay, 1995; Compton, 2001; Ramsay and Cooper, 2002). Relatively low charcoal content at this time suggests a decrease in regional fire frequency and wetter environmental conditions as recorded on mainland Kenya (Rucina *et al.*, 2010).

Late Holocene to the present day

During the late Holocene, the decrease of *R. mucronata* and *S. alba* and increase in *Bruguiera*/*Ceriops* and *A. marina*, together with a small increase in *Xylocarpus* recorded in subzone 4C-UU-2b, indicates that landward fringes of the mangroves experienced greater freshwater influence. Combined with an increase in herbaceous taxa, indicative of more terrestrial influence, this suggests less inundation frequency possibly corresponding to a sea level fall at around 500 ^{14}C yr B.P. (Åse, 1981). Moreover, after 1407-1310 cal yr B.P., an increase in herbaceous taxa, combined with an increase in charcoal frequency, particularly the presence of larger fragments (> 60 μm), in zone B-UU-1, may be coeval with the Medieval Warm Period (MWP) that was characterised by drier conditions recorded throughout East African region from 1200 to 500 cal yr B.P. (Alin and Cohen, 2003; Vincens *et al.*, 2003; Rucina *et al.*, 2010). However, this shift in ecosystem and fire regime may also relate to the earliest human settlement recorded in Unguja Ukuu around A.D. 500 (Juma, 2004). Associated with this settlement is the increased use of mangroves providing materials for the mud-timber buildings and for trade, the latter being highly organised and extensive along the Swahili coast (Juma, 2004). Soon after this period, the charcoal accumulation decreases suggesting a decline in the regional fire frequency either due to wetter environmental conditions and/or the collapse of Unguja Ukuu after around A.D. 900 (Juma, 2004). Along the coasts of Zanzibar, the number of archaeological sites increased from A.D. 1100 to 1400 concomitant with the presence of large fragments of charcoal > 60 μm and a slightly decreased *R. mucronata* content from 75 cm towards the top indicating ecosystem disturbance; this is at a time of increased settlements and overseas trade (Horton and Clark, 1985; Kessy, 2003; Juma, 2004). After this period, the charcoal accumulation increases, particularly the larger fragments, reflecting a greater fire frequency close to Unguja Ukuu and possibly drier conditions evidenced by the appearance of herbaceous taxa, possibly implying the burning of woody trees and re-establishment by grasses and sedges in the last 530 cal yr B.P. This is further evidence of human interaction with mangrove ecosystems in Zanzibar, possibly relating to re-occupation of an Islamic settlement around A.D. 1450-1600 in

Unguja Ukuu and the Portuguese arrival (McIntyrn and McIntyrn 2009; Nimaga, 2011). Omani colonisation resulted in the development of urbanisation in Zanzibar from around early A.D. 1500. The recent decrease in *R. mucronata*, and increase in *S. alba*, from zone A-UU-2 and subzone B-UU-2b may represent the utilisation of mangrove woods during the last centuries, and particularly the exploitation of *R. mucronata* that provides high quality charcoal, firewood and building materials (Semesi *et al.*, 1998; Shunula, 2002; Semesi *et al.*, 2001; Ngoile and Shunula, 1992). Mangrove pole trading began during the ninth and tenth centuries across the Indian Ocean (Horton and Middleton, 2000). The exploitation of mangroves in Zanzibar for charcoal and firewood has been increasing with the growth of Zanzibar town (Masoud, 1991; Shunula, 2002) and deforestation for mariculture ponds (Mmochi *et al.*, 2001; Kruitwagen *et al.*, 2008) have had detrimental consequences. A strong charcoal signal in subzones B-UU-2b and 4C-UU-2b and peaks of the large charcoal particles > 60 μm in subzones 4C-UU-2b, demonstrates the increasing anthropogenic activity in the region.

A-UU-1 and B-UU-1 record late Holocene mangrove development at different times: the seaward site prior to 278-(-4) cal yr B.P. and the central site prior to 1407-1310 cal yr B.P. (Figures 4.3, 4.4). The late Holocene regression of the sea may therefore have caused suitable conditions for mangrove establishment in the last millennia. The timing of the late Holocene sea level fall recorded from subzone 4C-UU-2b corresponds to pollen records from B-UU-1 core sites during the late Holocene around 1400 cal yr B.P. The occurrence of shell fragments in the stratigraphy of A-UU-1, and the recent decrease in *R. mucronata* combined with a coherent and marked increase in *S. alba* from zone A-UU-2 and subzone B-UU-2b suggest increased inundation frequency, probably as a result of sea level rise during the last centuries (IPCC, 2010). Such an interpretation is also supported by a decrease in charcoal and high sediment accumulation through the uppermost parts of the core. However, it is difficult to differentiate a recent historical phase of sea level rise from the impact of anthropogenic activities on ecosystem dynamics particularly during the period of human occupation and at the relatively low resolution of the current analysis in the historical period.

Conclusions

A multi-core and multi-proxy study including stratigraphic, pollen and charcoal analyses, set within a radiocarbon dated chronological framework, from Unguja Ukuu has shown the dynamic nature of the mangrove ecosystems on Zanzibar during the Holocene. Current species distribution plotted against the altitude gradient is a useful aid in the reconstruction of past sea level fluctuations. The changes in mangrove composition over the past 7000 years result from interactions between sea level change, environmental variability, anthropogenic and geomorphological activity. Mangrove ecosystems were established in Unguja Ukuu from at least the early Holocene. There is evidence for a higher mid Holocene sea level rise after about 7000 cal yr B.P. as mangroves migrated landward. A short-term dramatic decrease in *S. alba*, and an increase in *Bruguiera*/*Ceriops* and *A. marina*, as well as the appearance of Poaceae, occurs after the mid Holocene indicative of a lower sea level. An increase in charcoal accumulation at this time is contemporaneous with dry conditions across the East African region but also coincides with the earliest habitation of Zanzibar. After this period sea level rose again until prior to 530 cal yr B.P. when increases in charcoal are likely to relate to drier environmental conditions. However, this may also relate to the earliest human settlement recorded in Unguja Ukuu. Further evidence of human interaction within mangrove ecosystems in Zanzibar is represented by a recent decrease in *R. mucronata* possibly following resource exploitation and use of the mangrove ecosystems for domestic purposes and trade, particularly from around 530 cal yr B.P. Recent shifts in mangrove composition and sedimentary accumulation may be related to historical rapid sea level change that has been the major driver influencing mangrove dynamics although this would need further targeted analysis to be adequately constrained.

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Chapter 5: Holocene sea level changes in Tanzanian coast

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Abstract A Holocene sea level curve, reconstructed from pollen analysis of past mangrove environments, is presented for the Tanzanian coastline. Three sites were investigated and detailed litho-and biostratigraphical analyses were undertaken and placed within a radiocarbon chronology. An early to mid Holocene sea level rise from ~ 8000 cal yr B.P. until prior to 4600 cal yr B.P. was recorded as indicated by a shift of mangroves landward in all three study sites. A mid Holocene sea level rise was subsequently recorded with two potential mid Holocene highstands at ~ 5800 cal yr B.P. and ~ 4700 cal yr B.P. probably resulting from the effects of continental levering. The sea level trend between 4400 and 2000 cal yr B.P. is unclear but it is possible that sedimentary erosion and/or estuarine migration occurred during the mid Holocene transgression. The late Holocene sea level was characterised by a potential highstand at ~ 530 cal yr B.P. before falling to a lower level than present at ~140 cal yr B.P. It is possible that in addition to eustasy, local uplift occurred resulting in regional variations of sea level changes.

Keyword: mangrove, East Africa, pollen analysis, far-field location

Introduction

Sea level fluctuations are a consequence of changes in the position of the land with respect to the sea due to eustatic, isostatic and tectonic factors. Change in sea level can result in physical and ecological coastal changes and has occurred throughout time (Pirazzoli, 1991). Sea level changes from "far-field" locations, where isostatic effects as a result of glacial loading and unloading are considered minimal (Clark *et al.*, 1978; Lambeck, 1993) remain poorly constrained due to limited research from these regions and therefore there are underexploited for reconstructing sea level change. People living by the sea are offered benefits for travel, trade and fertile land use for settlement and therefore have adapted to the challenging environmental conditions for survival in the coastal zone (Breen and Lane, 2003). An understanding of the factors influencing sea level and sea level change are useful to predict current and future changes in the coastal environment.

Holocene sea level changes from "far-field" locations are as a result of eustatic components as well as equatorial syphoning and hydro-isostasy (continental levering) dependent on the width of the continental shelf (Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). Equatorial ocean syphoning is represented by a migration of seawater from "far-field" ocean basins during deglaciation to the collapsing forebulges at the "near-field" continental margins causing sea level fall to be recorded in "far-field" locations (Mitrovica and Peltier, 1991). Continental levering occurs when water loading due to deglaciation causes continental subsidence and an influx of water from the offshore areas to the continent inducing sea level fall at the areas distant from continental margins (Lambeck and Nakada, 1990; Mitrovica and Milne, 2002; Gehrel and Long, 2008).

The first eustatic sea level record from a "far-field" location was from Barbados and showed the late glacial to the early Holocene eustatic sea level trend (Fairbanks, 1989). Sea level was 120 m below the present sea level at around 17,000 ^{14}C yr B.P. and continued rising until 7800 ^{14}C yr B.P. with two rapid sea level rises due to meltwater pulses following freshwater release from ice-dammed lakes bracketed by a transition phase of reduced sea level rise rate around 11,000 ^{14}C yr B.P. Sea level records from "far-field" locations have since been recorded from various locations; for example, the Indian Ocean (Katupotha and Fujiwara, 1988; Banjeree, 2000), Southeast Asia (Hanebuth *et al.*, 2000; Horton *et al.*, 2005; Bird *et al.*, 2007) and Australia (Lambeck and Nakada, 1990; Larcombe *et al.*, 1995). In the northern Indian Ocean region, two mid-late Holocene highstands were recorded from beach ridges and coral terraces along the east coast of India (Banjeree, 2000) and from coral and marine shells along the southwest and south coasts of Sri Lanka (Katupotha and Fujiwara, 1988). These mid Holocene records show a highstand occurring at 7300 and 6500 cal yr B.P. followed by the late Holocene highstands at 4300 and 3200 cal yr B.P. in India and Sri Lanka, respectively. In Australia, Holocene sea level change has been reconstructed along the coasts, including the Great Barrier Reef, using a range of proxies with some studies suggesting a highstand at around 6000 cal yr B.P. (Lambeck and Nakada, 1990; Larcombe *et al.,* 1995) whereas others indicate a highstand during the late Holocene at 3900 cal yrs B.P. (Baker *et al.,* 2001).

The record of Holocene sea level change along the East African coast is poorly constrained (Pirazzoli, 1991; Camoin *et al.*, 2004) with reconstructed sea level changes recorded from only a few locations using a range of different proxies (Figure 5.1, Table 5.1). A study using cores from coral reefs, and dating and elevation of reef terraces on the Mayotte foreslopes in the Comoro Islands, Mauritius and Réunion Island (Camoin *et al.*, 1997; 2004; Zinke *et al.*, 2003) suggested a rapid rise occurred from 10000 to 7500 cal yr B.P. followed by a slower rise until sea level stabilised at the present sea level around 3000 cal yr B.P. with no higher sea levels than present sea level recorded (Figure 5.1, Table 5.1). A study of sea level changes based on archaeological data from East Africa, including Zanzibar, also revealed no evidence of a Holocene highstand and recorded sea level of at -0.5 m amsl (above mean sea level) in Unguja Ukuu at around 1200-1000 cal yr B.P. and -1 m amsl during the Medieval period (around 600-800 cal yr B.P.) (Mörner, 1992). This corroborates with the signature from a study of raised coastal terraces in Kenya that indicates a fall in sea level 500 years ago (Åse, 1981).

A different pattern of sea level change was recorded from the coast of Mozambique where sea level is thought to have reached its present level at 7000 ^{14}C yr B.P., with a highstand of 2.5-3 m above the present level about 6000 ^{14}C yr

B.P., declining to the present level between 2000-1000 ^{14}C yr B.P. (Jaritz *et al.*, 1977). The accuracy of this data set however is unclear as it is unknown which datum level is referred to. Another study based on beachrocks along the South African coastline (Ramsay, 1995; Ramsay and Cooper, 2002) showed a highstand of 3.5 m above present sea level at 5100 cal yr B.P. (4540 ^{14}C yr B.P.) followed by fluctuations between marine regressions and transgressions (Figure 5.1, Table 5.1). A minor highstand of 1.5 m above the present level occurred at 1500 cal yr B.P. (1610 ^{14}C yr B.P.) before falling to its present level at 900 cal yr B.P. (910 ^{14}C yr B.P.). A study based on radiocarbon ages of sediment from a saltmarsh on the southwest coast of Africa suggested that there were two Holocene highstands of sea level at 6700 cal yr B.P. (5910 ^{14}C yr B.P.) and at 1200 cal yr B.P. (1390 ^{14}C yr B.P.) (Compton, 2001). These records from Mozambique (Jaritz *et al.*, 1977) and South Africa (Ramsay, 1995) indicate two sea level highstands during the Holocene (Table 5.1). A recent study using multi-proxy analyses from Macassa Bay, southern Mozambique indicates that two possible highstands occurred around 6600-6300 cal yr B.P. (5580 ^{14}C yr B.P.) and 4000-1100 cal yr B.P. (3740-1250 ^{14}C yr B.P.) before falling to present-day level (Norström *et al.*, 2012). A study of fringing coral along the east coast of Africa showed the regeneration of fringing reefs, suggesting sea level rise from 18,000 yr B.P. to the mid Holocene (5000-6000 yr B.P.). In addition, the progradation of beach plains is recorded in many places including southeast Zanzibar representing a sea level fall during the mid to late Holocene (Arthurton, 2003). This is contradictory to a study by Rijsdijk *et al.* (2011) who investigated mass mortality of giant tortoises and other vertebrates in Mauritius and suggested a fall in sea level to 1.3 m below mean sea level from 4300 to 4100 cal yr B.P.; a time that corresponds to the megadrought event across tropical Africa (Gasse, 2000; Marchant and Hooghiemstra, 2004).

Thus, there are discrepancies in the nature and timing of Holocene sea level fluctuations across the Indian Ocean. It is possible, however, that a more complex pattern of land uplift occurred along the East African coast related to the interplay of eustatic and isostatic and/or tectonic activities. Åse (1978; 1981) investigated raised coastal terraces along the Kenyan coast and found eight levels that probably relate to higher sea levels. The terraces at 10-11 m are thought to represent sea level 3000 years ago and the terraces at 1.5 m are thought to represent sea level altitude 500 years ago. Differential land uplift with greater uplift towards the northern Kenya coast is thought to be responsible for this pattern. However, it might be possible that the difference in terrace altitude was solely due to a marine transgression at around 3000 years ago and sea level then fell during the Medieval period. Studies of beach ridges and terraces along the Tanzanian and Zanzibar coastlines (Alexander, 1969; Muzuka *et al.*, 2004) suggested that minor sea level fluctuations, in combination with land uplift to the north of Dar es Salaam, probably 3600-6000 years ago, occurred following cessation of eustatic sea level rise.

Sea level records within the Southwest Indian Ocean (Table 5.1, Figure. 5.1) show considerable uncertainty on the timing and duration of Holocene sea level fluctuations for several reasons. The different proxies that allow the indicative meaning of the sea level index points to be established may not be comparable between studies. Some sea level index points may have large indicative ranges and different degrees of precision (Woodroffe and Horton, 2005). The different datum levels from various environmental settings and varying distances from formerly major glaciated centres at different latitudes may give rise to different isostatic rebound in the locations. All these potential areas of uncertainty in the sea level records will be compounded by dating uncertainties.

Mangrove as sea level indicators

Research on sea level reconstruction from "far-field" locations traditionally has focused on coring and dating corals (Pirazzoli, 1988; Fairbanks, 1989; Colonna *et al*., 1996; Camoin *et al.*, 1997; 2004). A few corals such as *Acropora palmata* grow within a narrow vertical range (e.g. less than ± 5 m) (Lighty *et al.*, 1982) and so can be used as reliable sea level indicators although the lower depth limits are poorly constrained leaving a large error (Blanchon and Shaw, 1995). Geomorphological features such as terraces are also used but again are prone to large errors as they are dependent on tidal range and possible storm events (Pirazzoli, 1991; 1996). A little used methodology in tropical environments is that of palaeoenvironmental reconstruction using pollen grains from coastal ecosystems. Mangrove ecosystems comprise evergreen trees and shrubs that are physiologically and morphologically adapted to grow in the sub tropical to tropical intertidal zone between mean sea level and high water spring tide (Woodroffe and Grindrod, 1991; Blasco *et al.*, 1996; Ellison and Farnsworth, 2001; Ellison, 2008). Mangrove ecosystem composition responds to changes in sea level by migrating landward or seaward with a rise or fall in sea level respectively. Mangrove zonation can then be related to sea level fluctuations through comparison to the relationship between contemporary vegetation assemblages and their inundation frequency with respect to sea level. Mangrove pollen preserved in sediment cores has been used to reconstruct past mangrove ecosystem dynamics elsewhere in the tropics (e.g. Cohen *et al.*, 2005; Horton *et al.*, 2005; Vedel *et al.*, 2006; Tossou *et al.*, 2008; Hait and Behling, 2009) and combined with an understanding of the present relationship of mangrove composition to the altitude of present sea level, can be used to reconstruct sea level fluctuations (Ellison, 1989; 2005; 2008). Englehart *et al.* (2007) developed a transfer function from a modern analogue of mangrove surface pollen assemblages, that has been used to predict the palaeo mangrove elevation with accuracies of ± 0.22 m.

In this paper, evidence of sea level change derived from three key mangrove locations along the Tanzanian coast are presented. These changes are placed in the context of existing sea level reconstructions from the region to provide the first synthesis of Holocene sea level and coastal changes for the East Africa.

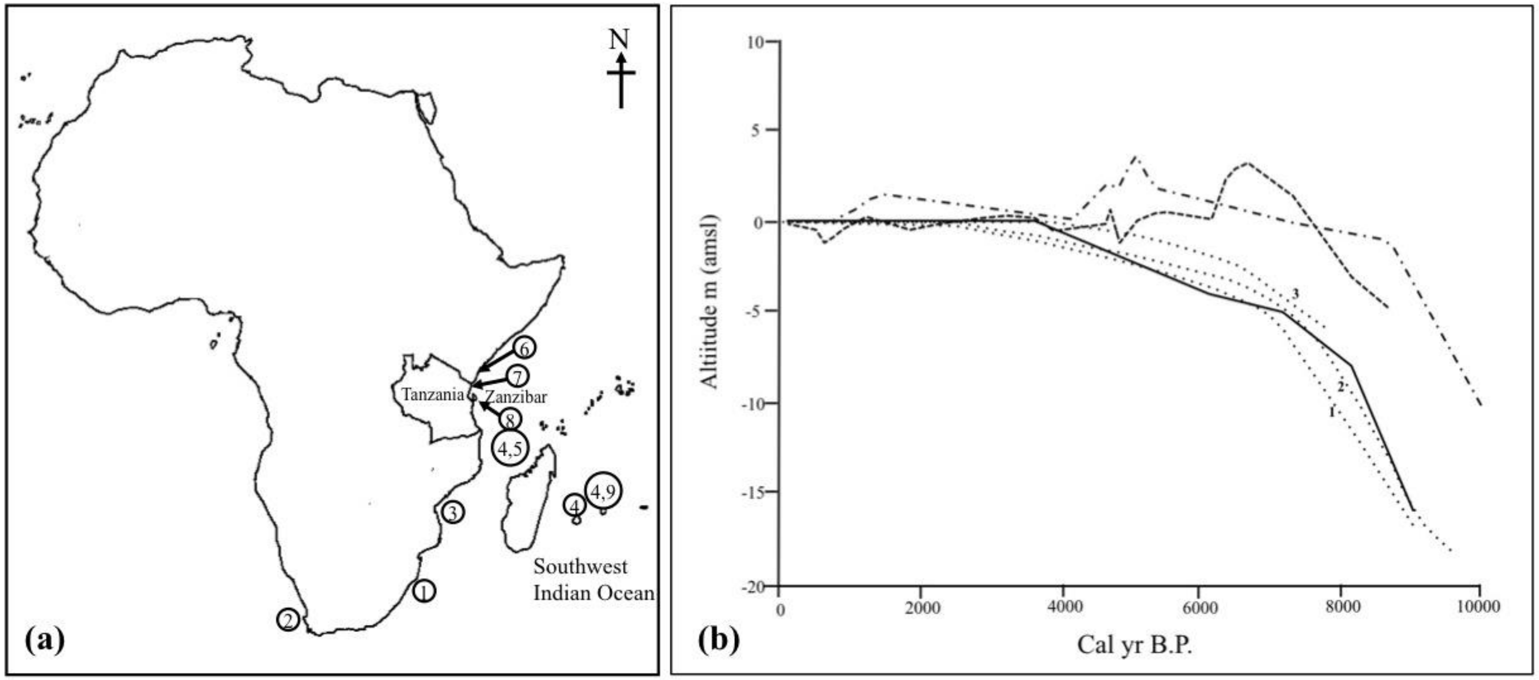

Figure 5.1. (a) Map of the Southwest Indian Ocean showing the location of sea level studies. Numbers refer to previous studies undertaken: (1) Ramsay and Cooper (2002), (2) Compton (2001), (3) Jaritz *et al.* (1977), (4) Colonna *et al.* (1996); Camoin *et al.* (1997), (5) Zinke (2000); Zinke *et al.* (2003), (6) Åse (1981), (7) Alexander (1969), (8) Muzuka *et al.* (2004), (9) Rijsdijk *et al.* (2011). (b) Composite diagram showing Holocene sea level curves from the Southwest Indian Ocean region (with calibrated dates) (Ramsay and Cooper (2002) in dash-dotted line and Compton (2001) in dashed line and Mauritius (1), Mayotte (2) and Réunion (Camoin *et al.* (1997; 2004) in dotted line and Zinke *et al*. (2003) in solid line.

Table 5.1. Summary of sea level reconstructions from the Southwest Indian Ocean region (HS, highstand; amsl, above mean sea level) (modified after Woodroffe and Horton, 2005)

Location and authors	Indicators used (if known)	Dating method	No. of Holocene highstands	Timing of mid-Holocene highstand	Magnitude of mid-Holocene highstand
1. South Africa (Ramsay and Cooper, 2002)	Beachrock, barnacles and attached oysters, estuarine fill sequences	Uranium series	2	1st HS-4650 ^{14}C yr B.P. (5074 cal yr B.P.) 2nd HS 1610 ^{14}C yr B.P. (1454 cal yr B.P.)	1st HS-3.5 m amsl 2nd HS-1.5 m above amsl
2.South Africa (Compton, 2001)	Saltmarsh organic material/molluscs	Radiocarbon	2	1st HS-6700 cal yr B.P. 2nd HS-1200 cal yr B.P.	1st HS-1 to 3 m amsl 2nd HS-0.5 to 2 m amsl
3.Mozambique (Jaritz *et al.*, 1977)	Unclear	Radiocarbon	1	6000 ^{14}C yr B.P.	2.5-3 m amsl
4. Mauritius, Réunion and Mayotte (Colonna *et al.*, 1996; Camoin *et al.*, 1997)	Fringing coral reefs	Uranium series	0	sea level stabilised at present level 3000 cal yr B.P.	No HS recorded-small atolls sinking through Holocene with ocean floor subsidence
5. Mayotte (Zinke, 2000; Zinke *et al.*, 2003)	Lagoon organic material/molluscs/corals	Radiocarbon	0	sea level stabilised at present level 2500 cal yr B.P.	No HS recorded

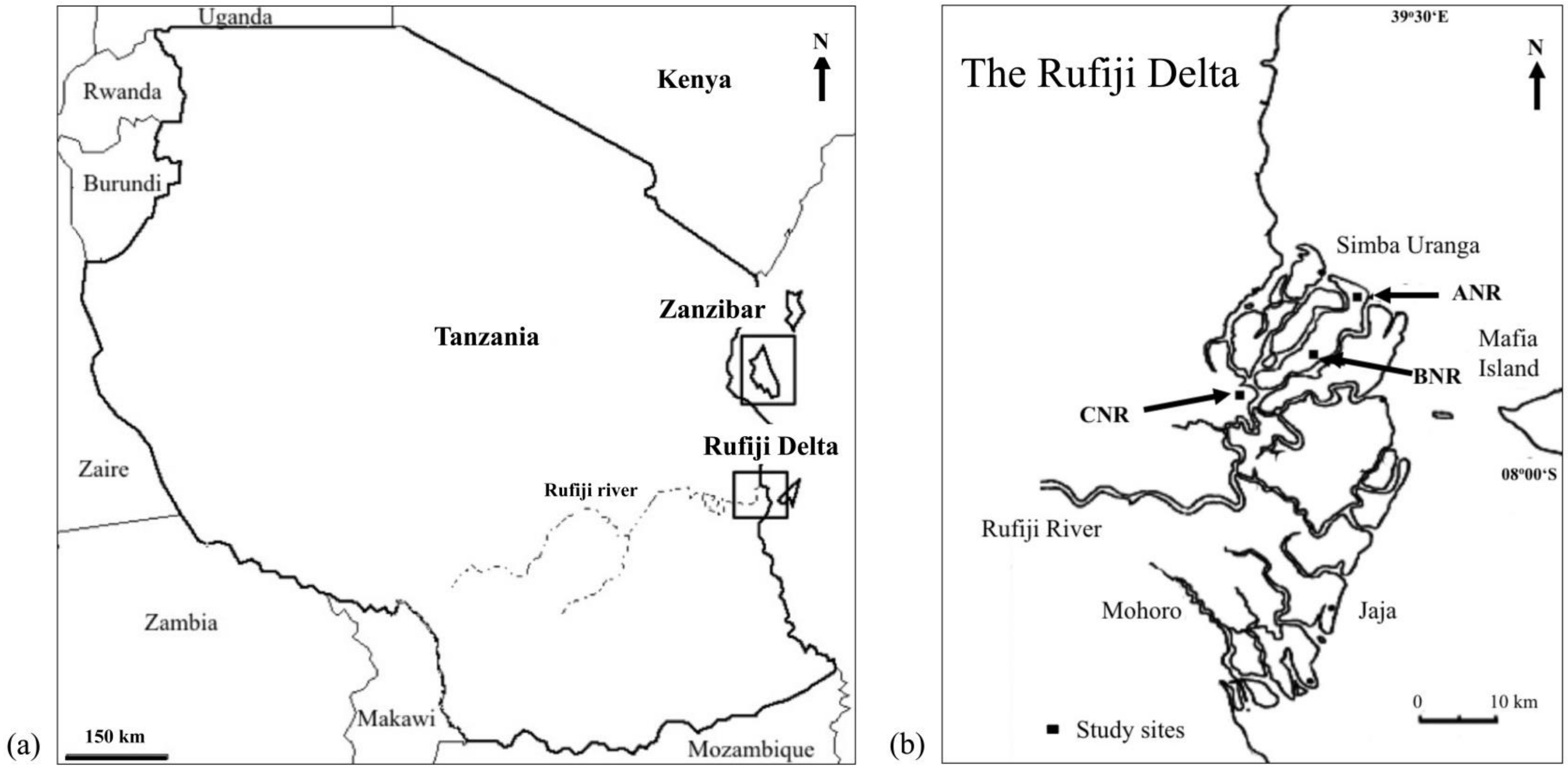

Figure 5.2 Map of Tanzania showing the location of the Rufiji Delta and Zanzibar. Inset b showing where sedimentary cores were taken from the Rufiji Delta.

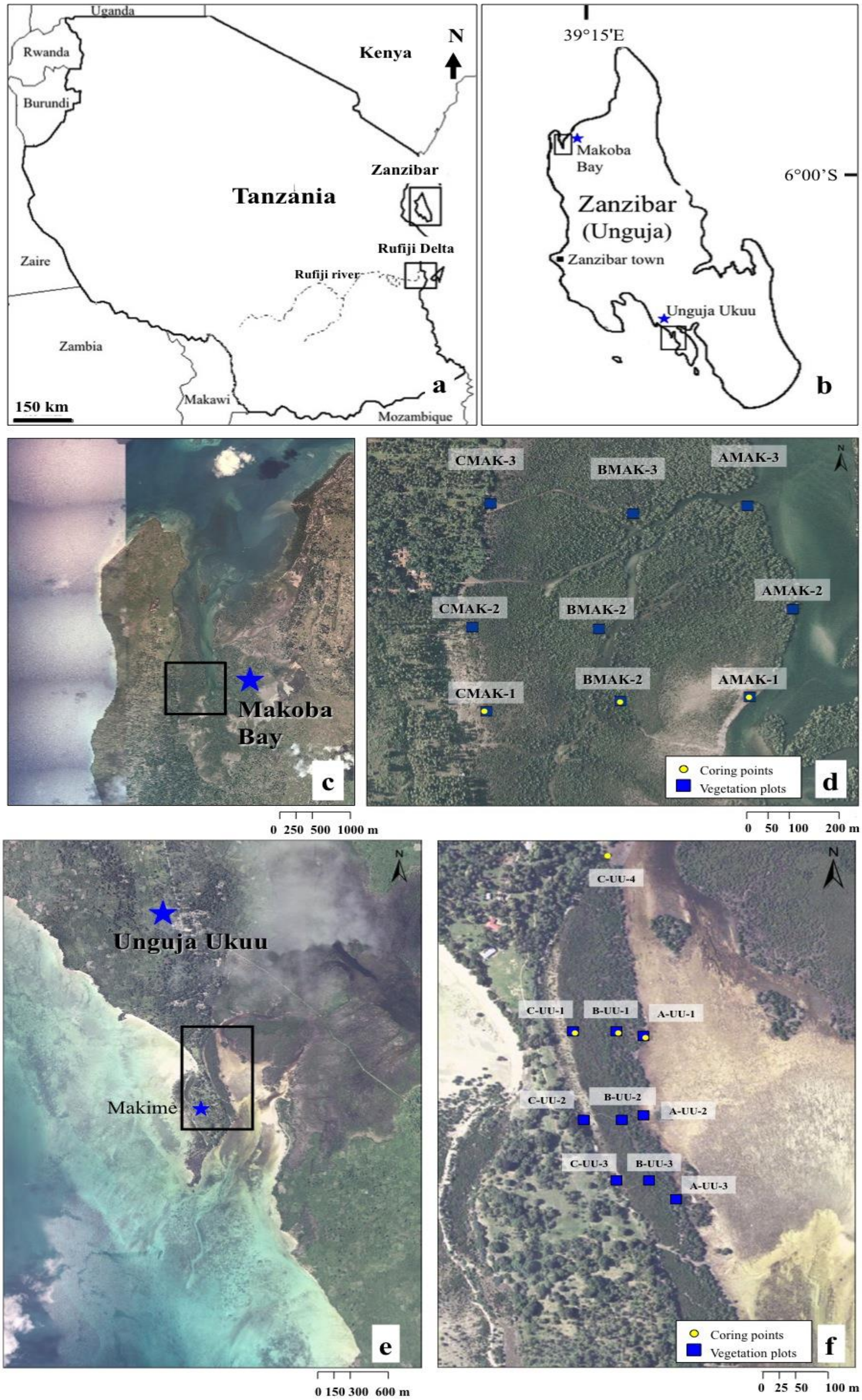

Figure 5.3. Map of Tanzania showing the location of Zanzibar (a) Makoba Bay and Unguja Ukuu (b). Inset c d, e and f show where sedimentary cores were taken and where the vegetation plots were located in Makoba Bay and Unguja Ukuu, respectively.

Study sites

Environmental setting

The three sites investigated (Figures 5.2, 5.3) are the northern Rufiji Delta (Tanzanian mainland), Makoba Bay and Unguja Ukuu (Zanzibar).

The Rufiji Delta is located in the Rufiji Basin characterised by Cretaceous limestones and shales, overlain by Miocene estuarine and marine bedrocks and Pliocene to Quaternary fluvial deposits (Kent *et al.*, 1971). The study area is located in a mangrove area that grades into paddy fields in the northern Rufiji Delta (Figure 5.2b). The deltaic plain formed at the Indian Ocean by the Rufiji river is approximately 65 km wide and extends inland 123 km. The delta is covered by sand, silt and clay derived from the alluvial system (Semesi, 1992) and a series of sand spit islands and submerged sand bars formed parallel to the seaward margins exist (Fisher *et al*., 1994). The mangrove substrata are formed approximately 2.5 m above mean sea level (Fisher *et al.*, 1994). The sediments of the mangrove areas are generally clayey silts and silty clays with sandy clays more dominant at higher elevations, and containing more organic matter. According to Francis (1992), the average tidal range, controlled by the semi-diurnal tide between the mangrove swamps and the ocean through the channels and creeks, is 2 - 2.5 m and approximately 3.3 - 4.3 m on high spring tides (Fisher *et al.,* 1994; Richmond *et al.,* 2002). The salinity of the water in the channels and in the soil of the delta ranges from 10.60 ‰ to 32 ‰ (Francis, 1992; Fisher *et al.* 1994).

Zanzibar is located on the continental shelf lying 40 km from the mainland and separated by the Zanzibar channel. It was connected to the mainland when sea level was 30-40 m below present mean sea level (Shaghude and Wannäs, 1998; 2000). Sea level transgressions during interglacial periods caused Zanzibar to become an island (Arthurton *et al*., 1999) and the last connection to the mainland probably occurred from the last glacial period prior to 10-15 ka B.P. (Hamilton, 1982; Camoin *et al*., 2004). Most of Zanzibar consists of Pleistocene reef limestone often outcropping on the east coast and commonly referred to as “coral rag” (Shunula, 2002) with alluvial deposits found in some areas (Schlüter, 1997; Arthurton *et al*., 1999). Zanzibar is generally flat, low-lying and covered by quartz sand (Arthurton *et al*., 1999) without large rivers (Shunula, 2002). It is influenced by a semi-diurnal tide, ranging from 2 m on neap tide to 4 m on spring tide (Mwandya *et al*., 2010). The shores form 1-3 km intertidal platforms and support mangrove development in sheltered bays (Arthurton *et al.*, 1999). The study areas are located in the northwest of Makoba Bay and the east Makime headland of Unguja Ukuu about 25 km northwest and south of Zanzibar town respectively (Figure 5.3b; 5.2c; 5.2e). Makoba Bay is covered by a 100-700 m wide belt of dense mangroves occurring in a north-south alignment with the majority of trees up to 4 m in height and some of the regeneration vegetation reaching heights of between 1 and 2 m. The area is characterised by shallow unconnected tidal creeks with minimal freshwater input from terrestrial runoff during the heavy rainy season when the mangrove areas may experience a temporary decrease in salinity (Mwandya *et al*., 2010). The third study site is located in Unguja Ukuu and is covered by a belt of dense mangroves varying between approximately 75-120 m in width and approximately 1 km in length occurring in a north-south alignment with the majority of trees reaching heights of between 1 and 2 m (Figure 5.3e; 5.2f). The site is restricted to the south by the sea, to the west by a ridge of deep sands about 3 m in height aligned in a north-south direction, and to the north by the villages of Unguja Ukuu and a creek bank in front of the mangrove area with a narrow sandy beach.

Methodology

Fieldwork and sampling

Three sediment cores (seaward, central and landward) were retrieved from each location from the mangrove ecosystems along a transect perpendicular to the coastline with an additional core taken from Unguja Ukuu. The transect length varied depending on the nature of the environmental setting and the variation in breadth of the mangrove area; this ranged from about 20 km in the northern Rufiji Delta, to 500 m in Makoba Bay and 80 m in Unguja Ukuu.

A peat auger was used to test the stratigraphy and a 50 cm long, 5 cm diameter Russian corer used to extract a sample core from overlapping adjacent boreholes. The characteristics of sediments were described using a modified version of the Tröels-Smith (1955) classification (Kershaw, 1997). The cores were extruded into P.V.C.

pipes, wrapped in aluminum foil and plastic film and then labelled and packaged for transportation to the University of York where they were stored at -18 ºC.

Vegetation plots

Vegetation plots were established to study the relationship between species composition and sea level altitude. In the Rufiji Delta, vegetation surveys were focused around the core locations. 10 m^2 vegetation plots were set up to establish plant percentages at each core location. In Zanzibar, a more detailed study at both sites allowed the plant and structural composition at different levels of inundation to be investigated. Vegetation in nine 20 m^2 nested quadrats were established from which surface sediment samples were collected. Altitudinal heights were obtained using a differential GPS (δGPS model Leica TCRA Total Station) and levelled relative to the Ministry of Lands and Environment Benchmark. Three vegetation quadrats are located at each core site in Zanzibar, two in seaward locations approximately 300 m apart, two in the mid-tide section and a further two in the landward region, to establish the relationship between modern mangrove assemblages and present altitude of the sea. This relationship can then be used to reconstruct past sea level fluctuations (Punwong *et al.*, submitted).

Palaeoecological analysis

2 cm^3 of sediment was extracted at intervals of 10 cm along the length of each core for pollen analysis and for measurements of the organic matter (OM) and carbonate (CO_3) content by loss on ignition (LOI) at 550 ºC and 950 ºC, respectively following procedures outlined by Heiri *et al.* (2001). Pollen and spores from sediment cores and surface samples were extracted using the acetolysis method (Erdtman, 1969; Faegri and Iversen, 1989). Sample residues were stored in silicone oil. More than 94% of pollen and spores were identified by comparison with pollen from extant mangrove specimens collected and identified from the study areas and modern mangrove references (Thanikaimoni, 1987; Punwong, 2008) and most of the unidentified grains comprise separate taxa. *Bruguiera gymnorhiza* and *Ceriops tegal* were grouped together as *Bruguiera/Ceriops* type because they could not be

distinguished under light microscope (Grindrod, 1985). The pollen content of some samples was very sparse and therefore insufficient to achieve a count of 200 grains. To determine the optimal grain count, pollen and spores in 5 samples from each site were counted and the number of taxa recorded for every 20 grains up to count of 200 grains. After 80 grains the number of new taxa did not increase. At least 150 pollen grains were therefore counted for each level after establishing that this number was sufficient to identify any new taxa. This count also conforms to other mangrove studies (e.g. Ellison, 1989). The pollen data are represented as percentage pollen frequency diagrams and are zoned using stratigraphically constrained cluster analysis, CONISS, based on sum of pollen and spores within the graphics software TILIA2 and TILIA*Graph (Grimm, 1991).

Chronology

Bulk sediment samples were selected for AMS dating and submitted to the Radiocarbon Dating Laboratories at the University of Waikato, New Zealand and the CHRONO Centre, Queen's University Belfast, UK. Range-finder dates were analysed at the start of the laboratory work with targeted dates selected once analytical work had been completed to focus on dating biostratigraphic changes. Two AMS ages determined from depths where there was particular uncertainty in the chronology were obtained from pollen concentrates following a modified pollen concentrate preparation (Vandergoes and Prior, 2003) to overcome the potential problems of contamination in the bulk samples. The dates were calibrated with the southern hemisphere calibration Shcal04 curve (McCormac *et al.*, 2004) using the software OxCal v4.10 (Bronk-Ramsey, 2009).

Results

Stratigraphy

The basal unit of BNR and CNR in the northern Rufiji Delta comprises organic matter and silt. Organic material including root fragments increase in the upper unit to the top of the core, where wood and bark fragments are also present. The boundaries between stratigraphic units in all three cores are transitional (Figure 5.4).

Stratigraphy of the three sample cores from Makoba Bay show that the deepest sediment is a grey silt unit containing some shell fragments which is overlain by a peat unit containing woody root fragments and fine sand in AMAK-1 and BMAK-1. Sand is found in the uppermost unit of all three cores. The boundaries between stratigraphic units in all three cores are transitional (Figure 5.4).

The basal unit of all sediment cores from Unguja Ukuu is grey sand and silt overlain by a peat with woody root fragments except in C-UU-4 where a silt unit is present. Some small shell fragments are also found in A-UU-1 and B-UU-1. Peat layers with sand and small fragments of woody plant roots alternate with organic sand layers throughout the sediment column in all four cores. Sand containing small fragments of woody plant root forms the top unit of B-UU-1, C-UU-1, and C-UU-4 while silt characterises the top unit of A-UU-1. The boundaries between stratigraphic units in all four cores are transitional (Figure 5.4).

Pollen analysis and vegetation survey

Fossil pollen and spores were identified and grouped into mangrove, back mangrove, terrestrial, herbaceous and pteridophytes categorised to reflect environmental tolerance. Pollen diagrams are shown in Supplementary figures 1-10. A mangrove zonation in the Rufiji Delta and Zanzibar has been developed based on a combination of Watson's (1928) and Santisuk's (1983) inundation classes and field-based observations of modern ecological occurrences of mangrove taxa (Figure 5.5). An understanding of the contemporary mangrove zonation is used to aid in interpreting ecosystem and environmental changes through the fossil record. *Avicennia marina* and *Sonneratia alba* are pioneer species found at the seaward edges of mangroves and are inundated from daily to several times a month although *A. marina* also appears in more landward locations. *Rhizophora mucronata* and *Bruguiera gymnorrhiza* form a thick belt in the inner mangroves. *R. mucronata* sometimes occurs in large homogeneous stands along the creeks. *B. gymnorrhiza* is typically found in the middle mangroves between *R. mucronata* and *Ceriops tegal* and appears in the area inundated by the sea several times a month. *C. tegal* and *Lumnitzera racemosa* appear in the upper intertidal and dry areas inundated infrequently during the month. *Xylocarpus granatum*, tolerant of more freshwater influence, represents a high intertidal species and occurs in landward fringes where environmental conditions are less saline but inundated infrequently during the month. *H. littoralis* is found on river banks characterised by low salinity and on landward areas usually flooded only two times a month. *Acrostichum aureum* appears in a transition zone to freshwater swamp.

Contemporary vegetation assemblages observed in the field revealed a distinct vertical relationship with present sea level. The altitudinal range of mangrove areas are between 1.7 and 3.5 m amsl, -1.6 and 1.5 m amsl, and 0 and 1.9 m amsl in the northern Rufiji Delta, Makoba Bay and Unguja Ukuu respectively. The reconstruction of palaeo-sea level changes is therefore determined through interpretation of the dominant mangrove taxa within the pollen records; *A. marina* is used as a proxy for the interpretation of sea level at ANR of the Rufiji Delta, as it dominates the pollen assemblage at this location. *R. mucronata* is used for interpretation in cores BNR and CNR (Rufiji) and all core sites in Zanzibar as it dominates the pollen assemblages. These trends in dominant taxa are combined with changes in other associated mangrove taxa and with field observations of modern ecological occurrences of taxa (Punwong *et al.*, submitted) as well as Watson's (1928) and Santisuk's (1983) inundation classes (Figure 5.4). Interestingly, *R. mucronata* and its association with *Bruguiera/Ceriops* and *S. alba* pollen, dominates mangrove assemblages throughout the fossil records. There are some remarkable changes between the percentages of *Bruguiera/Ceriops* and *S. alba* pollen throughout the pollen assemblages from all coring sites in Zanzibar. These two pollen types originate from different contemporary mangrove habitats and their parent taxa have different tolerances to sea level inundation. Therefore, sea level can be reconstructed using the changes in these mangrove taxa. The relative proportions of *Sonneratia*/(*Bruguiera/Ceriops*) (S/BC), *Sonneratia*/*Rhizophora* (S/R) and *Rhizophora/*(*Bruguiera/Ceriops*) (R/BC) with the present day vegetation plots show a strong relationship between pollen proportion and inundation according to Watson's (1928) and Santisuk's (1983) classes. The changes in the relative proportions of S/BC, S/R and R/BC from each vegetation plot are used to characterise the inundation regime of the past mangrove ecosystems. For example, in Makoba Bay, the calculated proportion of S/BC is 0, S/R is 0 and R/BC is 0.3-0.5 for the high mangrove assemblages at the highest altitudes (1.04 to 1.54 m amsl) inundated infrequently during a month. Thus, an increase in the ratios of S/BC, S/R and R/BC indicates an increase in altitude of the sea level. These ratios are applied to infer mangrove position as low, medium, and high mangrove classes with respect to the sea level with transitions between these classes calculated within Tables 5.2 and 5.3.

Chronology

Nine radiocarbon dates have been obtained from the northern Rufuji Delta (Table 5.4). The radiocarbon dates show a complex age-depth relationship between 4821-4453 cal yr B.P. and the modern deposition in BNR and also between 799-680 cal yr B.P. and the modern deposition in CNR. The two radiocarbon ages recorded as "modern" dates suggest reworking by mechanical or biogeochemical processes. The most likely causes of contamination result from root penetration down the sediment column taking young material to depth and/or tidal creek migration resulting in sedimentary erosion and subsequent re-deposition. The dates from 19 cm (BNR) and 115 cm (CNR) are rejected for sea level reconstructions.

Thirteen radiocarbon dates have been obtained from Makoba Bay (Table 5.4). The radiocarbon results from cores BMAK-1 (96 and 195 cm) and CMAK-1 (107 and 172 cm) demonstrate a complex age-depth relationship and it is likely that reworking of mangrove sediments may have occurred through root penetration introducing younger carbon at depth and mixing of older sediments in the upper column. However, two dates at 97 cm and 196 cm from a newly applied pollen concentrate method give sensible age-depth relationships. The date of 97 cm gives an older age than dates obtained at 106 and 158 cm and is likely to be more reliable; dating pollen concentrates potentially removes sources of error caused by dating sediment matrices of unknown provenance. Moreover, a relatively continuous accumulation rate, no abrupt change in stratigraphy and similar pollen compositions of cores AMAK-1 and BMAK-1 suggest reliable dates for 1525-1385 cal yr B.P. in AMAK-1, 2107-1880 cal yr B.P. for BMAK-1. We therefore reject dates from core BMAK-1 (96, 106, 158 and 195 cm) and CMAK-1 (107 and 172 cm) for sea level reconstructions.

Six radiocarbon dates have been obtained from Unguja Ukuu (Table 5.4). The radiocarbon results from core C-UU-4 (42 cm) record modern age deposition sediment, probably due to contamination as described above and we therefore reject this date for sea level reconstruction.

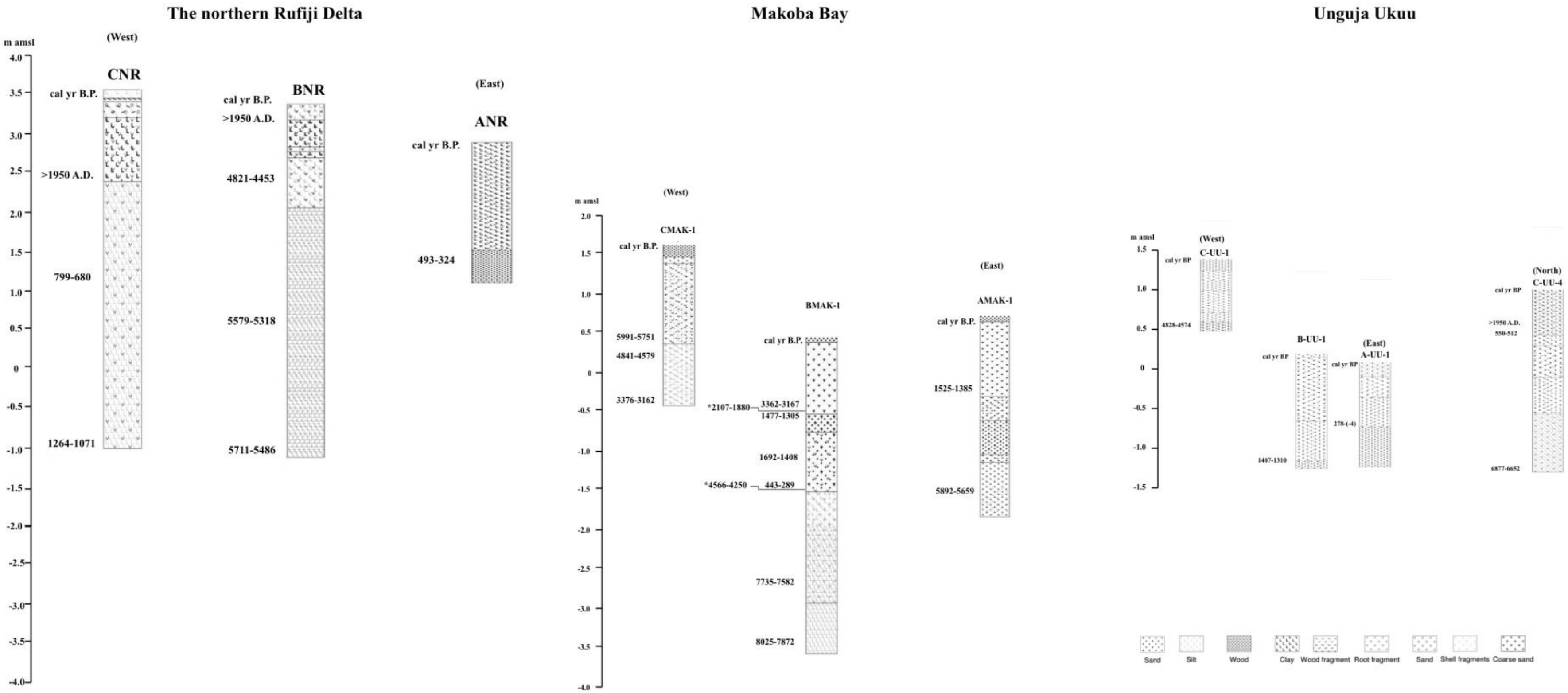

Figure 5.4. Stratigraphy of core sites from the northern Rufiji Delta, Makoba Bay and Unguja Ukuu with calibrated ^{14}C dates (amsl = above mean sea level).

Table 5.2. Vegetation plots of Makoba Bay showing plant percentages, surface pollen percentages, *S. alba/*(*Bruguiera/Ceriops*) (S/BC), *Sonneratia*/*Rhizophora* (S/R) and *Rhizophora/*(*Bruguiera/Ceriops*) (R/BC) ratios of surface samples and inundation frequency with reference to Watson's (1928) and Santisuk's (1983) classes.

Plot	Altitude amsl (m)	Plant percentages (%)	Pollen percentages (%) of surface samples	S/BC ratio	S/R ratio	R/BC ratio	Inundation frequency during a month	Mangrove classes
AMAK-3	-1.567	*A. marina* (14.89), *S. alba* (85.11)	*A. marina* (12.7), *Bruguiera/Ceriops* (2.7), *R. mucronata* (22), *S. alba* (60.7), Monolete (2)	22.8	2.29	9.95	Daily (56-62)	Low mangrove
AMAK-2	-1.113	*A. marina* (48.39), *R. mucronata* (38.71), *S. alba* (12.9)	*A. marina* (17.3), *Bruguiera/Ceriops* (4), *R. mucronata* (57.3), *S. alba* (21.3)	5.4	0.37	14.33		
	(-0.523)-(-0.016)			1.3-5.4	0.04-0.07	14.33-19.02	Several times to daily (20-56)	Low-middle mangrove
BMAK-3	-0.523	*R. mucronata* (100)	*A. marina* (1.3), *Bruguiera/Ceriops* (4.6), *R. mucronata* (87.5), *S. alba* (3.9), Poaceae (0.7), Monolete (2)	1.3	0.07	19.02	Several times (20-45)	Middle mangrove
BMAK-2	-0.016	*B. gymnorrhiza* + *C. tegal* (70.9), *R. mucronata* (29.1)	*A. marina* (1.3), *Bruguiera/Ceriops* (21.1), *R. mucronata* (73.7), *S. alba* (3.3), Poaceae (0.7)	0.2	0.04	3.49		
BMAK-1	0.454	*C. tegal* (43.14), *R. mucronata* (56.86)	*A. marina* (2.6), *Bruguiera/Ceriops* (21.1), *R. mucronata* (69.7), *S. alba* (3.3), Poaceae (2), Cyperaceae (1.3)	0.2	0.05	3.30		
AMAK-1	0.60	*C. tegal* (95.31), *R. mucronata* (4.69)	*A. marina* (5.9), *Bruguiera/Ceriops* (32), *R. mucronata* (56.9), *S. alba* (5.2),	0.2	0.09	1.78		
	0.60-1.04			0-0.2	0-0.09	0.46-1.78	Infrequently to several times (2-45)	Middle-high mangrove
CMAK-3	1.04	*B. gymnorrhiza* + *C. tegal* (100)	*Bruguiera/Ceriops* (61.8), *R. mucronata* (28.3), *S. alba* (0), *Acrostichum aureum* (1.3), Poaceae (2.6), Cyperaceae (2.6), Monolete (2)	0	0	0.46	Infrequently (2-20)	High mangrove
CMAK-1	1.513	*C. tegal* (100)	*Bruguiera/Ceriops* (66.5), *R. mucronata* (28.7), *S. alba* (0), Poaceae (1.8), Cyperaceae (1.8), Monolete (1)	0	0	0.43		
CMAK-2	1.545	*C. tegal* (100)	*Bruguiera/Ceriops* (76.3), *R. mucronata* (19.7), *S. alba* (0), *Acrostichum aureum* (2.6), Poaceae (1.3)	0	0	0.26		

Table 5.3. Vegetation plots of Unguja Ukuu showing plant percentages, surface pollen percentages, *S. alba/*(*Bruguiera/Ceriops*) (S/BC), *Sonneratia/Rhizophora* (S/R) and *Rhizophora*/(*Bruguiera*/*Ceriops*) (R/BC) ratios of surface samples and inundation with reference to Watson's (1928) and Santisuk's (1983) classes.

Plot	Altitude amsl (m)	Plant percentages (%)	Pollen percentages (%) of surface samples	S/BC ratio	S/R ratio	R/BC ratio	Inundation frequency during a month	Mangrove classes
A-UU-3	0.04	*B. gymnorrhiza* + *C. tegal* (7.4), *R. mucronata* (47.7) , *S. alba* (44.9)	*A. marina* (2.0), *Bruguiera/Ceriops* (13.9), *R. mucronata* (53), *S. alba* (31.1)	2.23	0.59	3.81		
A-UU-1	0.10	*C. tegal* (4.8), *R. mucronata* (63.2), *S. alba* (32)	*A. marina* (1.9), *Bruguiera/Ceriops* (15.4), *R. mucronata* (69.1), *S. alba* (13.6)	0.88	0.20	4.48	Several times to daily (45-62)	Low mangrove
B-UU-1	0.17	*C. tegal* (13.3), *R. mucronata* (60.1), *S. alba* (26.6)	*A. marina* (2.5), *Bruguiera/Ceriops* (24.8), *R. mucronata* (54.8), *S. alba* (17.8)	0.72	0.25	2.21		
	0.17-0.24			0.17-0.72	0.25-0.33	0.69-2.21	Several times (20-45)	Middle mangrove
A-UU-2	0.24	*C. tegal* (63.0), *R. mucronata* (20.7), *S. alba* (16.3)	*A. marina* (2.6), *Bruguiera/Ceriops* (51.9), *R. mucronata* (35.7), *S. alba* (9.1), *L. racemosa* (0.6)	0.17	0.33	0.69		
B-UU-2	0.89	*C. tegal* (90.6), *R. mucronata* (9.4)	*A. marina* (3.2), *Bruguiera/Ceriops* (72.9), *R. mucronata* (20.6), *S. alba* (3.2),	0.04	0.16	0.28		
B-UU-3	1.02	*C. tegal* (68.2), *R. mucronata* (31.8)	*A. marina* (1.9), *Bruguiera/Ceriops* (62.3), *R. mucronata* (33.1), *S. alba* (2.6)	0.04	0.08	0.53		
C-UU-1	1.38	*C. tegal* (100)	*A. marina* (2.5), *Bruguiera/Ceriops* (73.9), *R. mucronata* (21.0), *L. racemosa* (1.3), Poaceae (1.3)	0.02	0.05	0.43	Infrequently to several times (2-45)	High mangrove
C-UU-3	1.92	*A. marina* (35.2), *C. tegal* (64.8)	*A. marina* (14.9), *Bruguiera/Ceriops* (57.8), *R. mucronata* (24.8), *S. alba* (1.2), *L. racemosa* (0.6), Poaceae (0.6)	0	0.00	0.28		
C-UU-2	1.94	*C. tegal* (81.9), *L. racemosa* (18.1)	*A. marina* (3.2), *Bruguiera/Ceriops* (59.7), *R. mucronata* (26.0), *L. racemosa* (9.7), Poaceae (1.3)	0	0.00	0.43		

Table 5.4. List of radiocarbon dates from three sites including calibrated ages of Shcal04 curve (McCormac *et al.*, 2004) using the software OxCal v4.10 (Bronk-Ramsey, 2009) and calculated sea level index points (SLIPs).

Site	**Core**	**Altitude (m amsl)**	**Depth (cm)**	**Code**	**$\delta^{13}C$**	**^{14}C yr B.P.**	**(2σ) Calibrated age range yr B.P.**	**Calibrated age yr B.P.**	**Indicative range (m amsl)**	**SLIP**	**Type of contact**
Northern Rufiji Delta	ANR		128	Wk-26854	-25.7	392 ± 30	493-324	409 ± 85	1.7 - 3.5	0.05 – (-1.85)	Positive
	BNR	3.25	19	UBA-15385	-22	> A.D.1950					
	BNR	2.98	46	UBA-15386		Failure to make graphite					
	BNR	2.37	107	Wk-26855	-23.0	4167 ± 30	4821-4453	4637 ± 184		0.67 – (-1.13)	Positive
	BNR	0.64	280	Wk-26856	-23.1	4751 ± 30	5579-5318	5449 ± 131		-1.06 – (-2.86)	Positive
	BNR	-0.99	443	Wk-26857	-22.4	4931 ± 30	5711-5486	5599 ± 113		-2.69 – (-4.49)	Positive
	CNR	2.36	115	UBA-15387	-29.5	> A.D 1950.					
	CNR	1.09	242	Wk-26858	-23.1	884 ± 31	799-680	740 ± 60		-0.61 – (-2.41)	Negative
	CNR	-0.94	445	Wk-26859	-20.5	1292 ± 30	1264-1071	1168 ± 97		-2.64 – (-4.44)	Negative
Makoba Bay	AMAK-1	-0.38	98	UBA-15378	-28.6	1615 ± 24	1525-1385	1455 ± 70	(-0.52)-0.60	(-0.98) – 0.14	Negative
	AMAK-1	-1.53	213	UBA-15379	-27.3	5078 ± 26	5892-5659	5776 ± 117	(-1.57)-(-1.11)	(-0.42) – 0.04	Negative
	BMAK-1	-0.51	96	UBA-15380	-26.6	3111 ± 24	3362-3167	3265 ± 98			
	BMAK-1*	-0.52	97	SUERC-41805	-26.4	2072 ± 35	2107-1880	1994 ±114	(-0.52)-0.60	(-1.12) – 0	Negative
	BMAK-1	-0.61	106	UBA-19415	-30.0	1543 + 25	1477-1305	1391 ± 86			
	BMAK-1	-1.13	158	UBA-16631	-33.0	1695 ± 50	1692-1408	1550 ± 142			
	BMAK-1	-1.50	195	UBA-15381	-28.0	309 ± 23	443-289	366 ± 77			
	BMAK-1*	-1.51	196	SUERC-42739		4024 ± 40	4566-4250	4408 ± 158	(-0.52)-0.60	(-2.11) – (-0.99)	Still stand
	BMAK-1	-2.75	320	UBA-19416	-25.4	6878 ± 36	7735-7582	7659 ± 77	(-1.57)-(-1.11)	(-1.64) – (-1.18)	Positive
	BMAK-1	-3.51	396	UBA-15382	-28.9	7202 ± 30	8025-7872	7949 ± 77	0.60-1.04	(-4.55) – (-4.11)	Positive

(* representing dates retrieved from pollen concentrates)

Table 5.4. List of radiocarbon dates from three sites including calibrated ages of Shcal04 curve (McCormac *et al.*, 2004) using the software OxCal v4.10 Bronk-Ramsey (2009) and calculated sea level index points (SLIPs) (cont.).

Site	Core	Altitude (m amsl)	Depth (cm)	Code	$\delta^{13}C$	^{14}C yr B.P.	(2σ) Calibrated age range yr B.P.	Calibrated age yr B.P.	Indicative range (m amsl)	SLIP	Type of contact
Makoba Bay	CMAK-1	0.44	107	UBA-15383	-26.1	5200 ± 35	5991-5751	5871 ± 120			
	CMAK-1	0.21	130	UBA-16632	-23.8	4239 ± 37	4841-4579	4710 ± 131			
	CMAK-1	-0.21	172	UBA-15384	-28.8	3117 ± 35	3376-3162	3269 ± 107			
Unguja Ukuu	A-UU-1	-0.81	91	UBA-16626	-26.2	169 ± 22	278-(-4)	137 ± 141	0.24-0.89	(-2.51) – (-1.05)	Negative
	B-UU-1	-1.21	138	UBA-16627	-32.2	1534 ± 23	1407-1310	1359 ± 48	0.89-1.94	(-3.15) – (-2.1)	Negative
	C-UU-1	0.60	78	UBA-16628	-31.0	4211 ± 25	4828-4574	4701 ± 127	0.24-0.89	(-0.29) – (0.36)	Positive
	C-UU-4	0.62	42	UBA-19485	-25.7	> A.D.1950					
	C-UU-4	0.42	62	UBA-16629	-25.5	560 ± 19	550-512	531 ± 19	0.04-0.24	(0.18) – (0.38)	Negative
	C-UU-4	-1.26	230	UBA-16630	-26.4	5973 ± 36	6877-6652	6765 ± 112	0.89-1.94	(-3.2) – (-2.15)	Positive

(* representing dates retrieved from pollen concentrates)

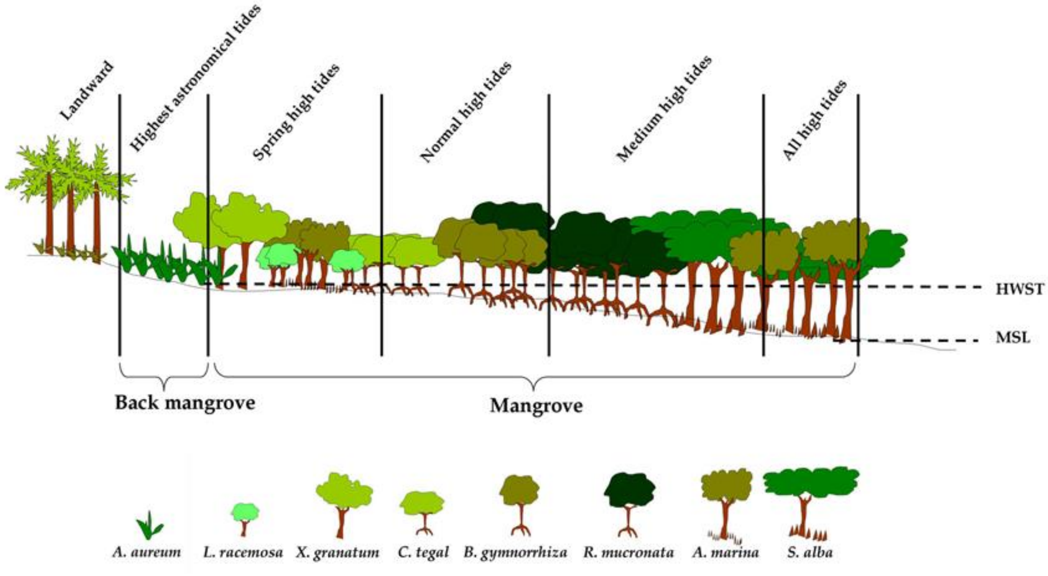

Figure 5.5. Summary cross section showing typical mangrove zonation in Zanzibar developed from Watson's (1928) and Santisuk's (1983) inundation classes and field observations

Sea level index points (SLIPs)

In order to reconstruct sea level change using mangrove sediments, it is necessary to know the altitudinal range within which the mangrove species occur as this represents the indicative range of the sea level index point (SLIP). For example, in the northern Rufiji Delta, the altitudinal range of mangrove occurrence is from 1.7 to 3.5 m amsl and this therefore provides the altitudinal range of the SLIP. For example, in BNR the radiocarbon date of 4637 cal yr B.P. at 107 cm could represent mangrove occurrence between the altitudes at 1.7-3.5 m amsl. The altitude of the top of BNR is 3.44 m amsl; the depth of 107 cm in BNR would therefore occur at 2.37 m amsl and the reconstructed sea level would be 1.7-3.5 m below 2.37 m amsl. We can therefore calculate the SLIP to be a maximum of 0.67 m and minimum of -1.13 m amsl (Table 5.4). To decrease the altitudinal range of the SLIP, we use the relationship between the ratios of S/BC, S/R and R/BC and the mangrove classes established from the contemporary vegetation to estimate former altitudinal ranges of the SLIP as identified from biostratigraphy of the pollen records in Makoba Bay and Unguja Ukuu (Figure 5.6; Table 5.4).

The altitudinal errors of the SLIPs also include a compaction factor of the sediment as estimated by Bird *et al*. (2004) that ranges from 17 to 31% of the accretion rate. Altitudinal errors are also present for compaction caused by coring equipment (Woodroffe, 2006) and levelling errors although there are much more negligible (Table 5.5).

Sea level tendency for each SLIP is determined using a combination of stratigraphy and the trend of mangrove pollen-based interpretation from each coring site. A positive tendency represents an increase in marine influence while a negative tendency represents a decrease in sea level at the sampling site. Local processes, such as changes in sediment input, can affect the regional signal of sea level change; accordingly, the same sea level tendency is not necessarily found at all sites at the same time. Moreover, the balance between local and regional processes is represented by the correlation of tendencies among sites (Shennan *et al*., 1995).

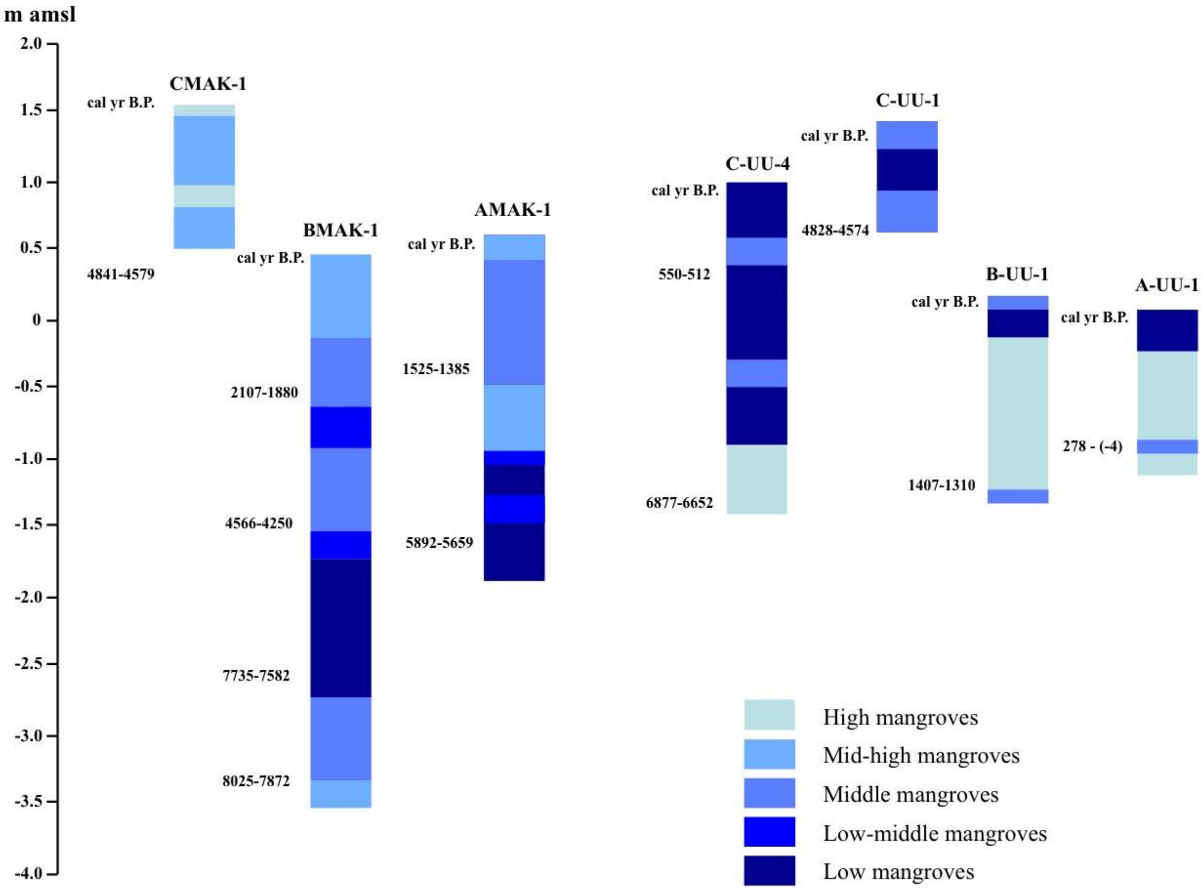

Figure 5.6. Biostratigraphy of core sites from Makoba Bay and Unguja Ukuu showing mangrove position as low, middle, high and intermediate mangrove classes inferred from the ratios of S/BC, S/R and R/BC.

Table 5.5. Sources of error for sea level index point calculation

Sources of error	Estimated total elevation error (m)
Compaction (after Bird *et al.*, 2004)	± 0.24%
Surveying (δGPS)	± 0.001
Compression due to coring equipment (after Woodroffe, 2006)	± 0.04
Vertical range of radiocarbon date	± 0.005

The indicative range of SLIP in the northern Rufiji Delta is 1.7-3.5 m obtained from the altitudinal range of mangrove area. An indicative range of SLIP in Makoba Bay and Unguja Ukuu is obtained from pollen-vegetation ratios as developed in Table 5.2 and 5.3 respectively.

Interpretation and discussion

Holocene mangrove dynamics history

By combining all cores from the three locations, applying insights on the relationship between contemporary vegetation and surface pollen spectra relationships and using the ratios of *S. alba* and *Bruguiera*/*Ceriops* (S/BC), *S. alba* and *R. mucronata* (S/R) and *R. mucronata* and *Bruguiera*/*Ceriops* (R/BC) in Zanzibar to reconstruct changes in sea level, the following sea level interpretation has been developed.

Early to mid Holocene

An early Holocene sea level rise is indicated from the pollen record of BMAK-1 from Makoba Bay (Figure 5.6) which allowed mangrove development from around 7872 – 8025 cal yr B.P. at 3.65 m below mean sea level. The ratios of S/BC, S/R and R/BC also suggest that the central core (BMAK-1) was occupied by middle-high mangroves contemporaneous to the present day mangrove composition located at AMAK-1, BMAK-1 and BMAK-2 (Figure 5.3b, 5.3c, 5.6; Table 5.2). A higher sea level rise was then recorded after this period for a relatively short duration until around 7735-7582 cal yr B.P. allowing mangroves to migrate landward and this area to support middle mangrove taxa. From 7735-7582 cal yr B.P. to around 4566-4250 cal yr B.P., sea level continued to rise as indicated by the ratios of mangrove pollen and the deposition of oyster shells in BMAK-1b and AMAK-1. This marine transgression caused the mangrove areas in these two coring sites to retreat further landwards and, in addition, allowed mangroves on the headland of Unguja Ukuu to establish at 1.26 m below mean sea level around 6877-6652 cal yr B.P. in C-UU-4. After this period, landward mangrove assemblages recorded in C-UU-4 subsequently became seaward mangrove assemblages supporting a body of evidence indicating that sea level continued to rise during the mid Holocene. It should be noted that the pollen record from both sites in Zanzibar reveal a similar age determination of 5711-5486 cal yr B.P. and a similar pollen record, lending support to the chronological and sea level interpretation. Mangroves were established at BNR in the northern Rufiji Delta since 5711-5486 cal yr B.P. The predominance of *R. mucronata* pollen suggests that this area was located in a low intertidal environment, a further indication of a higher sea level relative to the present day. However, soon after around 5991-5751 cal yr B.P. there was a short period of lower sea level within this mid Holocene sea level rise suggested by change in the ratios of pollen taxa from core AMAK-1 and C-UU-4 (Figure 5.6). A sea level fall caused the mangrove communities to migrate seawards becoming low-middle mangroves in AMAK-1 and middle mangroves in C-UU-4 from low mangroves. This trend is concomitant with a decrease in *R. mucronata* pollen and decreased sedimentation rate (2.1 mm yr^{-1}) causing mangroves to retreat seaward in BNR prior to 4820-4450 cal yr B.P. Another period of sea level rise followed causing mangroves to retreat landward and AMAK-1 and C-UU-4 to be characterised by low mangroves. Moreover, a mid Holocene sea level rise resulted in high mangrove establishment at 0.46 m amsl in CMAK-1 after 4840-4580 cal yr B.P. and middle mangroves establishment at 0.63 m amsl in C-UU-1 after 4830-4570 cal yr B.P. This mid Holocene sea level rise occurred until prior to 4566-4250 cal yr B.P., when sea level started to fall as indicated by the change from low mangroves to low-middle mangroves in BMAK-1.

Mid Holocene to the present day

After around 4400 cal yr B.P., there was a variation in sea level patterns along the Tanzanian coast. A lower sea level is recorded in Makoba Bay by the change in mangrove composition from low mangrove to middle mangrove assemblages in AMAK-1 and BMAK-1 (Figure 5.6) combined with lower sedimentation rates (0.27 mm yr^{-1}). This resulted in mangroves retreating seaward until the late Holocene around 1990-1450 cal yr B.P. The similarity in altitude at -0.38 m amsl in AMAK-1 and at -0.52 m amsl in BMAK-1 supports similar age determinations and mangrove composition dominated by middle mangroves. However, a short-lived sea level rise appeared prior to 1990 cal yr B.P. suggested by a change from middle to low-middle mangrove assemblages. A sea level rise is recorded at Unguja Ukuu as low mangroves occupied C-UU-1 and C-UU-4 after the mid Holocene until around 530 cal yr B.P. This apparent discrepancy in sea level is probably due to local processes including mangrove composition response to sediment input and/or erosion among sites, resulting in localised sea level changes.

From the late Holocene to the present sea level fell in Makoba Bay suggested by the change of middle mangroves to mid-high mangroves in AMAK-1 and BMAK-1 and the change of mid-high mangroves to high mangroves in CMAK-1. The late Holocene pollen records from the Rufiji Delta and Unguja Ukuu also support this marine regression. A reduction in mangrove pollen and increase in back-mangrove and terrestrial grasses in the landward site of the Rufiji Delta (CNR) after 1264-1071 cal yr B.P resulted in a shift of mangroves seawards. Sea level fluctuated suggested by some changes between mangroves, back-mangrove and terrestrial grasses until prior to 799-680 cal yr B.P. Sea level started to fall after about 799-680 cal yr B.P. allowing terrestrial vegetation to develop recorded by a gradual change from mangroves characterised by *R. mucronata* pollen to terrestrial vegetation and the replacement of mangroves by herbaceous taxa. The late Holocene sea level fall in Unguja Ukuu was recorded from B-UU-1 indicated by the change from middle mangroves to high mangroves after 1407-1310 cal yr B.P. Sea level probably continued falling in Unguja Ukuu represented by the change from low mangroves to middle mangroves after around

530 cal yr B.P. in C-UU-4 and an occurrence of high mangroves after 278-(-4) cal yr B.P. in A-UU-1. However, changes from high mangroves to low mangroves in A-UU-1, B-UU-1 and C-UU4 corresponding to an increase in *A. marina* at the top of ANR are likely to be a possible sea level rise during the last millennia.

Sea level reconstruction

The evidence from the Rufiji Delta, Makoba Bay and Unguja Ukuu is used to reconstruct sea level change (Figures 5.7, 5.8 and 5.9 respectively). Combining the 16 sea level index points, the wider context of Holocene relative sea level changes from Tanzania are considered (Figure 5.10). Interestingly, all three sites provide evidence for a phase of early-mid Holocene and late Holocene relative sea level change. The composite sea level curve shows that around 7900 cal yr B.P., sea level probably occupied the Tanzanian coast at (-5.1)-(-2.7) m amsl provided by the mangrove deposits from Makoba Bay (Figures 5.7, 5.10) suggesting the earliest evidence of Holocene sea level rise. After this period, a rapid sea level rise at a rate of 9.3 mm yr^{-1} occurred until 7700 cal yr B.P. followed by a lower sea level until 6800 cal yr B.P. at an altitude of (-4.3)-(-0.2) m amsl. It is possible that sea level rose, close to the present sea level (0.07 m amsl) at around 7700 cal yr B.P.

Comparing the Tanzanian sea level curve with other curves from the mainland coast and offshore islands in the Southwest Indian Ocean, it can be seen that although the pattern of sea level change did not occur uniformly, the general trend of sea level changes through the early-mid Holocene seems to be in agreement (Figure 5.11). An early Holocene sea level rise is documented along the coasts in the Southwest Indian Ocean (Colonna *et al*., 1996; Camoin *et al*., 1997; 2004; Zinke, 2000; Compton, 2001; Ramsay and Cooper, 2002; Zinke *et al*., 2003). A small meltwater pulse from Antarctic melting ice sheets recognised at around 7600 cal yr B.P. observed in the Carribean (Blanchon and Shaw, 1995) is likely to be concomitant with the timing of sea level rise in Tanzania at around 7900 cal yr B.P. Sea level rose again confirmed by positive tendencies from 6800 cal yr B.P. until around 4700-4600 cal yr B.P. with a maximum estimated sea level at around 5800 cal yr B.P at 1 m amsl occurring in Makoba Bay. However, a short period of lower sea level occurred from 5800 to 5600 cal yr B.P. at an altitude of (-6.4)-0.2 m amsl and rose again until 4700-4600 cal yr B.P. when sea level possibly reached the estimated highest altitudes at 1.2-2.8 m amsl in Unguja Ukuu and the Rufiji Delta, respectively. This demonstrates that relative sea level was potentially higher than present mean sea level before falling below present mean sea level at (-3.7)-0.6 m amsl around 4400 cal yr B.P. Thus there was a clear signal of mid Holocene sea level rise recorded at all three sites.

The Tanzanian sea level curve shows a potentially higher sea level than present (5800 cal yr B.P. and 4700 cal yr B.P) and appears a similar trend to the sea level record from South Africa (Compton, 2001; Ramsay and Cooper, 2002) (Figure 5. 11). The mid Holocene sea level rise in Tanzania is also supported by a marine transgression phase in Mozambique (Norström *et al.*, 2012) where a highstand is recorded around 6600-6300 cal yr B.P. The mid Holocene transgression is well represented from the Southern Hemisphere in "far-field" locations (Isla, 1989) relating to the final stage of ice melting from the Late Devensian ice sheets (Lambeck and Nakada, 1990; Fleming *et al.*, 1998) and/or the Holocene melting ice sheets from Antarctica, Greenland and mountain glaciers during the early Holocene until 5000 cal yr B.P. (Milne *et al.*, 2005). It is possible that variations in the timing of the melting of these sources of water produce variable mid Holocene highstands at different times. Evidence from Mauritius, Mayotte and Réunion Island (Camoin *et al.*, 1997; 2004; Zinke *et al.*, 2003) suggest no highstand occurred. The differences between the sea level curves from islands and the Tanzanian sea level curve may result from isostatic influences relating to the difference in the geographical locations (Clark *et al.*, 1978). The Holocene highstand at small offshore islands is likely to be less marked than at the continental margins due to the effects of continental levering (Lambeck and Nakada, 1990; Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). However, maximum amplitudes of the highstand recorded from South Africa are likely to be higher than the potential maximum transgression at around 5800 cal yr B.P. and 4700 cal yr B.P. in Tanzania due to continental levering (Compton, 2001; Ramsay and Cooper, 2002). In addition to eustatic changes, the mid Holocene highstand also resulted from a combination of factors such as hydro-isostaty and a thermal expansion of seawater caused by warmer ocean temperatures (Ramsay, 1995, Woodroffe and Horton, 2005). In subtropical latitudes, such as South Africa, the steric expansion influencing the Holocene sea level oscillations (Ramsay, 1995; Compton, 2001) may be considered as another factor enhancing the highstand amplitude.

From 7700 to 5800 cal yr B.P., a mid Holocene sea level rise is recorded in Tanzania although there is a potential lower sea level at around 6800 cal yr B.P. A short period of lower sea level between 5800-5600 cal yr B.P. contradicts the sea level rise from the northeastern coast of South Africa that occurred during 5700-5100 cal yr B.P. (Ramsay, 1995; Ramsay and Cooper, 2002) but probably coincides with the sea level curve from the southern Langebaan Lagoon salt marsh, South Africa (Compton, 2001) and the freshwater dominant in the estuary due to sea level fall centered at around 6300 to 4000 cal yr B.P. These variable records are likely to be due to variations in local processes occurring at the sites. After around 4600 to 4400 cal yr B.P., a lower sea level was recorded in Tanzania as well as in the South African records (Ramsay and Cooper, 2002; Compton, 2001).

There is a possible hiatus in the sea level curve from Tanzania from 4400 and 2000 cal yr B.P. that may be due to erosion of the mangrove peat when the sea level reached the highest altitude around 4700 cal yr B.P. This would be as a result of mangroves not being able to keep pace with this transgression causing a lack of mangrove peat in CMAK-1 at Makoba Bay and C-UU-1 at Unguja Ukuu (Figure 5.6). This is also reflected by the complex geomorphology of Unguja Ukuu as at the same altitude in C-UU-4, A-UU-1 and B-UU-1 pollen records relate to the mid Holocene in the former core and late Holocene in the latter two cores. In addition, the discrepancy in the age-depth relationship and poor pollen preservation at the depth of 30-90 cm in BNR probably contributes to the body of evidence for a mid Holocene sea level rise. Comparison with sea level curves in this region shows that it is unlikely that a sea level rise occurred at this time (Ramsay and Cooper, 2002). Lowstands occurred in South Africa after the mid Holocene transgression (Compton, 2001) corroborating the biostratigraphic records obtained in this study. A possible marine transgression with a highstand was recorded from Macassa Bay (Mozambique) during 4000-1100 cal yr B.P. (Norström *et al.*, 2012) and from evidence recorded from dated coral in

Madagascar during 2000-3000 ^{14}C yr B.P. (Battistini *et al*., 1976; Camoin *et al.*, 2004). However, pollen records from all sites in Makoba Bay and C-UU-1 and C-UU-4 of Unguja Ukuu indicate that mangrove development continued suggesting that the mid Holocene sea level influenced these sites and sea level tended to fall up until the late Holocene. This may have allowed suitable conditions for mangroves in A-UU-1 and B-UU-1 to establish from the late Holocene and corresponds to the progradation of beach plains in Zanzibar (Arthurton, 2003).

The late Holocene sea level record after 2000 cal yr B.P. until 140 cal yr B.P. is a slightly better fit with the sea level curves from South Africa (Compton, 2001; Ramsay and Cooper, 2002) (Figure 5.11) as well as Mozambique (Norström, *et al.*, 2012) demonstrating sea level fluctuations occurring in the last thousand years. Sea level was relatively stable from 2000 to 1500 cal yr B.P. with a maximum sea level of 1.4-1.5 m amsl and a minimum sea level of (-3.0)-(-2.5) followed by a fall until 1200 cal yr B.P (Figure 5.10). This record is supported by a second northeastern South Africa record indicating a sea level fall from around 1400 cal yr B.P. to present sea level (Ramsay and Cooper, 2002). The evidence from archaeological sites indicates that sea level was approximately -0.5 m amsl at Unguja Ukuu from 1300-1000 cal yr B.P. (Mörner, 1992). This is in good agreement with the Tanzania sea level fall suggesting sea level never attained present sea level ((-6.3)-0.3 m amsl) during 1400-1200 cal yr B.P. (Figure 5.11).

A further sea level rise occurred after this period to 740 cal yr B.P. and it is likely that sea level was below the present sea level prior to around 740 cal yr B.P. at an altitude of (-4.8)-1.8 m amsl. This concurs with records from the ruins in southeastern Tanzania (Kilwa) suggesting sea level was about -1 m amsl during 800-600 cal yr B.P (Mörner, 1992). Sea level rose until at 530 cal yr B.P. with a potential maximum sea level higher than present sea level ((-0.4)-0.8 m amsl), followed by a sea level fall until 140 cal yr B.P. indicating that sea level was lower than present mean sea level at (-3.3)-(-0.2) m amsl. This is in good agreement with the study on raised terraces along the Kenyan coast indicating sea level started to fall 500 years ago (Åse, 1978; 1981). On the other hand, data from Mozambique (Norström *et al.*, 2012) and southern Langebaan Lagoon in South Africa (Compton, 2001) show somewhat conflicting results with the Tanzanian sea level curve indicating sea level fall after 1200 cal yr B.P. Local land uplift as recorded along the coast of Tanzania (Alexander, 1969; Muzuka *et al.*, 2004) toward Kenya (Åse, 1978; 1981) is probably responsible for this contradiction in the sea level curves.

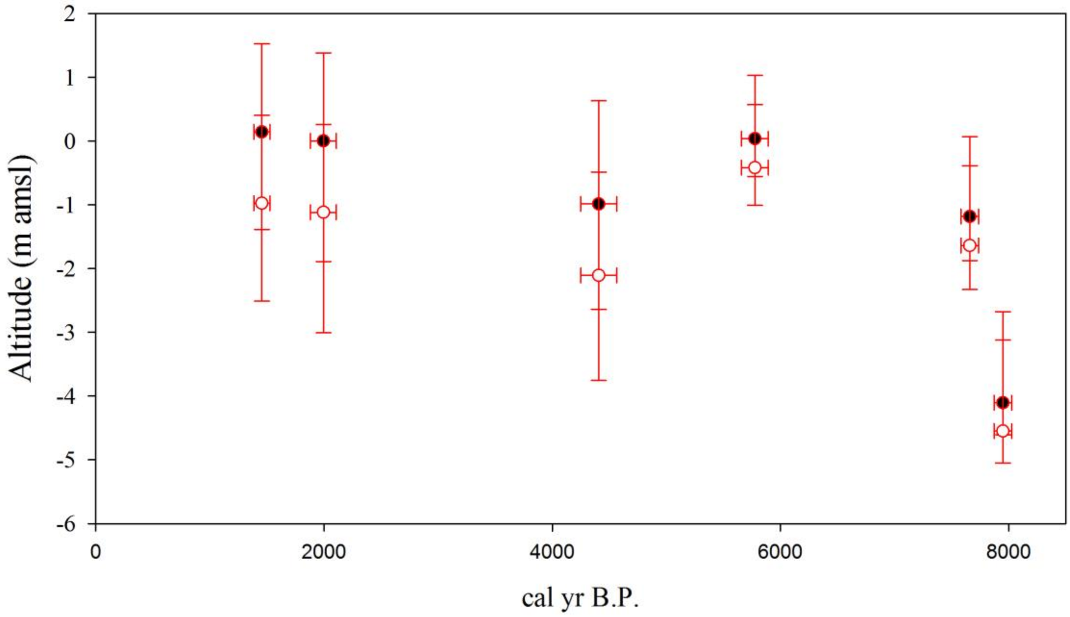

Figure 5.7. Sea level curve for Makoba Bay with horizontal error bars (from ^{14}C date) and vertical error bars as defined in Table 5.5.

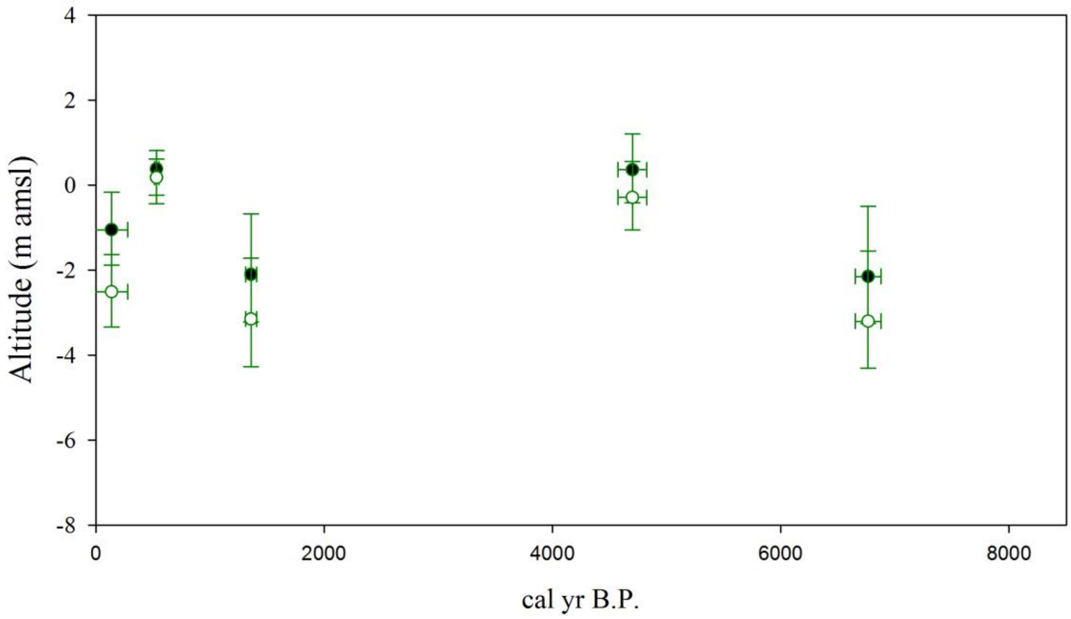

Figure 5.8. Sea level curve for Unguja Ukuu with horizontal error bars (from ^{14}C date) and vertical error bars as defined in Table 5.5.

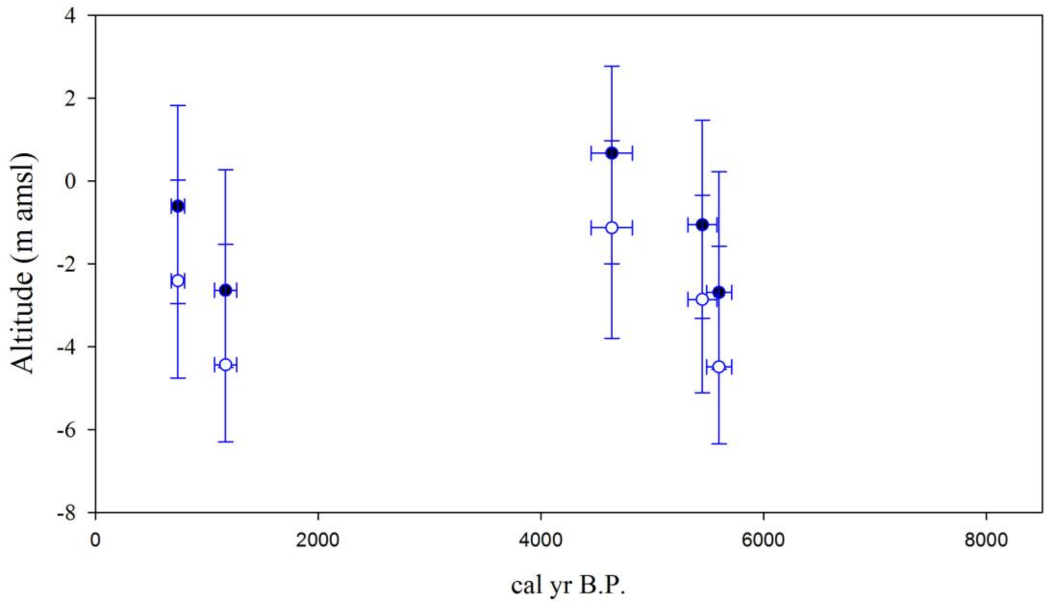

Figure 5.9. Sea level curve for the northern Rufiji Delta with horizontal error bars (from ^{14}C date) and vertical error bars as defined in Table 5.5.

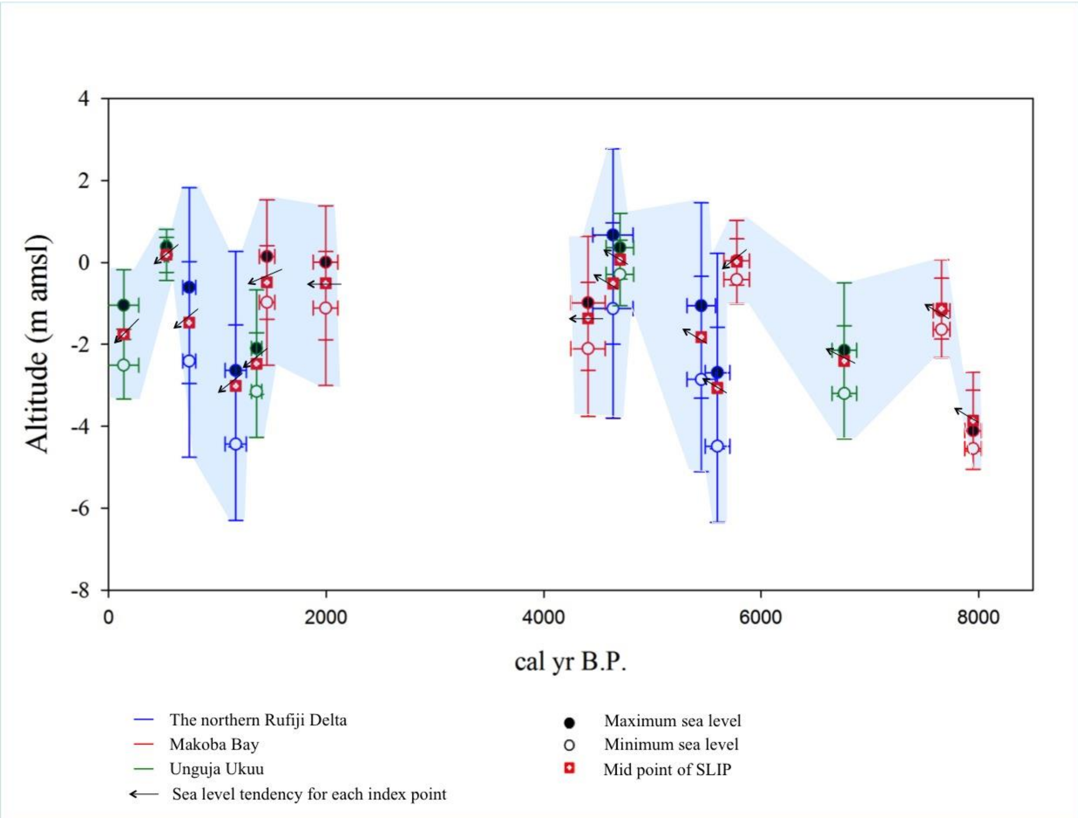

Figure 5.10 Composite sea level curve for the northern Rufiji Delta (blue line), Makoba Bay (red line) and Unguja Ukuu (green line).

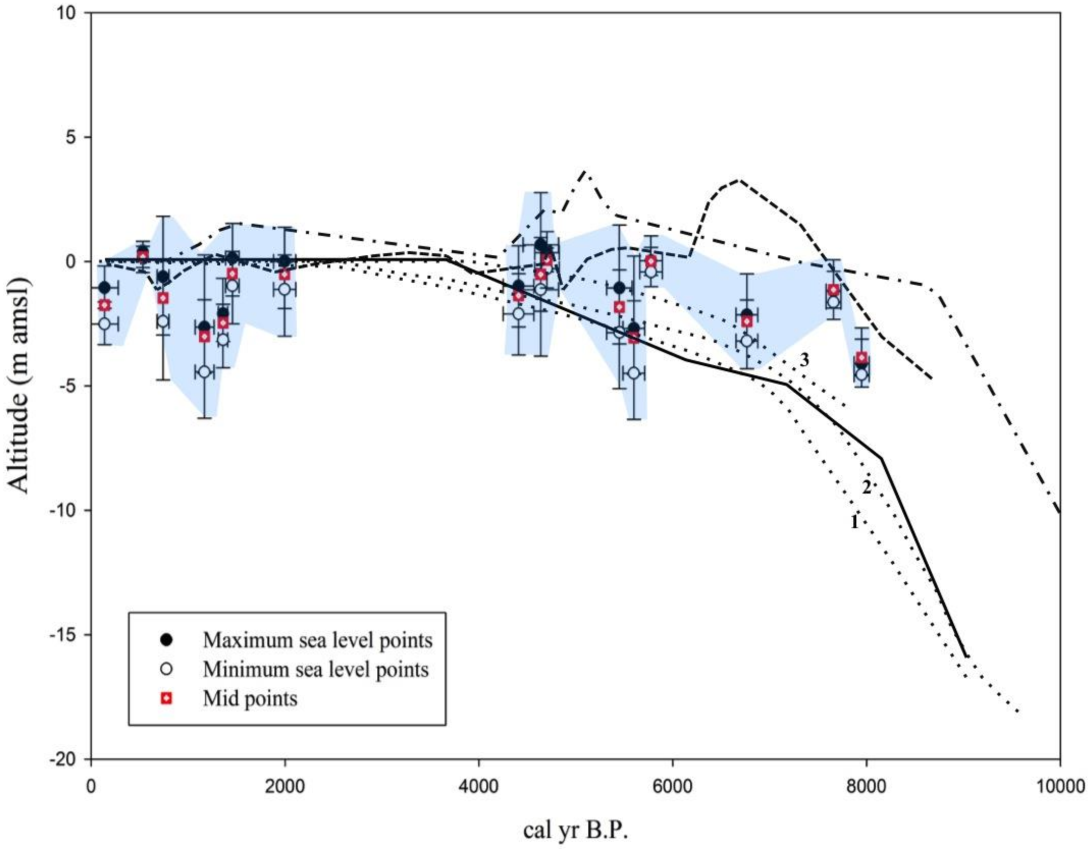

Figure 5.11. Sea level index points from this study for the Tanzanian coast plotted alongside sea level curves from the southwest Indian Ocean region, from South Africa (Ramsay and Cooper (2002) in dash-dotted line and Compton (2001) in dashed line and Mauritius (1), Mayotte (2) and Réunion (Camoin et al. (1997; 2004) in dotted line and Zinke *et al*. (2003) in solid line.

Conclusions

The synthesis of Holocene sea level and coastal changes for three locations in Tanzania have been reconstructed, using mangrove pollen. A sea level curve present an early-mid, mid and late Holocene sea level record and the site-specific sea level pattern across the Tanzanian coast. An early-mid to mid Holocene sea level rise occurred from ~ 8000 cal yr B.P. prior to 4600 cal yr B.P. with two potential mid Holocene highstands at ~ 5800 cal yr B.P. and ~ 4700 cal yr B.P. However, two short periods of relative sea level fall during 7700-6800 cal yr B.P. and 5800-5600 cal yr B.P. were recorded. Although there is uncertainty of the sea level fluctuations between 4400 and 2000 cal yr B.P., the pollen records suggested a sea level fall during this period probably due to sedimentary erosion /or estuarine migration along the Unguja Ukuu shore and the Rufiji Delta during the mid Holocene transgression. The late Holocene sea level fluctuations were documented with a potential highstand ((-0.4)-0.8 m a msl) at ~ 530 cal yr B.P. before falling at lower level than present level ((-1.8)-(-0.2) m amsl) at ~140 cal yr B.P.

The Tanzanian sea level curve indicates a similar trend to the mid Holocene sea level record from South Africa probably reflecting isostatic influences and the effects of continental levering. Sea level fall during the last 500 year is in good agreement with the Kenyan coast, although the data conflict with the trends recorded from Mozambique and Langebaan Lagoon in South Africa that indicate sea level fall after 1200 cal yr B.P. Local land uplift may be a factor in driving these variations in sea level changes. These discrepancies highlight the need for further research particularly by incorporating additional records from other East African areas as well as developing new data sets that will enable the development of a pollen-based transfer function that would improve the resolution of sea level reconstruction from “far-field” locations.

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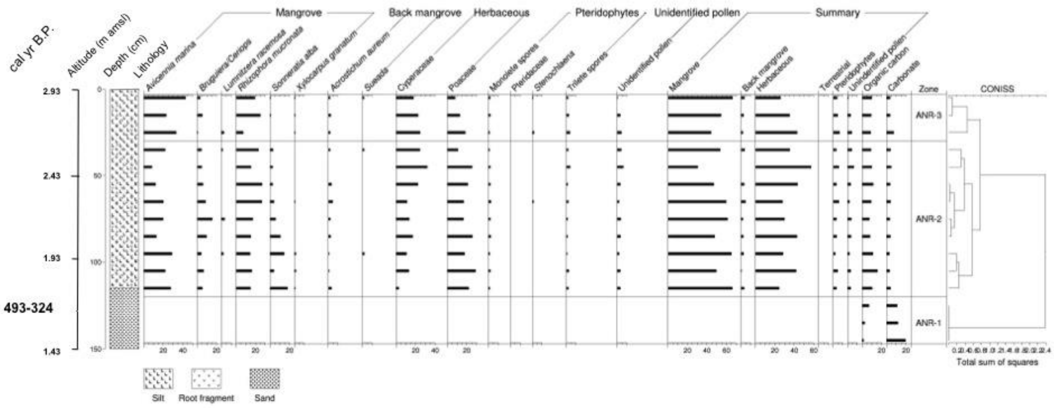
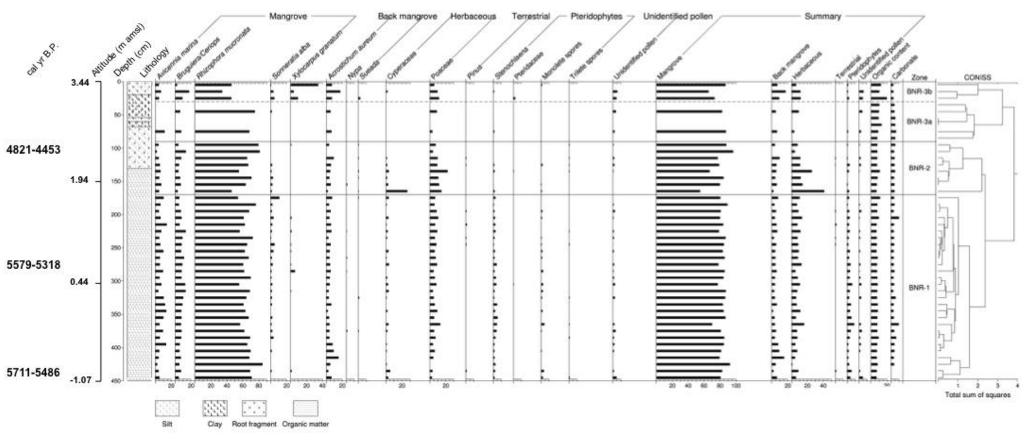
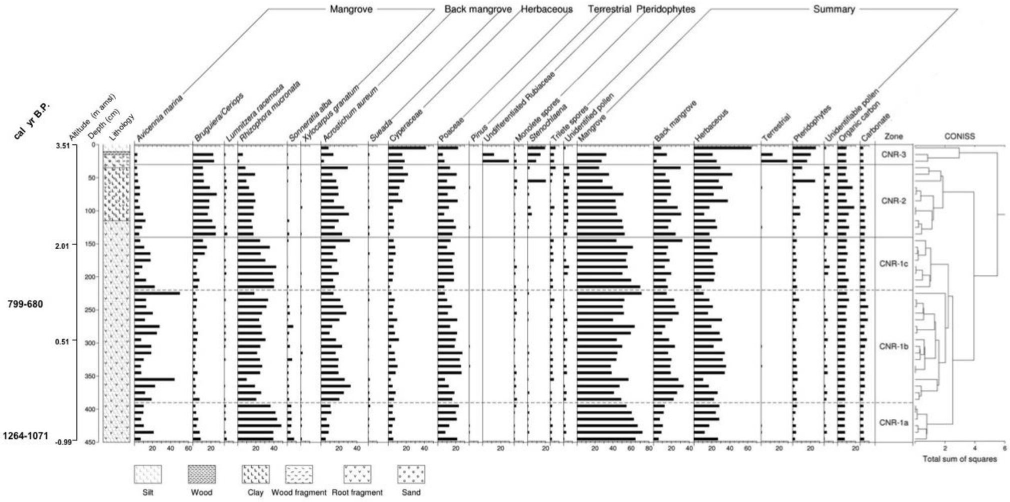
Supplementary figures



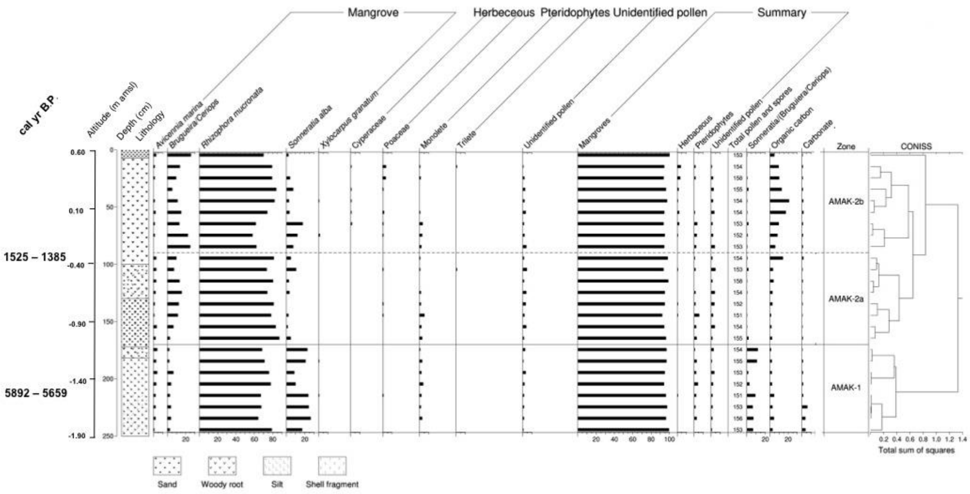
Supplementary figure 1. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the seaward site of the northern Rufiji Delta (ANR).



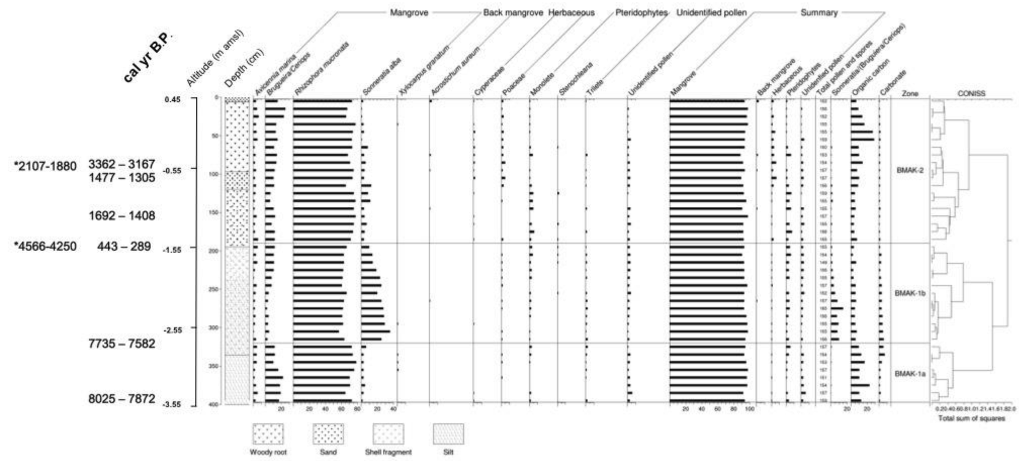
Supplementary figure 2. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the central site of the northern Rufiji Delta (BNR).



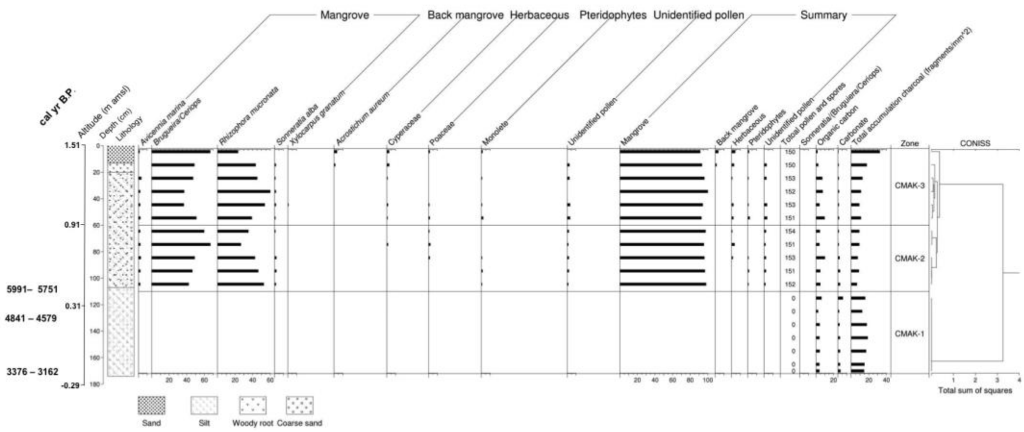
Supplementary figure 3. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the landward site of the northern Rufiji Delta (CNR).



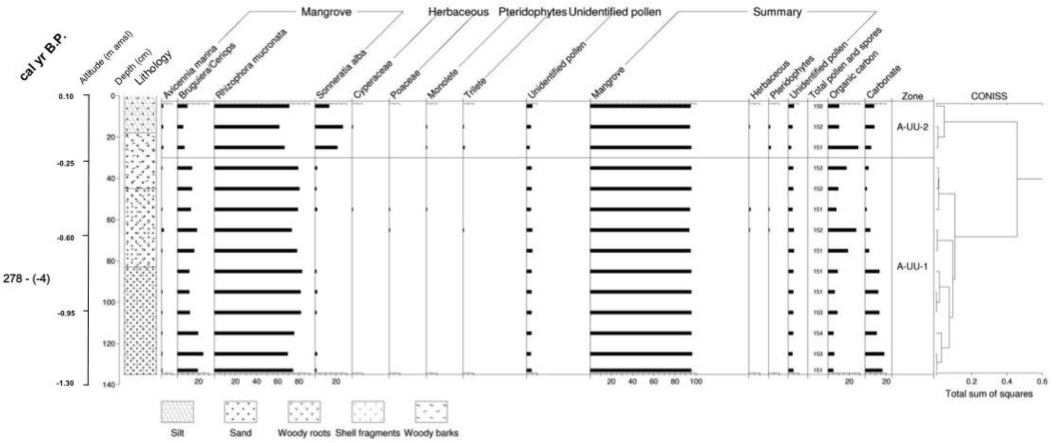
Supplementary figure 4. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the seaward site of the Makoba Bay (AMAK-1).



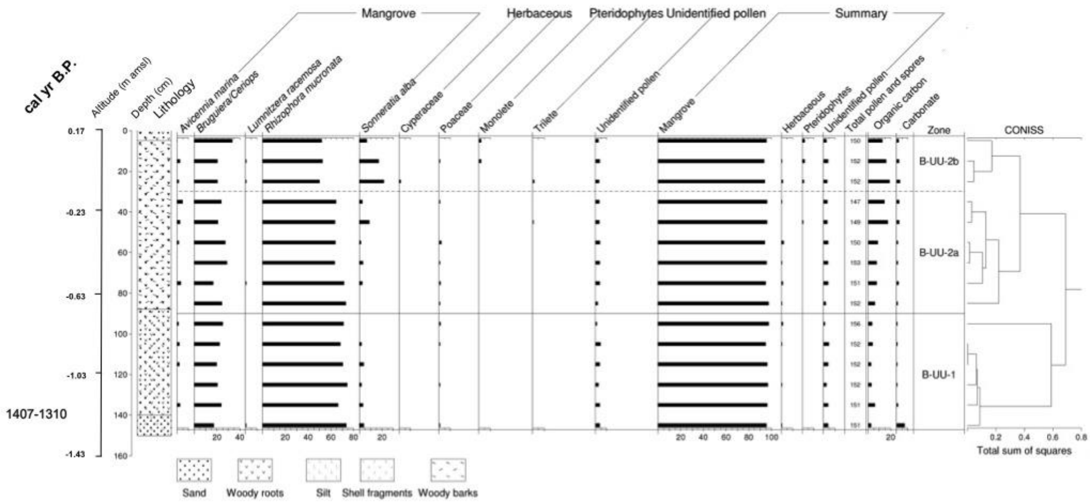
Supplementary figure 5. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the central site of Makoba Bay (BMAK-1) (* representing dates retrieved from pollen concentrates).



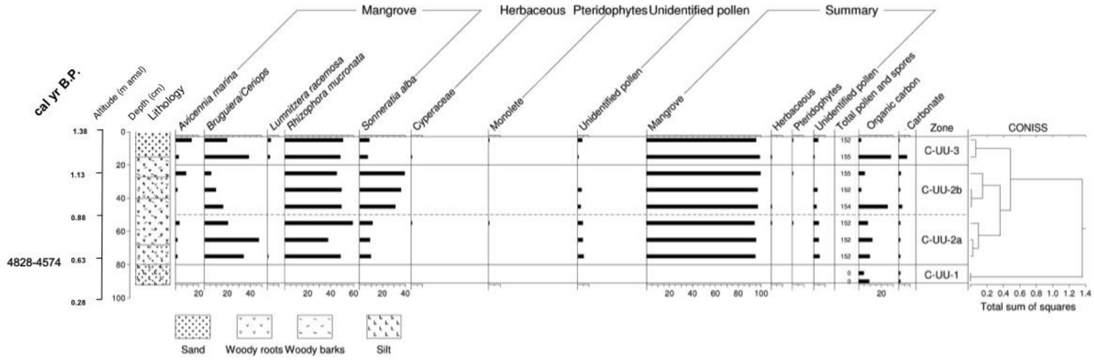
Supplementary figure 6. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the landward site of Makoba Bay (CMAK-1).



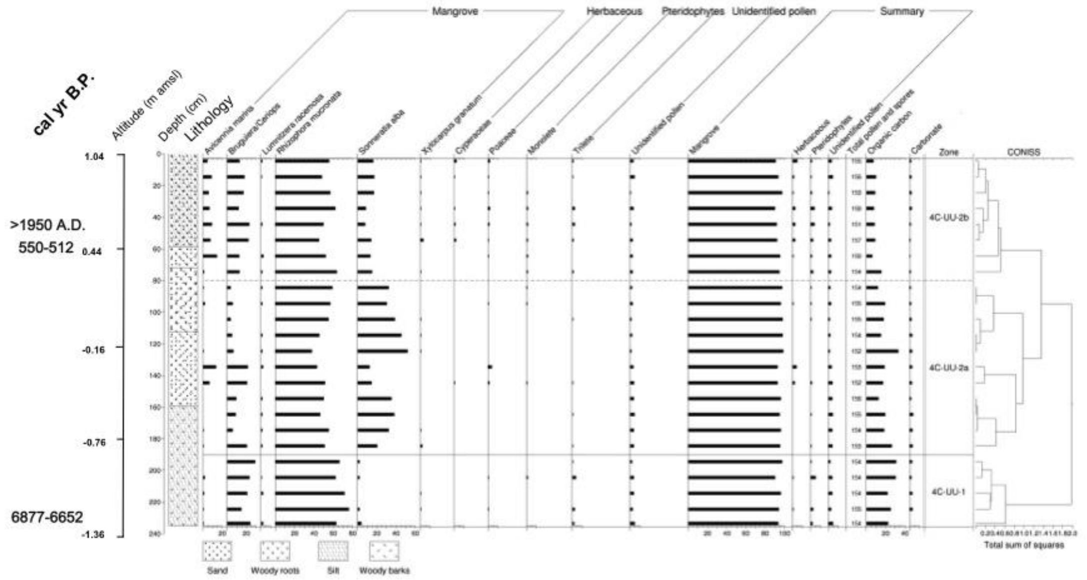
Supplementary figure 7. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the seaward site of Unguja Ukuu (A-UU-1).



Supplementary figure 8. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the central site of Unguja Ukuu (B-UU-1).



Supplementary figure 9. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the landward site of Unguja Ukuu (C-UU-1).



Supplementary figure 10. Diagram showing percentage pollen frequency, organic carbon and carbonate profiles from the additional site of Unguja Ukuu (C-UU-4).

Chapter 6: Discussion, future work and conclusions

This study is the first attempt to reconstruct the Holocene environmental history along the Tanzanian coast. This chapter provides (i) a synthesis of the results and conclusions of the research within the context of the original aims and objectives; (ii) an evaluation of the research methodology applied in this study; and (iii) some suggestions of future directions for palaeoecological research along the Tanzanian coast.

Review of aim and objectives

The overall aim of the study is to reconstruct the Holocene environmental history at three locations along Tanzanian coast using a multi-proxy palaeoecological approach. The results of this study will further our understanding of how mangroves reflect environmental variables and establish how humans have interacted with mangrove ecosystems over the recent past. Moreover, this study will provide a new coastal palaeoenvironmental study from Tanzania where very little is known about the Holocene mangrove dynamics and contribute to the body of evidence for sea level fluctuations in the Southwest Indian Ocean.

Three palaeoecological records were analysed to reconstruct Holocene palaeoenvironments along the Tanzanian coast and results were published in two papers (Punwong *et al.*, 2012; Punwong *et al.*, *in press*) with a further manuscript presently under re-review and another to be submitted imminently.

To achieve these aims, several specific objectives are set as follows:

1. *To characterise mangrove ecosystem dynamics at three key locations along the Tanzanian coast.*

Palaeoecological records from three locations reveal that mangrove ecosystems have not remained stable due to their response to environmental changes. However, these records also demonstrate the site-specific responses to environmental influences. Mangroves in the Rufiji Delta were more influenced by freshwater and terrestrial inputs than the other sites in this study. The riverine mangrove systems in the Rufiji Delta are subjected to numerous controls on sediment accumulation, erosion and re-deposition and are characterised by a very dynamic sedimentary environment. Hampered by chronological uncertainies and a problematic age-depth relationship, interpretation of environmental changes in the Rufiji Delta is more difficult. The records show fluctuating mangroves at the central sites from the mid Holocene (~5600 cal yr B.P.) until the late Holocene when mangroves covered the landward site covering a large area of the delta. Mangroves were gradually more influenced by terrestrial vegetation from the late Holocene until present day.

Results from Makoba Bay and Unguja Ukuu provide stronger records of mangrove ecosystem dynamics than that of the Rujifi Delta due to different mangrove settings where freshwater and terrestrial inputs are minimal. The Makoba Bay and Unguja Ukuu records indicate that, although mangroves were always dominant and there are no changes in the total vegetation composition, some individual mangrove taxa that are particularly sensitive to sea level fluctuations, have changed within the mangrove communities. The Zanzibar records reveal that fluctuations of mangroves occurred from ~8000 cal yr B.P. to present day with a marked occurrence of low mangroves during a mid Holocene sea level rise. Changes in mangrove composition from the uppermost part of the cores at Unguja Ukuu indicate sea level rise toward the present day in contrast to the records from the cores in Makoba Bay. This discrepancy is probably explained by the resolution of the analysis and/or sensitivity to sea level rise due to the lower altitude of the sites.

2. *To establish the relationship between mangrove tree distribution, pollen deposition and inundation frequency with respect to sea level to aid in the reconstruction of past environments and sea level changes.*

It was crucial to understand how pollen assemblages reflect the parent vegetation to develop an informed interpretation of palaeoecological sequences and ensuing environmental reconstruction. Thus, in this study the indices of associations for mangrove pollen types (Davis, 1984) and correlation coefficients of mangrove pollen deposition and tree distribution were established allowing fossil mangrove pollen to be used as a reliable and accurate tool to reconstruct past coastal ecosystem dynamics and also to infer sea level changes.

The specific contemporary mangrove habitats and zonation can be used as a technique to develop a relationship between relative mangrove pollen proportions and inundation frequency with respect to present sea level. Additionally, the relationship of the present day mangrove species distribution along different altitudinal gradients is also confirmed by the results from Inverse Distance Weighting analysis developed at Unguja Ukuu. As a consequence, the mangrove ecosystem can be reconstructed using changes in the relative pollen proportions of *Rhizophora/*(*Bruguiera/Ceriops*), *Sonneratia*/(*Bruguiera/Ceriops*) and *Sonneratia*/*Rhizophora* to identify the inundation regime of the mangroves; these proportions allowing a more precise estimate of past sea level altitude to be established. This is the first attempt to use mangrove pollen in this innovative way to reconstruct sea level and environmental changes.

3. *To reconstruct Holocene environmental history including the influences of sea level and climate changes.*

Reconstructed environmental history along the Tanzanian coast based on multi-proxy palaeoecological approaches has been documented and sea level index points created. The sea level curve shows significant changes in the mid and late Holocene. A mid Holocene sea level rise was documented from ~ 8000 cal yr B.P. to prior to 4600 cal yr B.P. with a potentially higher sea level than present at 5800 cal yr B.P. and 4700 cal yr B.P and two short periods of relative sea level fall from 7700 to 6800 cal yr B.P. and from 5800 to 5600 cal yr B.P. Coastal squeeze occurred in Zanzibar at ~ 4700-4600 cal yr B.P. due to a sea level rise that coincidied with humid conditions as indicated by low charcoal content. A sea level fall was recorded after 4600 cal yr B.P. until 4400 cal yr B.P. There is uncertainty about sea level changes between 4400 and 2000 cal yr B.P. due to chronological challenges. The possible hiatus in the sea level record may be explained by sedimentary erosion and/or estuarine migration along the Unguja Ukuu shore and the Rufiji Delta during the mid Holocene sea level rise. Sea level fluctuations occurred in the last thousand years with a potentially higher sea level higher present at ~ 530 cal yr B.P. before falling to a lower level than present at ~140 cal yr B.P. The fluctuating charcoal records also suggested variable humid environmental conditions during the late Holocene.

4. *To investigate the nature and timing of human interaction on mangroves and possible inter-connections to ecosystem-societal developments along the Tanzanian coasts.*

Multi-proxy analyses including pollen and charcoal allow establishment of a record of human interaction on mangroves along the Tanzanian coast. A robust evidence of recent human interaction was present from the Rufiji Delta and Unguja Ukuu. Although the earliest record of human occupation in Unguja Ukuu dates back to around 4000 cal yr B.P., it is likely the earliest intensive human interactions with mangrove were recorded after ~ 530 cal yr B.P. suggested by an increase in large charcoal fragments. This was a time of increased settlement and overseas trade (Horton and Clark, 1985; Kessy, 2003; Juma, 2004) when mangroves were exploited as fuelwoods and poles for societal development. As a consequence of this, harvesting of particular mangrove species had an effect on ecosystem dynamics leading to the succession of other species as evidenced in the pollen records. In addition to mangrove harvesting for pole trading along the Swahili coast, the Rufiji Delta palaeoecological records also demonstrate influences of human impact on mangrove ecosystems such as the damming of the river and the destruction of mangrove areas for rice cultivation in the last millennium.

Research methodology

Selection of suitable sites for palaeoecological investigation

As the Tanzanian coast contains extensive mangrove areas both in terms of the abundance and diversity, there are many potential areas for the study of mangrove dynamics in East Africa. However, locating suitable sites in large and inaccessible mangrove areas for palaeoecological analysis is challenging. Accordingly, a selection of suitable sites for palaeoecological study was derived from a discussion with researchers and experts in the field. Initial fieldwork was undertaken in the northern as well as in southern part of the Rufiji Delta to search for potential sites. Local villagers and/or the chief from each site helped to locate the mangrove areas and the accessible routes. The difficulty of access in large estuarine mangroves combined with tidal regimes mean that the time in which cores can be extracted is limited as well as the spatial area that can be covered. Moreover, the Rufiji Delta was too large in extent to carry out adequate vegetation surveys within the restricted fieldwork time frame.

Several sites were explored in Zanzibar including Chwaka Bay, a National Park of Zanzibar which had an extremely dense and extensive fringing mangrove forest. However, this site proved unsuitable due to unpromising stratigraphy as well as the difficulty of access through thick prop roots. Makoba Bay and Unguja Ukuu were investigated and proved suitable sites for coring and for improvisation of the vegetation surveying method. Therefore, three cores at each location in the Rufiji Delta and Zanzibar were retrieved from a transect perpendicular to the shoreline as seaward, central and landward cores with an additional core taken from Unguja Ukuu to study spatial shifts in vegetation along altitudinal gradient within the sites.

Levelling

Establishing the altitude of the sites is essential in order to reconstruct relative sea level altitudes. A differential global positioning system (δGPS) was used to enhance the quality of location data gathered using global positioning system (GPS) receivers. The advantage of δGPS is that the accuracy of the levelling is in the order of millimeters. All coring points and vegetation quadrats were levelled and all tied to the mean sea level relative to the National Datum using a known Triangulation point in TTP 353 located in Kibiti (Rufiji Delta) and the Ministry of Lands and Environment Benchmark (Zanzibar). All points had to be established in open sky areas to ensure good satellite network configuration. The survey was thus limited to the open areas behind the mangroves. With this limitation, the receiver pole extension was used over the tree canopy and the height of the pole noted.

Palaeoecological approaches

Pollen analysis was the primary technique employed in this research alongside stratigraphical observation. The chronology was provided by radiocarbon dating. Charcoal analysis was applied on a core in which the pollen record indicated the presence of a terrestrial input signal as well as more recent human impacts. Loss on ignition (LOI) was undertaken although the results were uninformative. In addition to pollen, diatom analysis was investigated as another proxy that could be used to reconstruct sea level, as diatom assemblages reflect salinity changes that can be related to fluctuations in sea levels. Transfer functions can then be used for precise sea level reconstruction (Horton *et al*., 2007). Samples were therefore also prepared for diatom analysis but the diatoms showed low preservation in all cores, probably due to dissolution affected by the high salinity and temperature conditions in the mangrove environment (Barker, *et al*. 1994; Reed, 1998).

Pollen analysis

Pollen analysis, the primary proxy used to investigate past vegetation changes in this study, is a useful research tool for reconstructing patterns of past environmental changes using pollen and spore identification (Faegri and Iversen, 1989). However, taphonomic processes including pollen productivity, pollen dispersal and transportation, pollen preservation, and sampling techniques have an effect on the representivity of the pollen to past vegetation (Lowe and Walker, 1997). Pollen grains have differing transport mechanisms and tend to be preserved differently. The relationship of how pollen assemblages reflect the parent vegetation should therefore be taken into account during the interpretation (Davis, 1984). In this study, pollen indices were developed in order to determine the relationship between pollen assemblages and vegetation. In addition to aiding in our understanding, these relationships aid in the investigation of past vegetation dynamics and reconstruct sea level. Low mangrove diversity in East Africa can be employed as an advantage as this can prevent overly complicated mangrove zonations (Ellison, 1989) and provide a straightforward relationship between each contemporary mangrove habitat and its inundation frequency with respect to present sea level. In the Rufiji Delta, the limited knowledge of contemporary vegetation impeded the use of the specific mangrove habitats to interpret the pollen record. Changing pollen sequences are interpreted in terms of broad mangrove migration that relate to sea level change and consequently have a large altitudinal range for reconstructing sea level. In Makoba Bay and Unguja Ukuu where contemporary vegetation data are available, mangrove proportions reflect the mangrove assemblages more precisely. These data allow for the development of the relationship between the altitudes of modern mangrove vegetation plots and mangrove pollen proportions set within each plot to provide a more specific interpretation of landward/seaward shift of mangrove classes. In terms of the contribution of the method to the sea level reconstruction, the development of this method allows a more precise estimatation of sea level index points to be obtained as the altitudinal range of each point is reduced. The method developed in this study has proved to be a potentially useful tool for reconstructing sea level from "far-field" locations. It is still important to research ways of reducing the altitudinal ranges of the sea level index points though, through further studies and the development of transfer functions in these regions.

Charcoal analysis

Fire regimes, a sensitive indicator of environmental response to arid climate, and fire and human interactions, can be investigated through charcoal analysis (Whitlock and Larsen, 2001; Conedera *et al*., 2009; Daniau *et al*., 2010). Although a chemical assay to measure relative frequencies of charcoal (Winkler, 1985) is widely used in African palaeoecological research (Bonnefille and Mohammed, 1994; Thevenon *et al*., 2003; Finch *et al*., 2009; Rucina *et al*., 2010), this technique is not able to distinguish between regional and local fires. Larger fragments imply the presence of a local fire, while smaller fragments derived from more remote locations may have been transported to the site by wind (Clark, 1988) or fluvial transport (Blackford, 2000). Counting charcoal on pollen slides has proved a reliable method of reconstructing past fire dynamics (Carcaillet *et al.* 2001). In this study, analysis of charcoal fragment size using pollen-slide counts to indicate the distance from the source of the fire was successfully employed allowing incidences of burning to be identified and determining the climate and/or human influences driving behind shift in the frequency and intensity of fire events.

Stratigraphy and chronology

The stratigraphy of the cores was analysed in the laboratory and described following the modified version of Tröels-Smith (1955) classification system (Kershaw, 1997). Stratigraphical analysis provides a useful tool in understanding the environment at the time of deposition (Nichols, 2009). At the start of the laboratory work, range-finder dates were obtained from the base of the core with targeted dating from different stratigraphic boundaries and key biostratigraphical horizons occurring later in the research. Although radiocarbon dating is constrained to the last 40000 years it remains the most widely applied and acceptable means of providing a chronological control for Late Quaternary studies (Huntley, 1996). Due to an apparent lack of macrofossils, leaves or wood fragments within the sediment cores, that can provide reliable and accurate dating (Grimm *et al*, 2009), bulk-sediment radiocarbon dating was used in this study and analysed by accelerator mass spectrometry (AMS). The 26 dates obtained from bulk mangrove sediment recorded a complex age-depth relationship with age reversals (4 samples) and modern ages (3 samples) reported from samples collected several decimeters below the ground surface (Figure 6.1). The errors within the dates obtained from the bulk sediment are likely to be caused by mangrove root penetration through the sediment sequences, introducing young carbon material at depth within the sequence and/or causing percolation of humic acids through leaching (Hammond *et al*., 1991). Additional causes of sediment contamination include bioturbation by fauna borrowing tunnels several decimeters deep down into the mangrove peat profiles and/or inwash of older carbon, or incorporation of dissolved carbonates could be responsible for the older dates due to the old-carbon reservoir effect (Vandergoes and Prior, 2003, Grimm *et al.*, 2009). However, despite the bulk AMS dates proving problematic, pollen diagrams from this study show undisturbed sequences, with no abrupt changes in pollen assemblages, therefore, indicating that the pollen assemblages are not subjected to mixing. Consequently, a new dating method, the AMS ^{14}C dating of pollen concentrates, was begun and is continuing to ascertain the ages of the sediments (Vandergoes and Prior, 2003).

Age-depth models of the cores were analysed and indicated that the basal age for each core ranged from ~8000 cal yr B.P. (BMAK-1 of Makoba Bay) to ~140 cal yr B.P. (A-UU-1 of Unguja Ukuu). A comparison of sedimentation rates showed a wide variation within the Rufiji Delta and Zanzibar sites (Fig.1). Although the chronology is problematic it would appear that the sedimentation rate range of 2.1-10.9 mm yr^{-1} for the Rufiji Delta was considerably higher than for Makoba Bay and Unguja Ukuu (0.3-6.6 mm yr^{-1}). This is probably due to the nature of the riverine mangrove setting where the river discharge transports freshwater and nutrient inputs from both upstream and estuarine sources within the Rufiji basin (Semesi, 1992; Fisher *et al.*, 1994) enhancing the sedimentation rate. The lower sedimentation rates in Makoba Bay and Unguja Ukuu were most likely due to the environmental setting with low terrestrial inputs and freshwater flow to the mangrove areas.

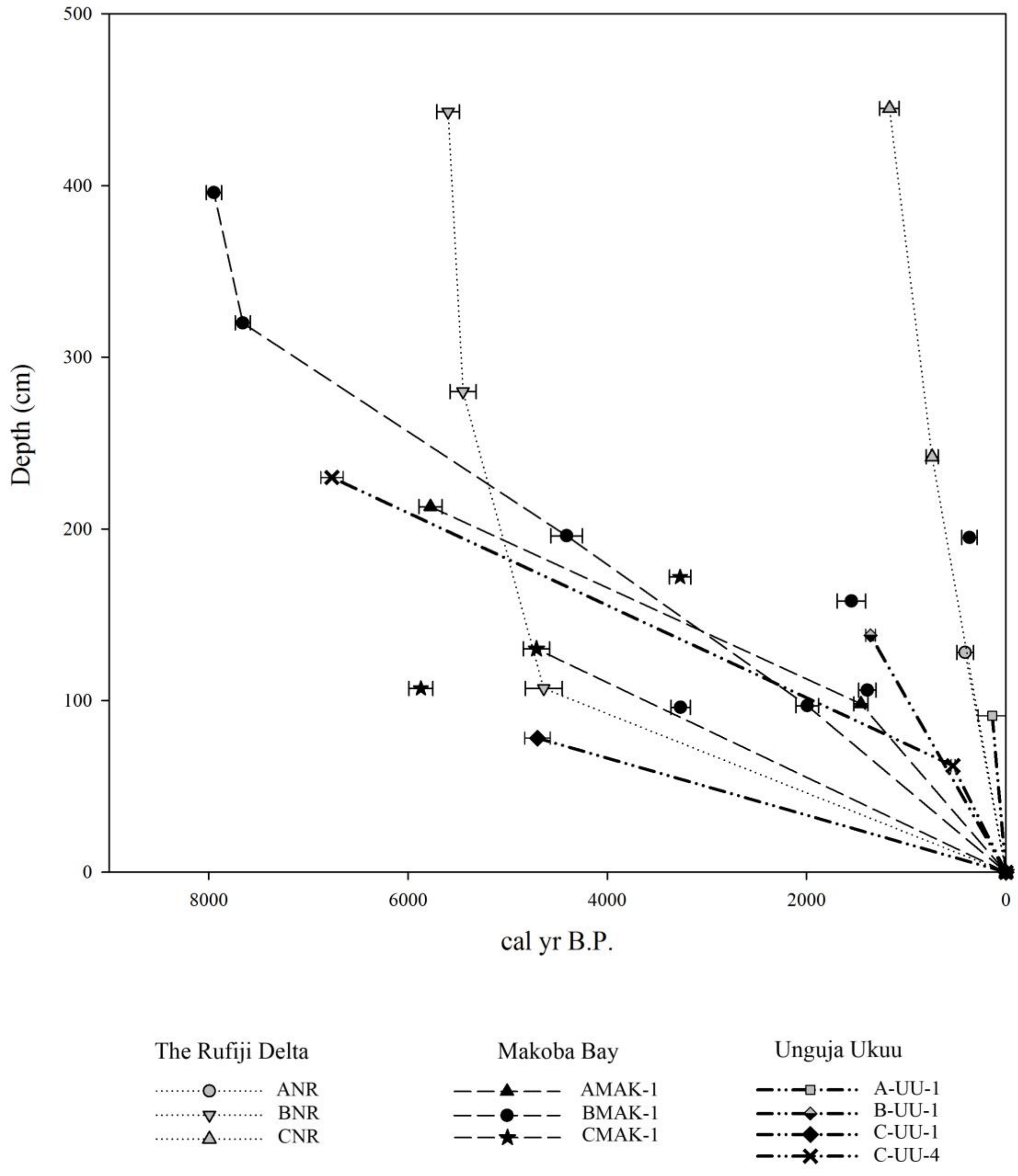


Figure 6.1. Comparative age-depth models for cores analysed in this study. For the exact meaning of zero years (origin), see page 79.

Future directions

This study represents three new palaeoecological records from coastal mangrove ecosystems along the Tanzanian coast on area that to date is under-researched. Conflicting reconstructions and difficulties encountered in dating suggest additional records and chronological control are needed with further research to determine a high resolution record of mid Holocene sea level changes and environmental changes. Also the study of the relationships between contemporary pollen distributions and present vegetation is also important for interpreting past environmental change. In the coastal environment, tidal inundation and bioturbation by fauna can cause mixing of surface sediments (Cohen, 2003). Consequently, annual pollen rain data along with additional contemporary mangrove vegetation and other environmental variables are required to develop a pollen-based transfer function (Engelhart *et al.,* 2007). These data should be applied to improve the reliability and accuracy of using pollen analogues for interpretation and the precision of sea level reconstruction. Moreover, in order to test the reliability of this technique to reconstruct sea level, it will be necessary to test it in other mangrove locations. These relationships can lead to improved precision and increase the body of evidence for constraining regional Holocene sea level. Moreover, other microfossils widely used for marine indicators such as foraminifera can be used to aid in sea level reconstruction.

Although the evidence on Tanzania demonstrates the site-specific responses of the records investigated it provides a contribution to studies of patterns of Holocene sea level changes in "far-field" locations. On a wider scale investigation of other sites of East Africa such as adjacent continental margin areas including Kenya and Mozambique as well as offshore islands would provide a regional record of environmental and sea level changes in East Africa to compare to the results from the Tanzanian coast as well as to distinguish regional and site-specific trends. The data would serve as critical mass to compare with the high-resolution records from the temperate latitudes to obtain a the better understanding of the relationship between "far-field" and "near field" sea level records. Continued development of dating of mangrove sequences using pollen concentrate samples is justified in order to open up “far-field” mangrove areas for future investigation.

Palaeoecological data of changes in the mangrove ecosystem structure demonstrates interaction of human activities along the Tanzanian coast for the last 500 years. The long-term ecological research can provide insight into ecosystem-societal relationships. These data can be integrated with maritime archaeological research for improved understanding of the development of past coastal settlement. Changes in mangrove composition and sedimentation rates reflecting human disturbance particularly in recent high resolution records, would prove a useful contribution to the knowledge base for the development of policies and/or public awareness for the sustainable utilization, management and conservation of these ecosystems in light of the future global climate changes.

Conclusions

The palaecological data presented in this study provide the first record of long-term mangrove dynamics which provides an insight into the environmental history along the Tanzanian coast. An innovative method using mangrove pollen to reconstruct long-term sea level changes has been developed. Combined with palaeoecological approaches applied in this research, the data presented further improves our understanding of how mangroves reflect environmental variables, particularly sea level change, and how humans have interacted with mangrove ecosystems over the recent past. The long-term insights of environment–ecosystem relationships have the potential to feed into improved management and conservation policies and/or increase public awareness for the sustainable utilization of mangrove ecosystems in an uncertain future of pervasive sea level and climate change.

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Appendix A Stratigraphical descriptions

Stratigraphic descriptions of core ANR of the northern Rufiji Delta

Altitude amsl (m)	Depth (cm)	Troels-Smith description (1955)
2.926 – 2.476	0-45	Ag^2,Tl^2,Dl+,Dh+, nig^2, $strf^0$, $elas^4$, sic^2
2.476 – 2.306	45-62	Ag^2,Tl^2,Dh+, nig^2, $strf^0$, $elas^4$, sic^2
2.306 – 1.616	62-131	Ag^2,Tl^2,Dl+,Dh+, nig^2, $strf^0$, $elas^4$, sic^2
1.616 – 1.426	131-150	Ga^4,Dl+,Dh+, nig^2, $strf^0$, $elas^0$, sic^2
1.426	150	

Stratigraphic descriptions of core Core BNR of the northern Rufiji Delta

Altitude amsl (m)	Depth (cm)	Troels-Smith description (1955)
3.4443 – 3.2443	0-20	Ag^2,Tl^2,Dl+,Dh+, nig^2, $strf^0$, $elas^4$, sic^2
3.2443 – 2.9043	20-54	As^2,Tl^2,Dl+Dh+, nig^2, $strf^0$, $elas^4$, sic^2
2.9043 – 2.8443	54-60	Ag^2,Tl^2,Dl+,Dh+, nig^2, $strf^0$, $elas^4$, sic^2
2.8443 – 2.7643	60-68	As^2,Tl^2,Dl+Dh+, nig^2, $strf^0$, $elas^4$, sic^2
2.7643 – (-1.7557)	68-520	Ag^3,Tl^1,Dl+Dh+,Sh+, nig^2, $strf^0$, $elas^4$, sic^2
-1.7557	520	

Stratigraphic descriptions of core CNR of the northern Rufiji Delta

Altitude amsl (m)	Depth (cm)	Troels-Smith description (1955)
3.5126 – 3.4726	0-4	
3.4726 – 3.1026	4-11	Ag^2,Dl^2, nig^2, $strf^0$, $elas^4$, sic^3
3.1026 – 3.3626	11-15	Dl^4, nig^2, $strf^0$, $elas^4$, sic^3
3.3626 – 3.2126	15-30	Ag^2,Dl^1,Dh^1, nig^2, $strf^0$, $elas^4$, sic^2
3.2126 – 3.1716	30-35	Ag^2,Gs^1,Dl^1, nig^2, $strf^0$, $elas^4$, sic^2
3.1716 – 2.3626	35-115	As^2,Tl^2,Dl+,Dh+, nig^2, $strf^0$, $elas^4$, sic^2
2.3626 – (-0.9874)	115-450	Ag^3,Tl^1,Dl+,Dh+,Sh+, nig^2, $strf^0$, $elas^4$, sic^2
-0.9874	450	

Stratigraphic descriptions of core AMAK of Makoba

Altitude amsl (m)	Depth (cm)	Troels-Smith description (1955)
0.60 – 0.53	0-7	Ga^4,Tl^+, nig^2, $strf^1$, $elas^0$, sic^2
0.53 – (-0.40)	7-100	Ga^1,Tl^2, Dl^1, nig^3, $strf^1$, $elas^0$, sic^1
(-0.40) – (-0.70)	100-130	Ga^2,Tl^2, nig^2, $strf^1$, $elas^0$, sic^1
(-0.70) – (-1.12)	130-172	Ga^3,Tl^1, Dl^+, nig^2, $strf^1$, $elas^0$, sic^1
(-1.12) – (-1.22)	172-182	Ga^2,Tl^2, nig^2, $strf^1$, $elas^0$, sic^1
(-1.22) – (-1.53)	182-213	Ag^2, Ga^2, Tl^+, nig^2, $strf^1$, $elas^2$, sic^1
(-1.53) – (-1.81)	213-241	Ag^2, Ga^2, Sh^+, part.$test^+$, nig^2, $strf^0$, $elas^2$, sic^1
(-1.81) – (-1.90)	241-250	Ag^3,Ga^1,Sh^+, part.$test^+$, nig^2, $strf^0$, $elas^3$, sic^1
-1.90	250	

Stratigraphic descriptions of core BMAK of Makoba

Altitude amsl (m)	Depth (cm)	Troels-Smith description (1955)
0.45 – 0.39	0-6	Ga^4, nig^3, $strf^1$, $elas^0$, sic^1
0.39– (-0.52)	6-97	Ga^1, Tl^2, Dl^1, nig^3, $strf^1$, $elas^0$, sic^1
(-0.52) – (-0.75)	97-120	Ga^3, Tl^1, , nig^3, $strf^1$, $elas^0$, sic^1
(-0.75) – (-1.50)	120-195	Ag^1, Ga^2, Tl^1, nig^3, $strf^1$, $elas^1$, sic^1
(-1.50) – (-1.91)	195-236	Ag^2, Ga^2, Tl^+, part. $test^+$, nig^2, $strf^1$, $elas^1$, sic^1
(-1.91) – (-2.38)	236-283	Ag^3, Ga^1, Tl^+, part. $test^+$, nig^2, $strf^1$, $elas^2$, sic^1
(-2.38) – (-2.91)	283-336	Ag^3, Tl^1, part. $test^{+,}$ nig^2, $strf^0$, $elas^4$, sic^1
(-2.91) – (-3.55)	336-400	Ag^4, Sh^+, nig^2, $strf^0$, $elas^4$, sic^0
-3.55	400	

Stratigraphic descriptions of core CMAK of Makoba

Altitude amsl (m)	Depth (cm)	Troels-Smith description (1955)
1.513 – 1.383	0-13	Ga^4, nig^3, $strf^1$, $elas^0$, sic^2
1.383 – 1.313	13-20	Ag^2, Ga^2, nig^3, $strf^1$, $elas^2$, sic^2
1.313 – 0.443	20-107	Ag^2, Ga^1, $Tl^{1,}$ nig^2, $strf^1$, $elas^1$, sic^2
0.443 – (-0.227)	107-174	Ag^2, Gs^1, Tl^1, nig^1, $strf^1$, $elas^0$, sic^2
-0.227	174	

Stratigraphic descriptions of core A-UU-1 of the Unguja Ukuu

Altitude amsl (m)	**Depth (cm)**	**Troels-Smith description (1955)**
0.042 – (-0.138)	0-18	Ag^3,Ga^1, Sh^+, nig^2, $strf^0$, $elas^2$, sic^1
(-0.138) – (-0.408)	18-45	Ga^1,Tl^2, Dl^1, nig^3, $strf^0$, $elas^0$, sic^1
(-0.408) – (-0.788)	45-83	Ga^2,Tl^2,Dl^+, nig^3, $strf^0$, $elas^0$, sic^1
(-0.788) – (-1.308)	83-135	Ag^1, Ga^3, Sh^+,, part. $test^+$, nig^2, $strf^0$, $elas^0$, sic^1
-1.308	135	

Stratigraphic descriptions of core B-UU-1 of the Unguja Ukuu

Altitude amsl (m)	**Depth (cm)**	**Troels-Smith description (1955)**
0.168 – 11.8	0-5	Ga^2,Tl^2, nig^3, $strf^0$, $elas^0$, sic^1
11.8 – (-71.2)	5-88	Ga^1,Tl^2, Dl^1, nig^3, $strf^0$, $elas^0$, sic^1
(-71.2) – (-123.2)	88-140	Ga^2,Tl^2,Dl^+, nig^3, $strf^0$, $elas^0$, sic^1
(-123.2) – (-133.2)	140-150	Ag^1, Ga^3, part. $test^+$, nig^2, $strf^0$, $elas^0$, sic^1
-133.2	150	

Stratigraphic descriptions of core C-UU-1 of Unguja Ukuu

Altitude amsl (m)	**Depth (cm)**	**Troels-Smith description (1955)**
1.376 – 1.226	0-15	Ga^3,Tl^1, nig^2, $strf^0$, $elas^0$, sic^1
1.226 – 1.106	15-27	Ga^1,Tl^2, Dl^1, nig^3, $strf^0$, $elas^0$, sic^1
1.106 – 0.976	27-40	Ga^2,Tl^2, Dl^+, nig^2, $strf^0$, $elas^0$, sic^1
0.976 – 0.696	40-68	Ga^1,Tl^2, Dl^1, nig^3, $strf^0$, $elas^0$, sic^1
0.696 – 0.576	68-80	Ga^2,Tl^2,Dl^+, nig^3, $strf^0$, $elas^0$, sic^1
0.576 – 0.456	80-92	Ag^1, Ga^3, Tl^+,, nig^1, $strf^0$, $elas^0$, sic^1
0.456	92	

Stratigraphic descriptions of core C-UU-4 of Unguja Ukuu

Altitude amsl (m)	**Depth (cm)**	**Troels-Smith description (1955)**
1.037 – 0.447	0-59	Ag^1,Ga^2,Tl^1, nig^3, $strf^0$, $elas^2$, sic^1
0.447 – 0.317	59-72	Ga^2,Tl^2, Dl^+, nig^2, $strf^0$, $elas^0$, sic^1
0.317 – (-0.088)	72-112.5	Ga^1,Tl^2, Dl^1, nig^3, $strf^0$, $elas^0$, sic^1
(-0.088) – (-0.553)	112.5-159	Ga^2,Tl^2, Dl^+, nig^3, $strf^0$, $elas^0$, sic^1
(-0.553) – (-1.313)	159-235	Ag^3, Tl^1,nig^1, $strf^0$, $elas^4$, sic^1
-1.313	235	

Appendix B: Pollen count data sheets

Pollen count data sheet of ANR (the northern Rufiji Delta)

Taxa	Depth (cm											
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**
Avicennia marina	75	36	54	36	13	19	31	31	22	44	34	43
Brugueira/Ceriops	5	8	1	7	7	9	13	24	16	6	10	8
Lumnitzera recemosa	0	0	4	2	0	0	0	5	0	3	0	0
Rhizophora mucronata	34	39	12	38	24	42	41	27	26	22	25	23
Sonneratia alba	1	1	0	5	4	4	6	9	18	22	6	28
Xylocarpus granatum	1	1	1	0	0	0	1	0	0	2	2	1
Acrostichum aureum	3	4	3	3	0	5	7	3	4	1	1	5
Sueada	3	0	0	3	0	0	0	0	0	3	0	0
Cyperaceae	31	35	40	40	50	35	17	21	29	16	20	4
Poaceae	14	20	30	18	40	33	26	26	44	27	45	34
Podocarpus	0	0	0	0	0	0	0	0	0	0	0	0
Monolete spores	3	3	2	2	3	3	4	3	4	2	3	2
Pteridaceae	0	0	0	0	0	0	0	0	0	0	0	0
Stenochlaena	1	0	3	0	0	0	2	0	0	0	0	0
Trilete spores	3	4	6	3	6	2	3	2	2	1	4	3
Unidentified pollen	1	5	7	7	10	5	3	6	6	3	5	5

Pollen count data sheet of BNR (the northern Rufiji Delta)

Taxa	Depth (cm)												
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**	**125**
Avicennia marina	8	9	2	0	0	0	0	11	0	7	1	10	18
Brugueira/Ceriops	4	22	4	0	5	0	0	7	0	7	7	18	15
Rhizophora mucronata	86	43	20	0	60	0	0	64	0	142	43	154	210
Sonneratia alba	1	4	2	0	1	0	0	0	0	0	0	0	5
Xylocarpus granatum	65	5	4	0	0	0	0	0	0	1	0	0	0
Acrostichum aureum	13	22	3	0	4	0	0	6	0	6	0	22	18
Nypa	0	0	0	0	0	0	0	0	0	0	0	0	0
Sueada	0	0	1	0	0	0	0	0	0	1	0	1	0
Cyperaceae	0	2	0	0	0	0	0	0	0	0	0	2	4
Poaceae	10	12	5	0	7	0	0	3	0	13	2	23	29
Podocarpus	0	0	0	0	0	0	0	0	0	0	0	1	1
Stenochlaena	0	1	0	0	0	0	0	1	0	0	0	0	3
Pteridaceae	0	0	1	0	0	0	0	0	0	0	0	0	0
Monolete spores	2	0	0	0	0	0	0	0	0	0	0	0	5
Trilete spores	0	0	0	0	0	0	0	0	0	1	0	1	1
Unidentified pollen	0	7	2	0	3	0	0	2	0	1	0	4	6

Pollen count data sheet of BNR (the northern Rufiji Delta) (cont.)

Taxa	**Depth (cm)**												
	135	**145**	**155**	**165**	**175**	**185**	**195**	**205**	**215**	**225**	**235**	**245**	**255**
Avicennia marina	19	13	18	12	22	10	7	14	32	17	10	13	22
Brugueira/Ceriops	12	16	17	8	11	7	11	17	12	30	19	17	16
Rhizophora mucronata	162	190	156	117	114	119	105	130	141	128	149	137	137
Sonneratia alba	3	7	5	3	23	3	2	7	4	3	1	10	7
Xylocarpus granatum	0	0	0	0	0	0	0	2	0	2	0	1	1
Acrostichum aureum	14	10	13	4	15	5	8	8	13	14	5	11	9
Nypa	0	0	2	0	0	0	0	0	0	1	0	0	0
Sueada	2	1	0	1	1	0	0	0	0	0	0	0	0
Cyperaceae	10	3	6	68	7	1	0	6	1	4	2	0	6
Poaceae	65	28	28	37	14	9	13	22	15	21	13	17	13
Podocarpus	0	0	0	0	0	0	1	0	3	0	1	1	0
Stenochlaena	4	0	0	4	5	1	2	4	5	6	3	1	4
Pteridaceae	1	0	0	0	0	0	0	0	0	0	0	0	0
Monolete spores	0	0	1	2	0	0	2	2	0	0	1	1	3
Trilete spores	1	0	0	0	0	0	0	0	0	1	0	1	0
Unidentified pollen	1	0	0	0	0	1	4	1	0	2	2	0	2

Pollen count data sheet of BNR (the northern Rufiji Delta) (cont.)

Taxa	**Depth (cm)**												
	265	**275**	**285**	**295**	**305**	**315**	**325**	**335**	**345**	**355**	**365**	**375**	**385**
Avicennia marina	12	13	21	12	17	8	22	24	27	18	11	20	9
Brugueira/Ceriops	23	20	18	18	28	28	21	18	15	14	15	17	12
Rhizophora mucronata	140	135	136	158	125	148	135	120	124	120	118	132	111
Sonneratia alba	3	5	2	2	4	3	3	3	0	3	2	4	5
Xylocarpus granatum	0	1	12	0	0	1	0	0	0	0	0	0	0
Acrostichum aureum	8	10	12	9	9	6	6	12	3	6	8	8	6
Nypa	1	0	1	0	0	0	0	0	0	0	0	2	0
Sueada	0	0	0	0	0	0	2	0	0	0	0	1	0
Cyperaceae	1	8	0	3	5	7	1	0	3	0	6	3	0
Poaceae	15	20	10	14	18	8	10	12	18	9	27	11	11
Podocarpus	0	0	0	0	0	0	0	0	0	0	0	0	0
Stenochlaena	3	9	3	7	8	3	2	9	4	9	9	8	4
Pteridaceae	0	0	0	0	1	0	0	0	0	0	0	0	0
Monolete spores	2	0	5	0	5	4	2	0	3	0	8	1	0
Trilete spores	0	0	0	0	0	0	1	0	0	0	1	0	1
Unidentified pollen	0	3	1	3	6	0	5	0	0	0	4	7	2

Pollen count data sheet of BNR (the northern Rufiji Delta) (cont.)

Taxa	**Depth (cm)**					
	395	**405**	**415**	**425**	**435**	**445**
Avicennia marina	21	8	3	4	4	8
Brugueira/Ceriops	9	9	5	9	7	7
Rhizophora mucronata	102	115	49	144	67	113
Sonneratia alba	0	2	0	0	1	0
Xylocarpus granatum	0	0	0	0	1	0
Acrostichum aureum	12	15	11	8	2	10
Nypa	0	0	0	0	0	0
Sueada	0	0	0	0	0	0
Cyperaceae	1	1	0	1	5	4
Poaceae	6	10	3	0	3	4
Podocarpus	0	0	0	0	1	0
Stenochlaena	2	2	1	4	2	2
Pteridaceae	0	0	0	0	0	0
Monolete spores	0	1	0	0	3	3
Trilete spores	0	0	0	0	0	1
Unidentified pollen	3	2	0	0	1	7

Pollen count data sheet of CNR (the northern Rufiji Delta)

Taxa	**Depth (cm)**												
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**	**125**
Avicennia marina	0	5	4	4	5	6	9	9	6	9	15	19	13
Brugueira/Ceriops	0	38	38	17	18	19	29	41	28	28	26	34	40
Lumnitzera recemosa	0	2	0	2	2	3	4	2	2	2	2	0	3
Rhizophora mucronata	0	9	2	13	30	15	19	28	30	27	28	24	26
Sonneratia alba	0	1	0	2	0	1	0	0	0	0	0	3	0
Xylocarpus granatum	0	0	0	0	1	1	0	0	0	2	0	0	0
Acrostichum aureum	13	23	5	46	20	27	29	30	22	40	49	31	24
Sueada	0	2	0	1	1	1	1	0	1	2	0	0	2
Cyperaceae	65	26	29	25	34	28	19	17	24	8	7	10	9
Poaceae	35	9	12	21	33	16	30	17	34	19	11	28	32
Podocarpus	0	0	0	0	0	0	1	0	0	0	0	0	1
Rubiaceae	0	21	47	0	0	0	0	0	0	0	0	0	0
Monolete spores	1	3	4	4	0	5	4	2	0	0	2	1	2
Stenochlaena	30	24	15	3	0	32	1	2	0	5	7	1	2
Trilete spores	9	7	7	9	4	3	0	1	1	7	4	1	2
Unidentified pollen	3	0	0	9	10	3	9	7	7	8	8	8	4

Pollen count data sheet of CNR (the northern Rufiji Delta) (cont.)

Taxa	**Depth (cm)**												
	135	**145**	**155**	**165**	**175**	**185**	**195**	**205**	**215**	**225**	**235**	**245**	**255**
Avicennia marina	8	10	16	27	28	13	8	20	38	80	20	19	31
Brugueira/Ceriops	41	18	23	20	8	5	7	11	9	4	7	5	2
Lumnitzera recemosa	5	1	1	0	2	2	3	1	1	0	2	0	1
Rhizophora mucronata	28	40	53	39	48	65	63	63	68	29	53	47	41
Sonneratia alba	3	2	0	0	0	1	0	0	2	1	1	3	4
Xylocarpus granatum	1	0	0	0	0	0	1	0	1	0	0	1	1
Acrostichum aureum	38	52	24	20	28	18	32	21	26	22	34	36	43
Sueada	2	0	0	2	0	1	0	1	1	1	2	0	0
Cyperaceae	2	9	11	12	8	7	9	7	2	5	11	8	7
Poaceae	26	23	15	28	25	26	29	28	12	12	16	23	17
Podocarpus	0	0	0	0	0	0	0	0	0	0	0	0	0
Rubiaceae	0	0	0	0	0	0	0	0	0	0	0	0	0
Monolete spores	1	1	1	0	1	4	2	0	3	2	4	1	4
Stenochlaena	0	0	0	0	0	1	0	1	0	2	0	0	1
Trilete spores	2	6	3	5	6	1	2	4	5	1	7	3	0
Unidentified pollen	6	1	3	1	4	9	7	1	2	0	1	2	2

Pollen count data sheet of CNR (the northern Rufiji Delta) (cont.)

Taxa	**Depth (cm)**												
	265	**275**	**285**	**295**	**305**	**315**	**325**	**335**	**345**	**355**	**365**	**375**	**385**
Avicennia marina	18	43	42	11	36	40	17	11	12	92	36	22	40
Brugueira/Ceriops	6	4	9	7	5	7	4	3	8	4	5	4	15
Lumnitzera recemosa	1	2	2	2	2	0	2	0	0	0	1	0	1
Rhizophora mucronata	37	40	45	48	48	46	42	43	41	20	30	49	43
Sonneratia alba	1	10	3	1	5	0	9	2	2	2	3	2	4
Xylocarpus granatum	0	0	0	0	1	4	1	1	1	0	0	1	1
Acrostichum aureum	32	19	16	26	45	35	33	30	32	54	52	48	43
Sueada	1	1	0	1	1	0	1	0	0	3	1	2	4
Cyperaceae	15	9	12	18	6	15	13	16	13	5	7	15	13
Poaceae	34	21	36	31	36	59	42	41	44	16	19	35	34
Podocarpus	0	0	0	0	1	0	0	1	0	0	0	0	0
Rubiaceae	0	0	0	0	0	0	0	0	0	0	0	0	0
Monolete spores	2	1	0	2	1	1	0	2	4	2	3	1	6
Stenochlaena	1	0	0	0	1	3	1	1	0	1	0	3	0
Trilete spores	4	3	2	4	3	5	5	4	4	8	0	3	3
Unidentified pollen	6	2	2	6	3	2	2	5	6	0	2	6	5

Pollen count data sheet of CNR (the northern Rufiji Delta) (cont.)

Taxa	Depth (cm)					
	395	**405**	**415**	**425**	**435**	**445**
Avicennia marina	20	20	15	21	46	14
Brugueira/Ceriops	5	7	12	8	16	18
Lumnitzera recemosa	3	2	3	0	3	5
Rhizophora mucronata	73	86	93	100	86	84
Sonneratia alba	9	9	10	9	8	16
Xylocarpus granatum	1	1	2	2	0	2
Acrostichum aureum	21	23	13	19	18	11
Sueada	4	0	2	2	1	1
Cyperaceae	10	9	15	9	8	11
Poaceae	47	41	45	26	18	46
Podocarpus	0	0	0	1	1	0
Rubiaceae	0	0	0	0	0	0
Monolete spores	4	1	0	1	1	1
Stenochlaena	1	3	1	1	3	0
Trilete spores	4	2	2	5	4	4
Unidentified pollen	0	2	1	4	6	1

Pollen count data sheet of AMAK-1 (Makoba Bay)

Taxa	Depth (cm)												
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**	**125**
Avicennia marina	4	2	2	0	2	3	2	2	0	4	4	4	3
Brugueira/Ceriops	39	21	15	8	17	23	20	34	38	15	11	21	24
Rhizophora mucronata	107	122	125	130	126	114	94	88	95	125	112	127	114
Sonneratia alba	3	0	6	11	4	5	27	18	11	7	16	4	5
Xylocarpus granatum	0	0	0	0	1	0	0	2	0	0	0	0	0
Cyperaceae	0	1	0	1	1	1	2	0	0	0	0	0	0
Poaceae	0	5	5	1	0	2	1	1	0	0	1	0	0
Monolete	0	1	2	0	0	1	5	4	3	1	1	0	2
Trilete	0	1	0	0	0	0	0	0	0	0	1	0	0
Unidentifiable pollen	0	1	3	4	3	5	2	3	6	2	7	2	6

Pollen count data sheet of AMAK-1 (Makoba Bay) (cont.)

Taxa	Depth (cm)											
	135	**145**	**155**	**165**	**175**	**185**	**195**	**205**	**215**	**225**	**235**	**245**
Avicennia marina	2	1	5	3	6	4	6	4	3	3	3	1
Brugueira/Ceriops	19	17	10	4	3	3	10	6	4	6	6	4
Rhizophora mucronata	123	118	128	135	105	110	116	118	101	103	100	121
Sonneratia alba	0	3	2	7	35	32	13	15	36	37	41	26
Xylocarpus granatum	0	0	0	0	0	1	0	0	1	0	0	0
Cyperaceae	0	0	0	0	0	0	0	0	0	0	0	0
Poaceae	1	1	0	0	0	0	0	0	1	0	0	0
Monolete	2	8	3	4	1	4	3	6	3	2	4	0
Trilete	0	0	0	0	0	0	0	0	0	0	0	0
Unidentifiable pollen	5	3	6	2	4	1	5	3	2	2	2	1

Pollen count data sheet of BMAK-1 (Makoba Bay)

Taxa	Depth (cm)												
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**	**125**
Avicennia marina	5	7	10	5	6	8	2	4	3	5	3	5	4
Brugueira/Ceriops	23	39	35	21	20	24	16	22	21	18	16	17	10
Rhizophora	11	10	10	12	11	11	11	10	10	11	11	10	12
mucronata	1	5	0	0	5	6	0	4	9	8	6	2	0
Sonneratia alba	3	1	1	4	5	1	12	5	8	6	5	19	13
Xylocarpus granatum	0	0	0	1	0	0	0	0	0	0	0	0	0
Acrostichum aureum	4	0	0	0	0	0	0	2	0	1	0	0	0
Cyperaceae	1	0	0	1	3	1	2	2	2	1	3	0	1
Poaceae	3	1	4	1	4	3	3	3	7	2	7	4	0
Monolete	1	1	1	1	1	0	2	6	0	1	1	4	7
Stenochleana	0	0	0	0	0	0	1	0	0	0	0	0	3
Trilete	1	0	0	0	0	0	0	3	0	1	1	1	0
Unidentifiable pollen	0	2	1	1	1	6	2	2	4	4	5	4	1

Pollen count data sheet of BMAK-1 (Makoba Bay) (cont.)

Taxa	**Depth (cm)**												
	135	**145**	**155**	**165**	**175**	**185**	**195**	**205**	**215**	**225**	**235**	**245**	**255**
Avicennia marina	2	2	6	3	3	9	8	5	7	3	1	6	4
Brugueira/Ceriops	9	16	19	12	18	18	18	16	16	16	12	12	6
Rhizophora mucronata	120	117	122	117	116	111	103	97	94	97	95	95	101
Sonneratia alba	17	5	6	10	6	5	15	21	21	29	36	39	30
Xylocarpus granatum	0	0	0	0	0	0	0	0	0	0	0	0	0
Acrostichum aureum	0	1	0	0	0	0	0	0	0	0	0	0	0
Cyperaceae	0	0	1	1	0	1	0	0	0	0	0	0	0
Poaceae	1	0	0	0	0	3	0	1	1	1	1	2	0
Monolete	6	7	0	4	9	3	5	6	2	4	4	0	2
Stenochleana	0	0	0	2	0	1	1	1	1	0	0	0	1
Trilete	0	2	0	0	2	0	1	2	2	1	2	0	2
Unidentifiable pollen	0	5	3	6	2	4	4	5	5	5	4	3	6

Pollen count data sheet of BMAK-1 (Makoba Bay) (cont.)

Taxa	**Depth (cm)**													
	265	**275**	**285**	**295**	**305**	**315**	**325**	**335**	**345**	**355**	**365**	**375**	**385**	**395**
Avicennia marina	3	3	4	3	1	5	7	6	6	3	2	5	8	4
Brugueira/Ceriops	5	3	6	5	7	4	18	18	15	25	33	28	30	27
Rhizophora mucronata	99	102	95	96	88	99	114	114	120	119	106	109	102	116
Sonneratia alba	39	45	44	45	55	39	9	4	4	4	4	7	4	2
Xylocarpus granatum	0	0	0	1	0	0	0	1	1	2	0	0	0	0
Acrostichum aureum	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Cyperaceae	0	0	0	1	0	0	0	0	0	0	0	0	1	1
Poaceae	1	1	0	0	1	1	0	1	1	0	1	0	0	0
Monolete	3	3	2	0	1	1	4	3	1	0	0	0	3	2
Stenochleana	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trilete	3	4	2	2	1	4	4	2	1	2	1	0	0	3
Unidentifiable pollen	3	4	3	2	1	3	1	5	4	2	4	5	9	4

Pollen count data sheet of CMAK-1 (Makoba Bay)

Taxa	**Depth (cm)**										
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**
Avicennia marina	2	0	5	3	3	3	3	3	4	3	3
Brugueira/Ceriops	100	73	72	56	56	77	92	101	75	70	64
Rhizophora mucronata	35	65	69	91	82	59	54	40	65	70	80
Sonneratia alba	0	2	1	2	2	1	1	0	3	3	2
Xylocarpus granatum	0	0	0	0	1	0	0	0	0	0	0
Acrostichum aureum	5	2	0	0	0	0	0	0	0	0	0
Cyperaceae	4	4	1	0	2	1	0	2	0	0	0
Poaceae	2	0	0	0	1	2	1	3	2	0	0
Monolete	2	0	1	0	1	3	0	0	1	2	1
Unidentifiable pollen	0	4	4	0	5	5	3	2	3	3	2

Pollen count data sheet of A-UU-1 (Unguja Ukuu)

Taxa	**Depth (cm)**													
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**	**125**	**133**
Avicennia marina	2	2	2	1	0	1	3	1	0	1	1	1	1	1
Brugueira/Ceriops	14	8	10	21	21	19	28	24	17	17	18	30	37	29
Rhizophora mucronata	106	93	100	121	122	119	111	118	125	123	125	116	106	112
Sonneratia alba	20	40	32	3	2	3	0	0	2	3	2	0	3	2
Cyperaceae	0	1	0	0	0	1	0	0	0	0	0	0	0	0
Poaceae	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Monolete	0	1	1	0	0	1	0	0	0	0	0	0	0	0
Trilete	0	1	2	0	0	0	1	0	0	0	0	0	0	0
Unidentified pollen	8	6	4	7	7	6	8	8	7	7	7	7	6	7

Pollen count data sheet of B-UU-1 (Unguja Ukuu)

Taxa	**Depth (cm)**										
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**
Avicennia marina	5	4	2	7	4	2	0	5	0	2	3
Brugueira/Ceriops	50	31	31	35	31	41	44	25	37	0	34
Lumnitzera recemosa	0	1	1	0	0	0	0	1	0	39	0
Rhizophora mucronata	78	80	76	95	95	96	97	108	111	111	104
Sonneratia alba	10	26	33	4	13	2	5	4	0	0	3
Cyperaceae	0	0	2	0	0	0	0	0	0	0	0
Poaceae	0	1	0	1	0	3	1	2	1	2	1
Monolete	3	3	0	0	0	0	0	0	0	0	0
Trilete	0	0	2	0	1	0	0	0	0	0	0
Unidentified pollen	4	6	5	5	5	6	6	6	3	2	7

Pollen count data sheet of B-UU-1 (Unguja Ukuu) (cont.)

Taxa	Depth (cm)			
	115	**125**	**135**	**145**
Avicennia marina	3	0	4	0
Brugueira/Ceriops	30	31	36	26
Lumnitzera recemosa	0	0	0	1
Rhizophora mucronata	107	113	100	111
Sonneratia alba	6	3	5	6
Cyperaceae	0	0	0	0
Poaceae	0	1	0	1
Monolete	0	0	0	0
Trilete	0	0	0	0
Unidentified pollen	6	4	6	6

Pollen count data sheet of C-UU-1 (Unguja Ukuu)

Taxa	Depth (cm)							
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**
Avicennia marina	21	4	14	2	0	5	2	2
Brugueira/Ceriops	39	60	9	15	25	31	72	52
Lumnitzera recemosa	4	3	0	0	0	0	0	1
Rhizophora mucronata	77	75	75	75	76	90	57	74
Sonneratia alba	13	11	61	55	48	17	14	15
Cyperaceae	0	1	0	0	0	1	0	0
Poaceae	0	0	0	0	1	0	0	0
Monolete	1	0	0	0	0	1	0	0
Trilete	0	0	1	0	0	0	0	0
Unidentified pollen	6	1	5	5	4	7	7	8

Pollen count data sheet of C-UU-4 (Unguja Ukuu)

Taxa	Depth (cm)												
	5	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**105**	**115**	**125**
Avicennia marina	7	14	9	10	14	12	22	2	1	3	0	0	1
Brugueira/Ceriops	20	28	26	18	35	35	19	20	6	9	6	8	10
Lumnitzera recemosa	2	1	0	0	2	0	4	2	2	2	0	2	2
Rhizophora mucronata	86	75	87	93	75	71	78	98	91	88	85	70	57
Sonneratia alba	25	37	26	13	12	22	20	23	50	47	60	70	79
Xylocarpus granatum	1	1	1	1	1	5	0	1	0	0	1	1	1
Cyperaceae	4	1	0	1	2	3	0	0	0	0	0	0	0
Poaceae	3	1	1	3	2	1	1	0	0	1	0	0	0
Monolete	0	0	2	2	2	2	2	2	1	1	0	0	0
Trilete	2	1	0	4	4	2	0	2	0	0	1	0	0
Unidentified pollen	5	7	1	5	2	4	4	4	3	4	2	3	2

Pollen count data sheet of C-UU-4 (Unguja Ukuu) (cont.)

Taxa	Depth (cm)										
	135	**145**	**155**	**165**	**175**	**185**	**195**	**205**	**215**	**225**	**235**
Avicennia marina	21	10	0	0	1	1	0	3	2	1	1
Brugueira/Ceriops	33	31	15	14	9	31	45	36	32	23	3
Lumnitzera recemosa	3	0	2	2	2	2	0	1	3	0	3
Rhizophora mucronata	66	78	78	72	85	78	102	96	110	118	97
Sonneratia alba	19	22	55	59	50	31	3	3	0	3	6
Xylocarpus granatum	0	0	0	0	1	3	0	0	1	1	0
Cyperaceae	0	1	0	0	0	0	0	0	0	0	0
Poaceae	6	2	0	0	0	0	0	1	0	1	0
Monolete	0	1	0	0	0	0	0	2	0	0	0
Trilete	0	1	0	1	0	1	1	6	0	4	3
Unidentified pollen	5	6	6	7	6	6	3	6	6	4	7

Appendix C Loss on Ignition (LOI) data sheets

LOI of core ANR of the northern Rufiji Delta

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	10.979	12.0725	11.6579	11.5912	11.5661	9.82	3.69
15	8.774	9.7519	9.4241	9.3645	9.3406	9.17	3.67
25	11.485	12.2675	12.0591	12.0089	11.9663	8.74	7.42
35	11.35	12.3967	11.9987	11.9405	11.9141	8.97	4.06
45	11.263	12.4654	11.9591	11.8901	11.8562	9.91	4.86
55	10.995	12.2223	11.7024	11.6222	11.5959	11.34	3.71
65	11.6354	12.9338	12.4102	12.339	12.3076	9.19	4.05
75	10.9695	12.2494	11.7852	11.7263	11.6991	7.22	3.33
85	11.2292	12.2643	11.8309	11.7827	11.7594	8.01	3.87
95	11.5972	12.678	12.1864	12.1218	12.1046	10.96	2.91
105	10.8753	11.8154	11.3903	11.3096	11.2928	15.67	3.26
115	11.0969	12.1518	11.7093	11.6469	11.6222	10.19	4.03
125	10.9546	12.1933	11.7503	11.6957	11.6087	6.86	10.93
135	10.8711	11.9813	11.7243	11.7033	11.6038	2.46	11.66
145	11.0663	12.4626	12.1853	12.1704	11.9519	1.33	19.52

LOI of core BNR of the northern Rufiji Delta

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	6.642	8.0299	7.5429	7.4327	7.4081	12.23	2.73
15	6.585	7.854	7.3876	7.3065	7.2814	10.10	3.13
25	6.836	8.0688	7.5091	7.3766	7.3562	19.69	3.03
35	6.319	6.8225	6.7622	6.7176	6.6989	10.06	4.22
45	6.745	7.8112	7.4492	7.3812	7.351	9.66	4.29
55	6.89	7.3456	7.2917	7.2541	7.2326	9.36	5.35
65	6.803	7.4761	7.3873	7.3104	7.2802	13.16	5.17
75	6.958	7.9399	7.8165	7.7408	7.6881	8.82	6.14
85	6.766	7.7099	7.6027	7.5386	7.4951	7.66	5.20
95	6.544	7.2648	7.1719	7.1235	7.091	7.71	5.18
105	6.454	7.8667	7.5042	7.4232	7.383	7.71	3.83
115	6.416	7.3354	7.2178	7.1578	7.1214	7.48	4.54
125	6.793	7.9733	7.7867	7.7127	7.6675	7.45	4.55
135	6.259	7.1753	7.0513	6.9674	6.9268	10.59	5.12
145	6.739	7.8668	7.7373	7.6575	7.6185	7.99	3.91
155	6.337	7.3855	7.2692	7.2041	7.165	6.98	4.19
165	6.534	7.6719	7.4847	7.4204	7.3789	6.76	4.37
175	6.36	7.6543	7.4998	7.3723	7.327	11.19	3.97
185	6.838	7.357	7.3035	7.2679	7.2473	7.65	4.43
195	6.445	7.5253	7.3665	7.2966	7.2652	7.59	3.41
205	9.135	10.1182	10.0505	9.964	9.8732	9.45	9.92
215	8.719	9.8731	9.7135	9.6444	9.6076	6.95	3.70
225	8.615	9.4864	9.3638	9.3138	9.2872	6.68	3.55
235	9.053	9.806	9.7077	9.6613	9.6371	7.09	3.70
245	8.506	9.5675	9.4095	9.3452	9.3099	7.12	3.91

LOI of core BNR of the northern Rufiji Delta (cont.)

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
255	8.881	10.1599	9.9321	9.8606	9.8257	6.80	3.32
265	8.494	9.7513	9.4474	9.369	9.3371	8.22	3.35
275	8.629	9.9152	9.7512	9.6692	9.6285	7.31	3.63
285	7.947	9.2749	9.0542	8.9716	8.9257	7.46	4.15
295	8.473	9.5881	9.4225	9.348	9.3186	7.85	3.10
305	8.132	9.3164	9.0781	9.0013	8.964	8.12	3.94
315	8.381	9.4091	9.2935	9.2252	9.1982	7.48	2.96
325	8.432	9.8431	9.6247	9.5375	9.5024	7.31	2.94
335	8.674	10.0598	9.7685	9.6788	9.6491	8.20	2.71
345	7.929	9.0711	8.7844	8.7134	8.6644	8.30	5.73
355	10.937	12.2124	11.9359	11.8584	11.8255	7.76	3.29
365	10.607	11.5628	11.4368	11.3728	11.3476	7.71	3.04
375	10.612	11.7624	11.5236	11.4536	11.4217	7.68	3.50
385	11.142	12.1586	11.9692	11.8923	11.8127	9.30	9.62
395	10.979	12.2511	11.9947	11.9178	11.8762	7.57	4.10
405	8.774	9.7499	9.5959	9.5362	9.4834	7.26	6.42
415	11.485	12.69	12.4989	12.4275	12.3842	7.04	4.27
425	10.995	11.5309	11.4639	11.4265	11.407	7.98	4.16
435	11.263	12.4259	12.2551	12.1846	12.1499	7.11	3.50
445	11.35	12.7686	12.57	12.4865	12.4389	6.84	3.90

LOI of core CNR of the northern Rufiji Delta

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	6.642	7.6094	7.3448	7.2767	7.2541	9.69	3.22
17	6.585	7.5203	7.1636	7.1098	7.0905	9.30	3.34
25	6.836	7.7174	7.4559	7.3976	7.3759	9.40	3.50
35	6.319	7.3154	6.8976	6.8402	6.8184	9.92	3.77
45	6.745	7.8391	7.4472	7.3855	7.3605	8.79	3.56
55	6.89	7.7784	7.4299	7.3715	7.3508	10.82	3.83
65	6.803	7.853	7.4332	7.3297	7.3053	16.42	3.87
75	6.958	8.418	7.905	7.823	7.7883	8.66	3.66
85	6.766	7.8475	7.3998	7.3357	7.3098	10.11	4.09
95	6.544	7.5781	7.0876	6.9887	6.9546	18.19	6.27
105	6.454	7.6908	7.1134	7.0329	7.0018	12.21	4.72
115	6.416	7.7426	7.2184	7.1425	7.1024	9.46	5.00
125	6.793	8.3942	7.6805	7.5692	7.5175	12.54	5.83
135	6.259	7.4731	6.9582	6.8931	6.8593	9.31	4.83
145	6.739	7.7094	7.281	7.2261	7.1988	10.13	5.04
155	6.337	7.5838	7.0304	6.9671	6.9357	9.13	4.53
165	6.534	7.9884	7.3401	7.2528	7.2138	10.83	4.84
175	6.36	7.5423	7.0249	6.9599	6.9187	9.78	6.20
185	6.838	7.8762	7.4364	7.3858	7.3566	8.46	4.88
195	6.445	7.3033	6.9771	6.9315	6.9056	8.57	4.87
205	9.135	10.2504	9.658	9.5958	9.5663	11.89	5.64
215	8.719	10.4403	9.592	9.5062	9.4581	9.83	5.51
225	8.615	9.6652	9.1418	9.089	9.0575	10.02	5.98
235	9.053	9.9632	9.4788	9.4256	9.4004	12.49	5.92
245	11.5263	12.7331	12.1825	12.1165	12.0587	10.06	8.81

LOI of core CNR of the northern Rufiji Delta

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
255	11.1967	12.4289	11.8523	11.7962	11.7589	8.56	5.69
265	10.8189	12.0321	11.5272	11.4578	11.3985	9.80	8.37
275	11.4312	12.3146	12.0659	12.0119	11.9809	8.51	4.88
285	11.2376	12.8337	12.1623	12.0873	12.0454	8.11	4.53
295	10.0585	11.6607	10.9581	10.8841	10.8172	8.23	7.44
305	8.506	9.778	9.2224	9.1605	9.1215	8.64	5.44
315	8.881	10.2351	9.6645	9.6026	9.5689	7.90	4.30
325	8.494	9.7385	9.2224	9.1667	9.1353	7.65	4.31
335	8.629	9.8613	9.3528	9.2946	9.261	8.04	4.64
345	7.947	8.8899	8.5002	8.4565	8.4275	7.90	5.24
355	8.473	10.093	9.4279	9.3499	9.3074	8.17	4.45
365	8.132	9.3968	8.9217	8.8604	8.819	7.76	5.24
375	8.381	9.6572	9.1387	9.0794	9.0475	7.83	4.21
385	8.432	9.6933	9.1623	9.1017	9.0791	8.30	3.09
395	8.674	10.0705	9.4832	9.4186	9.3898	7.98	3.56
405	7.929	9.1458	8.612	8.558	8.534	7.91	3.51
415	10.937	12.2573	11.6744	11.6172	11.5919	7.76	3.43
425	10.607	11.8492	11.3183	11.2631	11.239	7.76	3.39
435	10.612	11.5733	11.1412	11.0979	11.0775	8.18	3.85
445	11.142	12.3172	11.7788	11.7289	11.7012	7.84	4.35

LOI of core AMAK-1 of Makoba Bay

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	6.642	7.8355	7.5189	7.4778	7.4735	4.69	0.49
15	6.585	8.0627	7.4936	7.4067	7.4006	9.56	0.67
25	6.836	7.779	7.4897	7.4239	7.4199	10.07	0.61
35	6.319	7.4764	7.0415	6.9494	6.9435	12.75	0.82
45	6.745	7.2323	6.9826	6.9332	6.9303	20.79	1.22
55	6.89	7.9968	7.3667	7.2853	7.278	17.08	1.53
65	6.803	8.2708	7.623	7.544	7.5365	9.63	0.91
75	6.958	8.527	7.9164	7.8368	7.8286	8.31	0.86
85	6.766	8.4427	7.8771	7.8131	7.8052	5.76	0.71
95	6.544	7.5699	7.0953	7.0171	7.0092	14.18	1.43
105	6.454	7.9922	7.611	7.5733	7.5685	3.26	0.41
115	6.416	7.7581	7.3835	7.3465	7.3405	3.82	0.62
125	6.793	8.0607	7.7802	7.7533	7.7489	2.72	0.45
135	6.259	7.5064	7.2536	7.2277	7.2238	2.60	0.39
145	6.739	8.2922	8.0256	8.0101	8.0067	1.20	0.26
155	6.337	7.9415	7.7493	7.7282	7.7244	1.49	0.27
165	6.534	8.4207	8.115	8.08	8.0715	2.21	0.54
175	6.36	8.3456	8.0968	8.075	8.0703	1.26	0.27
185	6.838	8.2119	7.9805	7.9591	7.9498	1.87	0.81
195	6.445	8.2661	7.9486	7.92	7.9058	1.90	0.94
205	9.135	10.6505	10.3645	10.337	10.3251	2.24	0.97
215	8.719	10.1355	9.7382	9.6914	9.6798	4.59	1.14
225	8.615	10.1305	9.8424	9.808	9.7386	2.80	5.65
235	9.053	10.5954	10.1608	10.1132	10.0732	4.30	3.61
245	8.506	10.2242	9.8693	9.8307	9.7799	2.83	3.73

LOI of core BMAK-1 of Makoba Bay

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	6.836	8.2858	7.9499	7.8803	7.8751	6.25	0.47
15	6.585	8.1824	7.6437	7.5503	7.5436	8.82	0.63
25	6.642	7.5679	7.2222	7.1413	7.1361	13.94	0.90
35	6.319	6.9924	6.7435	6.6732	6.6684	16.56	1.13
45	6.745	7.6283	7.1848	7.0664	7.0598	26.92	1.50
55	6.89	7.6707	7.2442	7.1427	7.1375	28.66	1.47
65	6.803	8.0633	7.5851	7.5123	7.5061	9.31	0.79
75	6.958	8.2378	7.7316	7.6553	7.6475	9.86	1.01
85	6.766	8.0076	7.5178	7.4101	7.4021	14.33	1.06
95	6.544	7.6604	7.3002	7.2441	7.2381	7.42	0.79
105	6.454	8.2959	7.5742	7.4619	7.4501	10.02	1.05
115	6.416	8.1686	7.5785	7.4802	7.4698	8.46	0.89
125	6.793	8.5229	8.1076	8.0472	8.0378	4.59	0.72
135	6.259	8.193	7.7173	7.6522	7.6413	4.46	0.75
145	6.739	8.2754	7.8667	7.8044	7.7887	5.52	1.39
155	6.337	8.1688	7.746	7.6919	7.6794	3.84	0.89
165	6.534	7.9795	7.6916	7.6539	7.6475	3.26	0.55
175	6.36	7.8329	7.5083	7.4633	7.4543	3.92	0.78
185	6.838	8.0945	7.7712	7.7034	7.6923	7.27	1.19
195	6.445	8.039	7.7379	7.6958	7.6842	3.26	0.90
205	9.135	11.3905	10.9884	10.9478	10.8998	2.19	2.59
215	8.719	10.2535	9.8064	9.7399	9.715	6.12	2.29
245	8.506	10.0078	9.7381	9.7066	9.6916	2.56	1.22
235	9.053	10.6625	10.3518	10.3123	10.2845	3.04	2.14
225	8.615	9.8513	9.4584	9.4109	9.3846	5.63	3.12

LOI of core BMAK-1 of Makoba Bay (cont.)

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
255	8.881	10.223	9.7744	9.7262	9.6982	5.40	3.13
265	8.494	9.9331	9.4277	9.3718	9.3406	5.99	3.34
275	8.629	9.9278	9.5062	9.4646	9.4391	4.74	2.91
285	7.947	8.7283	8.4906	8.466	8.4432	4.53	4.19
295	8.473	9.3696	9.0681	9.0376	9.013	5.13	4.13
305	8.132	9.193	8.7326	8.6906	8.6625	6.99	4.68
315	8.381	9.6287	9.1154	9.0756	9.0333	5.42	5.76
325	8.432	8.9148	8.7046	8.6787	8.6648	9.50	5.10
335	8.674	9.6769	9.1845	9.1213	9.0864	12.38	6.84
345	7.929	8.8611	8.3571	8.2854	8.2721	16.75	3.11
355	10.937	11.9029	11.4989	11.4408	11.4332	10.34	1.35
365	10.607	11.3479	11.0637	11.0176	11.0097	10.09	1.73
375	10.612	11.2028	10.9169	10.8472	10.8449	22.86	0.75
385	11.142	11.7948	11.5808	11.5362	11.5284	10.16	1.78
395	10.979	11.7171	11.3871	11.3368	11.3335	12.33	0.81

LOI of core CMAK-1 of Makoba Bay

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	8.774	10.2248	10.1889	10.1642	10.1561	1.75	0.47
15	11.485	12.9869	12.9421	12.9064	12.8973	2.45	0.62
25	10.995	11.9153	11.8618	11.8003	11.792	7.10	0.96
35	11.263	11.8212	11.7858	11.7459	11.74	7.63	1.13
45	11.35	12.569	12.4978	12.4518	12.4376	4.01	0.88
55	11.5263	13.22	13.0053	12.8609	12.367	9.76	1.08
65	11.1967	13.0109	12.854	12.7805	12.7634	4.43	0.99
75	10.8189	12.83	12.7345	12.6624	12.647	3.76	0.80
85	11.4312	12.4933	12.3516	12.2584	12.2411	10.13	1.88
95	11.2376	12.2997	12.1716	12.1269	12.1051	4.79	2.33
105	10.0585	10.9308	10.8607	10.8221	10.8037	4.81	2.29
115	11.6354	12.5233	12.4525	12.4011	12.3803	6.29	2.55
125	10.9695	12.891	12.8098	12.7668	12.3567	2.34	1.24
135	11.2292	12.815	12.7241	12.6636	12.6391	4.05	1.64
145	11.5972	13.3332	13.1658	13.1028	13.0698	4.02	2.10
155	10.8753	13.1178	12.9029	12.82	12.7732	4.09	2.24
165	11.0969	13.6659	13.4181	13.3283	13.2734	3.87	2.30
170	10.9546	12.8376	12.6793	12.6149	12.5671	3.73	2.69

LOI of core A-UU-1 of Unguja Ukuu

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	6.642	7.4659	7.2755	7.2092	7.1557	10.47	8.45
15	6.585	7.1576	7.0766	7.0269	6.9841	10.11	8.71
25	6.836	7.3212	7.0694	7.0029	6.9897	28.49	5.66
35	6.319	6.8745	6.7121	6.6441	6.6315	17.30	3.21
45	6.745	7.3564	7.2716	7.2208	7.2121	9.65	1.65
55	6.89	7.6691	7.627	7.5704	7.5598	7.68	1.44
65	6.803	7.2378	7.0731	7.0015	6.9885	26.51	4.81
75	6.958	7.2919	7.152	7.1156	7.1084	18.76	3.71
85	6.766	8.1588	7.7369	7.6487	7.5179	9.08	13.47
95	6.544	7.4904	7.2725	7.2267	7.1373	6.29	12.27
105	6.454	7.253	6.9722	6.9263	6.8574	8.86	13.30
115	6.416	7.3057	7.2837	7.2388	7.1442	5.17	10.90
125	6.793	7.8049	7.5199	7.4775	7.3468	5.83	17.98
135	6.259	7.3523	7.0648	7.0247	6.894	4.98	16.22

LOI of core B-UU-1 of Unguja Ukuu

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	6.739	7.4099	7.3907	7.309	7.2965	12.54	1.92
15	6.337	6.8536	6.8281	6.7502	6.7395	15.86	2.18
25	6.534	7.3287	7.0759	6.974	6.9572	18.80	3.10
35	6.36	7.2401	7.1067	6.9989	6.9824	14.44	2.21
45	6.445	8.0475	7.3557	7.1981	7.1773	17.31	2.28
55	6.838	7.6463	7.6002	7.5357	7.5268	8.46	1.17
65	9.135	9.8104	9.7787	9.7306	9.7233	7.47	1.13
75	8.719	9.0793	9.0725	9.0459	9.0397	7.52	1.75
85	8.506	10.049	9.7387	9.6644	9.6516	6.03	1.04
95	9.053	9.7899	9.7829	9.7567	9.7509	3.59	0.79
105	8.615	9.6066	9.5224	9.4869	9.4793	3.91	0.84
115	8.881	9.4552	9.4508	9.4354	9.4319	2.70	0.61
125	8.494	9.1167	9.1082	9.0898	9.0858	3.00	0.65
135	8.629	9.0166	9.0102	8.9873	8.9824	6.01	1.29
145	7.947	8.9069	8.8665	8.8421	8.7756	2.65	7.23

LOI of core C-UU-1 of Unguja Ukuu

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	8.132	8.2772	8.2722	8.2692	8.2683	2.14	0.64
15	8.381	8.771	8.668	8.5875	8.58	28.05	2.61
25	8.432	9.5108	9.2024	9.1609	9.1476	5.39	1.73
35	8.674	9.6113	9.5103	9.4909	9.4822	2.32	1.04
45	7.929	8.4386	8.2091	8.1383	8.1303	25.28	2.86
56	10.937	11.6595	11.5286	11.4816	11.4743	7.94	1.23
65	10.607	11.391	11.3123	11.2284	11.2196	11.90	1.25
75	10.612	11.0465	10.9992	10.9614	10.9565	9.76	1.27
85	11.142	13.0516	12.9143	12.8346	12.8123	4.50	1.26
90	10.979	11.2525	11.2289	11.2059	11.2024	9.20	1.40

LOI of core C-UU-4 of Unguja Ukuu

Depth (cm)	Empty crucible	Wet weight	105 C	550 C	950 C	LOI550	LOI950
5	8.132	9.0427	8.7351	8.6909	8.6825	7.33	1.39
15	8.381	9.5908	9.1664	9.0869	9.074	10.12	1.64
25	8.432	9.9439	9.3607	9.2751	9.2583	9.22	1.81
35	8.674	9.9008	9.4789	9.416	9.3994	7.81	2.06
45	7.929	9.2516	8.726	8.656	8.6471	8.78	1.12
55	10.937	12.0643	11.6642	11.5972	11.5911	9.21	0.84
65	10.607	12.3485	11.844	11.7687	11.7621	6.09	0.53
75	10.612	11.6835	11.1803	11.0911	11.0847	15.70	1.13
85	11.142	12.322	11.9126	11.8197	11.8119	12.06	1.01
95	10.979	12.5031	11.6988	11.5591	11.5489	19.41	1.42
105	8.774	10.0256	9.3789	9.2704	9.2595	17.94	1.80
115	11.485	12.8128	12.1432	12.0438	12.0281	15.10	2.39
125	10.995	12.0737	11.3916	11.2599	11.2501	33.21	2.47
135	11.263	12.2709	11.7023	11.6195	11.6086	18.85	2.48
145	11.35	12.4402	11.8465	11.7605	11.7495	17.32	2.22
155	11.5263	12.5461	12.0829	12.0126	12.0048	12.63	1.40
165	11.1967	12.1539	11.6499	11.5608	11.5453	19.66	3.42
175	11.4312	12.3546	11.8406	11.7648	11.7539	18.51	2.66
185	10.8189	11.7883	11.175	11.0804	11.0699	26.57	2.95
195	11.2376	11.848	11.4937	11.4148	11.4084	30.81	2.50
205	10.0585	11.0534	10.467	10.3424	10.3358	30.50	1.62
215	11.6354	13.0619	12.3043	12.1569	12.1396	22.04	2.59
225	10.9695	12.422	11.5622	11.4116	11.3948	25.41	2.83
235	11.2292	12.3324	11.7453	11.6295	11.6195	22.44	1.94

Appendix D: Raw charcoal count data sheets

Raw charcoal count of CNR (the northern Rufii Delta)

Depth (cm)	3-10 µm	10-20 µm	20-40 µm	40-60 µm	>60 µm
5	324	296	118	26	21
15	98	105	49	12	5
25	118	178	112	31	18
35	119	224	146	57	40
45	133	183	143	39	34
55	127	175	62	8	14
65	141	120	57	8	14
75	50	167	61	12	15
85	53	61	12	2	1
95	46	112	62	11	12
105	50	55	29	9	14
115	34	81	32	8	9
125	34	51	12	4	2
135	30	67	25	6	4
145	49	59	33	6	11
155	59	66	38	7	8
165	29	23	12	4	4
175	30	33	23	8	9
185	58	67	40	4	9
195	80	67	32	3	3
205	34	58	18	2	7
215	10	26	18	2	5
225	26	76	27	6	5
235	23	50	23	5	3
245	21	58	23	2	5
255	18	55	23	3	7
265	61	95	44	6	7
275	30	55	37	3	8
285	50	77	40	1	4
295	38	61	48	4	8
305	45	89	42	14	13
315	42	77	34	9	9
325	17	35	19	5	9
335	35	73	54	3	12
345	20	56	37	5	9
355	11	46	27	11	15
365	15	66	31	8	10
375	53	86	50	5	12
385	52	83	56	10	13
395	28	44	35	4	4
405	23	57	24	7	2
415	17	14	12	2	2
425	13	14	7	1	3
435	18	19	13	1	2
445	27	25	11	2	0

Raw charcoal count of AMAK-1 (Makoba Bay)

Depth (cm)	3-10 µm	10-20 µm	20-40 µm	40-60 µm	>60 µm
5	243	33	15	10	12
15	220	35	17	8	8
25	230	30	13	8	8
35	216	25	17	3	3
45	193	24	8	4	1
55	206	21	16	4	3
65	216	29	14	2	4
75	232	32	17	3	1
85	241	25	23	5	1
95	261	26	29	3	4
105	305	21	15	5	2
115	325	24	16	3	2
125	330	30	19	4	3
135	312	39	23	5	3
145	383	37	24	3	1
155	443	33	20	4	1
165	427	31	29	4	4
175	392	35	24	4	1
185	381	32	14	2	3
195	366	37	16	10	1
205	246	36	21	3	2
215	218	24	17	3	1
225	202	19	13	7	0
235	252	23	12	5	2
245	208	22	17	3	0

Raw charcoal count of BMAK-1 (Makoba Bay)

Depth (cm)	3-10 µm	10-20 µm	20-40 µm	40-60 µm	>60 µm
5	193	30	12	8	10
15	213	38	8	11	7
25	224	48	9	8	5
35	253	31	13	5	1
45	245	29	10	2	2
55	246	41	8	5	1
65	243	49	8	3	1
75	285	43	9	5	2
85	274	32	6	4	3
95	377	47	10	3	2
105	225	18	1	0	1
115	254	21	6	0	1
125	204	16	7	6	2
135	169	16	6	3	3
145	226	18	4	3	2
155	192	12	11	2	2
165	177	10	4	3	2
175	178	16	13	3	4
185	201	25	8	3	3
195	253	19	10	7	3
205	256	32	27	11	2
215	242	45	28	7	4
225	256	49	23	7	6
235	271	34	5	3	6
245	184	42	15	8	1
255	193	28	13	6	2
265	187	35	14	7	1
275	226	29	17	7	2
285	183	24	21	1	2
295	178	46	15	7	0
305	167	34	16	7	2
315	192	38	14	8	3
325	195	31	9	5	0
335	175	41	20	5	2
345	175	25	17	7	4
355	170	17	8	9	3
365	163	33	17	6	2
375	164	25	12	5	1
385	209	21	16	5	1
395	214	18	8	3	1

Raw charcoal count of CMAK-1 (Makoba Bay)

Depth (cm)	3-10 µm	10-20 µm	20-40 µm	40-60 µm	>60 µm
5	214	21	13	8	11
15	213	38	9	10	5
25	194	19	10	5	2
35	186	18	9	5	1
45	166	26	7	3	2
55	184	30	11	6	3
65	218	31	8	3	1
75	149	13	7	6	1
85	145	25	5	1	2
95	157	27	9	3	2
105	168	31	4	3	0
115	242	23	12	3	2
125	237	36	6	5	2
135	211	44	6	4	1
145	213	45	9	8	2
155	257	44	7	7	1
165	206	49	3	4	3
175	252	43	6	4	3

Raw charcoal count of B-UU-1 (Unguja Ukuu)

Depth (cm)	3-10 µm	10-20 µm	20-40 µm	40-60 µm	>60 µm
5	80	176	30	8	6
15	70	179	55	9	9
25	116	352	108	16	12
35	61	96	22	6	4
45	60	94	37	8	1
55	70	155	20	6	6
65	96	148	31	6	3
75	111	155	31	3	1
85	64	85	23	2	0
95	33	61	24	1	0
105	88	87	14	2	0
115	123	176	36	5	2
125	127	156	22	6	1
135	59	92	13	4	0
140	78	37	7	1	0
145	57	32	6	1	0

Raw charcoal count of C-UU-4 (Unguja Ukuu)

Depth (cm)	3-10 µm	10-20 µm	20-40 µm	40-60 µm	>60 µm
5	700	185	37	2	6
15	629	253	77	11	4
25	640	176	24	2	1
35	980	152	33	5	0
45	917	82	7	1	0
55	646	69	8	0	0
65	1064	86	1	0	0
75	347	54	2	0	0
85	317	29	2	0	0
95	154	12	1	0	0
105	617	76	9	1	0
115	232	14	2	0	0
125	218	17	1	0	0
135	606	126	9	3	0
145	448	67	3	2	0
155	307	24	3	0	0
165	334	20	1	0	0
175	490	31	0	0	0
185	245	18	2	0	0
195	358	16	1	0	0
205	298	11	2	0	0
215	191	11	0	0	0
225	364	32	4	0	0
235	306	34	4	1	0