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Holocene mangrove dynamics and relative sea-level changes along the Tanzanian coast, East Africa

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Abstract There is continued uncertainty regarding the rate, timing, duration and direction of Holocene sea-level for the Indian Ocean, and indeed the wider tropical realm. We present the first synthesis, and a new chronology, for Holocene relative sea-level (RSL) using a range sediment cores retrieved from mangrove ecosystems in three locations along coastal Tanzania. This study applies the relationship of ratios between the key mangrove taxa of *Sonneratia*:(*Bruguiera/Ceriops*) (S/BC) (ranging from 0 – 22.9) and *Sonneratia*:*Rhizophora* (S/R) (ranging from 0 – 2.29), vegetation and altitude to interpret mangrove dynamics and refine the vertical errors associated with relative sea level change. The variations in mangrove taxa ratios in the sediment cores obtained from each site shows mangrove development at different periods during the Holocene from around 7900 cal yr BP. An early to mid-Holocene RSL rise occurred from ~7900 to ~4600 cal yr BP that may have reached a higher level than present. A lower RSL occurred after 4600 cal yr BP, resulting in mangroves retreating seaward at all three study locations, before a low magnitude RSL rise occurred between 4400 and 2000 cal yr BP. Another RSL rise is recorded at ~ 500 cal yr BP before falling to a level lower than present at ~100 cal yr BP. There is evidence of a recent RSL rise recorded from mangrove ratios during the last century. In addition, the sedimentation rates among sites are relatively different due to different altitudinal ranges with freshwater input, sediment supply and progradation having significantly more effect in the Rufiji Delta (2.1-10.9 mm cal yr^{-1}) than at the Zanzibar sites (0.3-6.6 mm cal yr^{-1}).

Keywords: Indian Ocean, pollen-vegetation relationships, far-field locations, Zanzibar, Rufiji Delta

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1. Introduction

Relative sea-level (RSL) (the height of the ocean with respect to the surface of the solid Earth) has fluctuated over time that has resulted in geophysical and ecological changes (Pirazzoli, 1991). Far-field sites, located at a distance from the major ice sheets, are important locations for reconstructing RSL changes. Far-field locations can provide important constraints on global RSL change when combined with more intensively studied temperate areas, where coastal adjustments following removal of ice loading are most acute, especially during the mid and late Holocene (Milne and Mitrovica, 2008).

Holocene RSL changes in far-field locations result from eustatic changes, equatorial syphoning and hydro-isostasy (continental levering) (Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). Equatorial ocean syphoning results from collapsing forebulges at the near-field continental margins that cause RSL fall to be recorded in far-field locations (Mitrovica and Peltier, 1991). Continental levering occurs when there is water loading due to deglaciation, that causes continental subsidence and an uplift of the adjacent continents, inducing RSL fall at areas distant from the continental margins (Lambeck and Nakada, 1990; Mitrovica and Milne, 2002; Gehrels and Long, 2008). RSL records from far-field locations have been produced from various locations including 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; Lewis et al., 2013). Holocene RSL changes have been reconstructed from Australia using a range of coastal and coral reef proxies; some studies suggest a highstand at ~6000 cal yr BP (Lambeck and Nakada, 1990; Larcombe et al., 1995), whereas others indicate a later highstand around 3900 cal yr BP (Baker et al., 2001). A review of geo-chronological data from along the southeast coast of Australia, indicates a highstand from 7700 cal yr BP that lasted until about 2000 cal yr BP, before falling to the present-day level (Sloss et al., 2007). In the northern Indian Ocean, two mid-late Holocene highstands, one at 7300 cal yr BP and another at 4300 cal yr BP, have been recorded from beach ridges and coral terraces along the east coast of India (Banerjee, 2000). These highstands were also recorded from corals and marine shells along the southwest and south coasts of Sri Lanka (Katupotha and Fujiwara, 1988) occurring at 6500 cal yr BP and 3200 cal yr BP.

Clearly far-field RSL records are of immense value for understanding and constraining sea level records but there is a range of timings and duration of these. In this paper we present evidence of RSL changes derived from three mangrove sediment records (Punwong et al., 2012; 2013a; 2013b) from sites on the Tanzanian coast. Combined, these data provide the first sea-level curve and a refined chronology for Holocene RSL and coastal changes for Tanzania. This study also uses the relationship between ratios of key mangrove taxa, vegetation and altitude to interpret mangrove dynamics and refine the vertical errors of RSL change. Holocene RSL changes are integrated with existing RSL reconstructions from the region to develop a reconstruction of Holocene RSL changes across the Southwest Indian Ocean.

1.1. Sea-level history in the southwest Indian Ocean

The record of Holocene RSL change along the East African coast, situated in the tectonically stable (Woodroffe and Horton, 2005) Southwest Indian Ocean, is poorly constrained (Pirazzoli, 1991; Camoin et al., 2004). Reconstructed RSL changes are available from only a few locations and use a range of different proxies (Figure 1a). Previous studies of RSL change on the continental coasts of east and southeast Africa (Mozambique and South Africa) indicate that RSL rose rapidly during the early Holocene and reached the present level by the mid Holocene (Jaritz et al., 1977, Ramsay, 1995; Ramsay and Cooper, 2002; Norström et al., 2012). Mid Holocene highstands of up to 3.5 m above the present level were recorded by 5000 cal yr BP, followed by subsequent falls to the present level in the late Holocene. A different RSL reconstruction derived from coral from the offshore islands (Mauritius, Mayotte and Réunion Island) shows that a rapid RSL rise occurred during the early Holocene reaching present level at ~3000 cal yr BP with no evidence for a mid Holocene highstand (Camoin et al., 1997; 2004; Colonna et al., 1997; Zinke et al., 2003). Although all RSL studies within this region record an early Holocene RSL rise, there is considerable uncertainty on the amplitude and timing of this. The varied environmental settings and distances from formerly glaciated areas would result in different isostatic contributions to RSL changes. For example, it is thought that small offshore volcanic islands are less affected by hydro-isostatic adjustment than those studies from continental locations due to the effects of continental levering during the mid and late Holocene (Camoin et al., 2004; Lambeck and Nakada, 1990; Mitrovica and Milne, 2002; Milne and Mitrovica, 2008). The different proxies used make it likely that the sea-level index points may not be comparable and some sea-level index points may have large indicative ranges and different degrees of precision (Jaritz et al., 1977; Ramsay, 1995; Ramsay and Cooper, 2002; Woodroffe and Horton, 2005; Norström et al., 2012).

1.2. Mangrove as sea-level indicators

Research on RSL reconstruction from far-field locations has traditionally focused on coring and dating corals (Pirazzoli, 1988; Fairbanks, 1989; Colonna et al., 1997; Camoin et al., 1997, 2004). However, sediments that accumulate within mangrove ecosystems can also be used to reconstruct RSL and coastal changes. Mangrove ecosystems are found in coastal tropical regions along the margins of the sea and lagoons; they are characterised by 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 the high water of spring tide (Woodroffe and Grindrod, 1991; Blasco et al., 1996; Ellison and Farnsworth, 2001; Ellison, 2008). Mangrove ecosystems respond to changes in sea level by migrating landwards with a rise in sea level or seawards with a fall (Gilman et al., 2008). Mangrove community composition is able to keep pace with sea-level changes (McIvor et al., 2013). For mangroves to be able to withstand sea level rise, the rates of sedimentary accretion within the mangrove has to be equivalent to the rate of sea-level rise (Ellison, 2015), otherwise mangroves may undergo *in situ* drowning leading to weakened root structures, dieback and disappearance (Gilman et al., 2008).

Santisuk (1983) and Watson (1928) classified mangroves into a series of inundation class zones according to ecological preference to monthly inundation frequency. *Rhizophora mucronata*, *Avicennia marina*, *Sonneratia alba*, *Bruguiera gymnorrhiza* and *Ceriops tegal* are classified as true mangroves or mangroves. The term true mangroves are also defined as mangroves representing trees and shrubs growing in the areas inundated by the normal to all high tides. Back mangroves such as *Heritiera littoralis* and *Acrostichum aureum* are plants growing in the areas inundated by the sea only during spring high tides, exceptional high tides, or during cyclones. The dominance of mangrove species which occurs in zones throughout the mangrove ecosystem can thus be an indicator of sea-level fluctuations by comparing the relationships between contemporary vegetation assemblages and their inundation frequency with respect to sea level.

Mangrove pollen has previously been used to reconstruct compositional changes in mangrove ecosystems (e.g. Cohen et al., 2005; Horton et al., 2005; Vedel et al., 2006; Tossou et al., 2008; Hait and Behling, 2009) including in East Africa (Punwong et al., 2012; 2013a; 2013b). Engelhart 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 precision of ± 0.22 m. A contemporary study into the relationships between mangrove pollen in surface sediment samples and the composition of the vegetation indicated that majority of pollen was local in origin reflecting vegetation in close proximity to the sampling sites (Punwong et al., 2013a, 2013b). Pollen accumulated in sediments underlying mangroves, in combination with an understanding of the present relationship of mangrove composition to the altitude of present sea level, can be used to reconstruct RSL fluctuations (Ellison, 1989; 2005; 2008; Punwong et al., 2012; 2013a; 2013b).

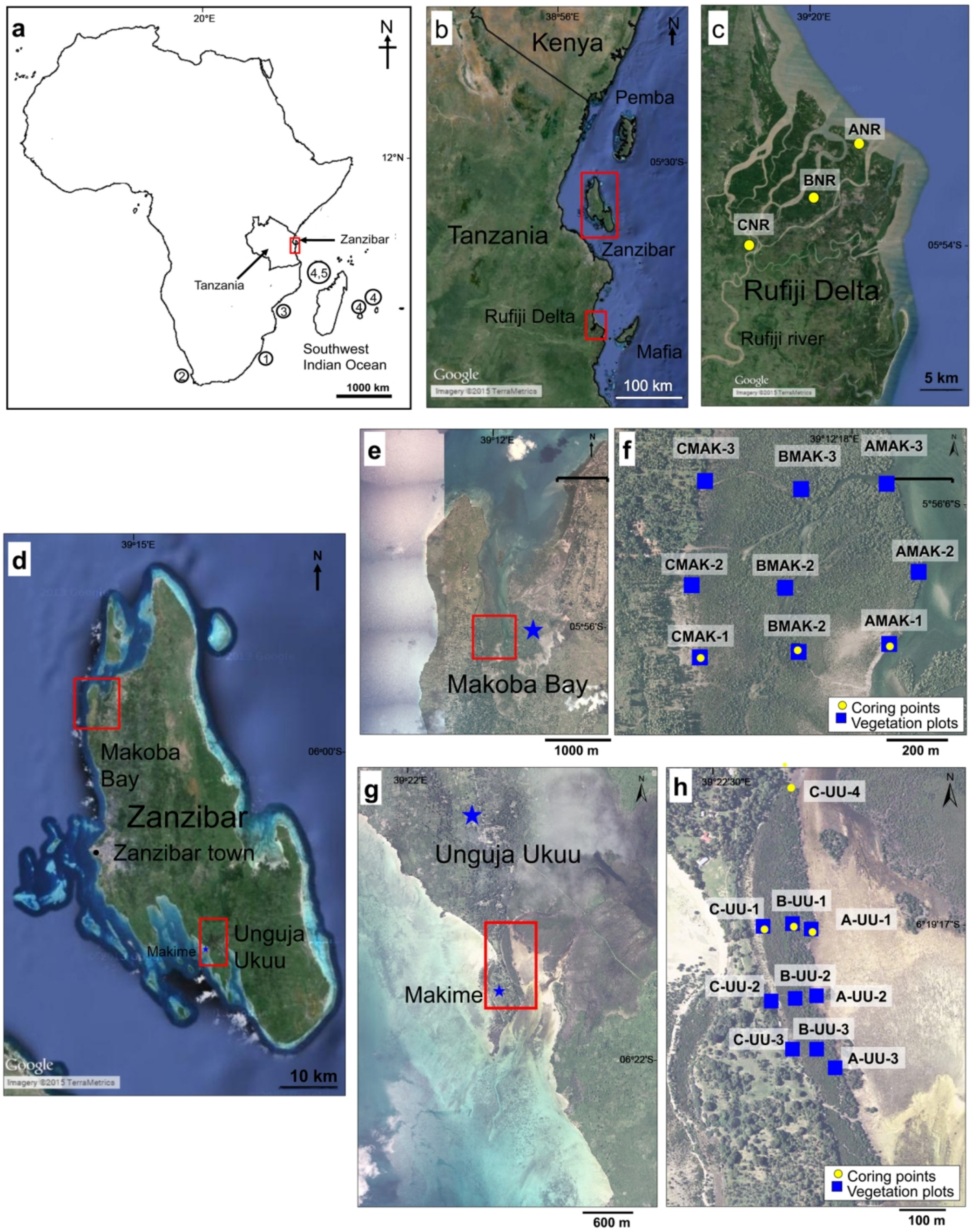

Figure 1. (a) Map of the Southwest Indian Ocean showing the location of Tanzania and previous sea level studies: (1) Ramsay and Cooper (2002), (2) Compton (2001), (3) Jaritz et al. (1977), (4) Colonna et al. (1996); Camoin et al. (1997), (5) Zinke (2000); Zinke et al. (2003). (b) Map of the coast of Tanzania showing the location of the Rufiji Delta (c) and Zanzibar (d). Inset e, f, g and h show where the sedimentary cores were taken and the location of vegetation plots located in Makoba Bay and Unguja Ukuu respectively.

2. Study sites

2.1. Geology and geomorphology

The three sites investigated are all characterised by mangrove forest and located in the northern Rufiji Delta (Tanzanian mainland), Makoba Bay and Unguja Ukuu (Unguja island, Zanzibar) (Figure 1b-h). The Rufiji Delta consists of mangrove forest that grades into paddy fields at higher elevations and supports the largest expanse of estuarine mangrove along the East African coast (Nshubemuki, 1993; Fisher et al., 1994; Richmond et al., 2002; Masalu, 2003; Mangora et al., 2016). The deltaic area is covered by fluvial sand, silt and clay (Semesi, 1992) (Figure 1c). A series of sand spit islands and submerged sand bars have formed parallel to the seaward margins (Fisher et al., 1994), while clayey silts and silty clays containing organic matter characterise the mangrove sediments. The average tidal range is 2 - 2.5 m and approximately 3.3 - 4.3 m on high spring tides (Francis, 1992; Fisher et al., 1994; Richmond et al., 2002).

Unguja Island (Zanzibar) is located on the continental shelf some 40 km from the mainland. The island has been periodically part of the mainland when sea level was 30-40 m below present sea level and the last separation from the mainland by sea-level inundation of the Zanzibar channel occurred at the end of the Pleistocene to early Holocene (Prendergast et al., 2016). Most of Unguja consists of Pleistocene reef limestone often outcropping on the east coast (Shunula, 2002) with alluvial deposits locally present (Schlüter, 1997; Arthurton et al., 1999) although there are no 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 study areas are located in the northwest of Makoba Bay (Figure 1d; 1e) and the east Makime headland of Unguja Ukuu (Figure 1d; 1g).

2.2. Climate

The rainfall pattern within the Rufiji Delta and on Zanzibar is largely controlled by the north and south migration of the Inter-tropical Convergence Zone (ITCZ). For the Rufiji delta, the northeast monsoon prevails from December to April bringing heavy rainfall (Goudie, 1996; Nicholson, 2001) and the southeast monsoon dominates from May to November bringing less rainfall (Fisher et al., 1994; Richmond et al., 2002). The average annual rainfall is about 1200 mm yr^{-1} (Semesi, 1992) and the temperature range throughout the year is 24 - 31 °C (Richmond et al., 2002). For Zanzibar, the northeast and southeast monsoons bring the long rains from March to May and short rains from October to December (Machiwa and Hallberg, 1995; Mwandya et al., 2010). The mean annual rainfall is about 1500 -1800 mm yr^{-1} (Knopp et al., 2008) and the average temperature range throughout the year is about 27 - 30 °C (Machiwa and Hallberg, 1995).

3. Methodology

3.1. Coring

Three sediment cores were retrieved from each site at a seaward, central and landward location using a Russian corer along a transect perpendicular to the coastline through the centre of mangrove forests to reduce the influence of local land-based edge effects such as erosion or progradation from creeks (Ellison, 2008). The core depths varied between 1 to 4.5 m (Table 1) and each site was cored until the sediment became impenetrable or bedrock was reached (Punwong et al., 2012; 2013a; 2013b). The transect length varied depending on the nature of the environmental setting and the extent of the mangrove area; this extended along 20 km in the northern Rufiji Delta (ANR, BNR, CNR), 600 m in Makoba Bay (AMAK-1, BMAK-1, CMAK-1) and 80 m at Unguja Ukuu (A-UU-1, B-UU-1, C-UU-1) (Figures 1c; 1f; 1h, Table 1). An additional sediment core was retrieved from Unguja Ukuu (C-UU-4) at a location away from the transect as it represents a longer sediment record than the other three cores.

3.2. Vegetation plots

To study the relationship between mangrove species composition, pollen accumulating in the sediment and RSL, nine 20 m^2 vegetation plots were set up to establish species percentages along an altitudinal gradient. At the three sites, there was considerable variation in the horizontal distance covered to accommodate the full range of the upper and the lower limits of mangroves. In the Rufiji Delta, the vegetation survey transect along the large riverine mangrove system with freshwater inputs covered 20 km. As the consequence, we were not able to carry out adequate vegetation surveys and to set up plots within the restricted fieldwork time frame. On Zanzibar the transects extended between 80 to 600 m of fringing mangroves characterised by a similar composition across the three sites. Given variations in the horizontal distance and vertical range, the mangrove gradient in Zanzibar is considered to be steeper than the Rufiji Delta. A more detailed study at both sites in Zanzibar allowed the ecosystem and structural composition at different levels of sea-level inundation to be determined and inform the reconstruction of past RSL fluctuations. Vegetation in nine 20 m^2 nested quadrats was surveyed and recorded and surface sediment samples were collected (Figures 1f; 1h) from three seaward, three central and three landward sites, then considered to be an upper intertidal, a middle intertidal and a lower intertidal mangrove classes, respectively. Five cm^3 of surface samples from the four corners and centre of each plot were collected and subsequently used to study the relationship between pollen presence and vegetation coverage. Altitudinal heights were obtained using a differential GPS (dGPS model Leica TCRA total station and Leica System 500 base and receiver with a manufacturer quoted vertical precision of ± 0.001 m). Initial calibration of the dGPS occurred against recognised National Datum benchmarks and subsequently all coring sites, vegetation plots and full range of mangrove sites were levelled and calibrated to mean tide level (MTL) (based on Admiralty Tide Tables, 2014). These altitudes were determined relative to a benchmark at Kibiti for the Rufiji Delta using a known actual base station Triangulation point (TTP 353) and the Ministry of Lands and the Environment Benchmark (Zanzibar).

3.3. Palaeoecological analysis

The cores were sub-sampled every 10 cm and the volume of each subsample was approximately 2 cm^3 for pollen analysis (Punwong et al., 2012; 2013a; 2013b). The relationship between pollen assemblages and vegetation composition was determined using three pollen association indices that reflect how accurately pollen types reflect the abundance of their parent plant (Davis, 1984). The three indices are ‘association index’ representing similar presence of the pollen and the associated plant in the vegetation, ‘under-representation index’ representing pollen percentages that are much lower than plant percentages, and 'over-representation index' representing pollen percentages that exceed plant percentages (Davis, 1984). Pearson's Correlation Coefficients were used to describe the relationship between pollen percentages extracted from the surface sediment and plant percentages from the nine vegetation plots in Makoba Bay and Unguja Ukuu.

3.4. Chronology

Twenty-six 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. At the start of the laboratory work, dates were obtained from the base of the core with targeted dating from different stratigraphic boundaries and key biostratigraphical horizons occurring as the research developed. Additionally, nine dates from AMAK-1 and BMAK-1 cores were obtained on organic concentrate samples following Woodroffe et al. (2015a). Each 1 cm^3 bulk sediment was deflocculated using $Na_4P_2O_4$ / NaOH, heated with 10% HCl and sieved through a 10, 63 and 90 μm mesh. The 10-63 μm sieving fraction was selected for dating as it contained fine organic material and pollen (Woodroffe et al., 2015a). The organic concentrate samples were submitted for dating to the Natural Environment Research Council (NERC) Radiocarbon Facility (East Kilbride) for AMS dating (NERC Radiocarbon Facility Allocation 1608.0312). All dates were calibrated using the southern hemisphere calibration Shcal04 curve (McCormac et al., 2004) using the software OxCal v4.10 (Bronk-Ramsey, 2009).

4. Results

4.1. Stratigraphy

Detailed stratigraphic descriptions and diagrams have been previously published (Punwong et al., 2012; 2013; 2013b). There were no abrupt stratigraphic boundaries between the units; they were gradational in all ten cores. The basal unit of BNR and CNR in the northern Rufiji Delta was comprised of organic matter and silt (Punwong et al., 2012). Organic matter amount, including root fragments, increased towards the top of the cores where wood and bark fragments were also present.

In the three cores retrieved from Makoba Bay, the deepest sediment was grey silt with some shell fragments (Punwong et al., 2013b). In cores AMAK-1 and BMAK-1 the silt unit was overlain by a peat unit containing woody root fragments and fine sand. Sand was found in the uppermost unit of all three cores.

The basal unit of A-UU-1, B-UU-1 C-UU-1 sediment cores from Unguja Ukuu was grey sand and silt with silt as the basal unit in C-UU-4 (Punwong et al., 2013a). All basal units were overlain by peat with woody root fragments. Some small shell fragments were also found in this unit in A-UU-1 and B-UU-1. Peat layers with sand and small fragments of woody plant roots alternated with organic sand layers throughout the sediment column in all four cores. Sand containing small fragments of woody plant root formed the top unit of B-UU-1, C-UU-1, and C-UU-4 while silt characterised the top unit of A-UU-1.

4.2. Pollen analysis and vegetation survey

Fossil pollen and spores were identified and placed into five main ecological groups: mangroves, back mangroves, terrestrial herbaceous, pteridophytes and unidentifiable pollen; the first two (mangroves, back mangroves), denote a tolerance to sea-water inundation (Punwong et al., 2012; 2013a; 2013b). Terrestrial taxa consisted solely of terrestrial herbaceous plants such as grasses and sedges that are not tolerant of salinity. An understanding of the contemporary mangrove species within the zones is used to underpin the interpretation of ecosystem and environmental changes through the fossil record. Nine mangrove species found in Tanzania within a zonation scheme developed through a combination of Watson's (1928) and Santisuk's (1983) inundation classes (mangroves and back mangroves) and field-based observations of modern ecological occurrences of mangrove taxa (Figure 2a) (Punwong et al., 2012; 2013a; 2013b) are therefore used as a modern analogue of mangrove pollen to interpret sea level. Low mangrove diversities and a linear relationship between contemporary mangrove habitat and inundation frequency negates the need for the use of transfer functions (Ellison, 1989; Engelhart et al., 2007).

Contemporary vegetation assemblages observed in the field based on Watson and Santisuk (1928) classes revealed a distinct vertical relationship with present sea level. The altitude of the upper and lower limits of the mangrove areas was +1.67 m to +3.47 m mean tide level (MTL) in the northern Rufiji Delta, -1.63 m to +1.47 m MTL in Makoba Bay, and -0.03 m to +1.87 m MTL at Unguja Ukuu. The altitudinal variation of the upper and lower limits of the mangrove areas at the three sites is due to different mangrove systems and environmental settings. In the northern Rufiji Delta, an estuarine mangrove ecosystem exists while at Unguja Ukuu and Makoba Bay, fringe mangroves with less freshwater input are found. For Makoba Bay we acknowledge it is unusual for mangroves to grow at -1.63 m MTL and is most likely caused by the geomorphology of the tidal creek system that allows seaward mangrove species, e.g. *Sonneratia alba*, to colonise altitudes below MTL.

The indices of pollen association (Davis, 1984) and correlation between the contemporary mangrove pollen records and contemporary vegetation showed that fossil mangrove pollen in Zanzibar have a close correlation between representivity in pollen spectra and the actual vegetation and can be used to reconstruct coastal ecosystem dynamics (Punwong et al., 2013a; 2013b). Strikingly, there are some notable changes between the percentages of *Sonneratia alba* and *Bruguiera*/*Ceriops* pollen throughout Zanzibar cores. At the present-day *Sonneratia alba* and *Bruguiera/Ceriops* appear at different altitudes; *Sonneratia alba* occurs in the lower intertidal zone whilst *Bruguiera* and *Ceriops* occur at higher intertidal areas. The relative pollen ratios of *Sonneratia*:(*Bruguiera*/*Ceriops*) (S/BC ratio) and *Sonneratia*:*Rhizophora* (S/R ratio) of the surface samples from each vegetation plot vary with altitudinal gradient (Table 2). An increase in the ratios of S/BC and S/R indicates a decrease in altitude of the mangrove ecosystem and associated sea level (Table 2). These ratios are applied to infer the mangrove altitude shift within the upper and lower altitudinal limits of the Makoba Bay and Unguja Ukuu study areas as a modern analogue of altitude mangrove classes (Table 2). In Makoba, the S/BC ratios of 5.4 – 22.8 and the S/R ratios of 0.37 – 2.29 represent lower intertidal mangroves; the S/BC ratios of 0.2 – 5.4 and the S/R ratios of 0.04 – 2.29 represent middle intertidal mangroves; the S/BC ratios of 0 – 0.2 and S/R ratios of 0 – 0.04 represent higher intertidal mangroves. At Unguja Ukuu, the S/BC ratios of 0.17 –

2.23 and the S/R ratios of 0.20– 0.59 represent lower intertidal mangroves; the S/BC ratios of 0 – 0.17 and the S/R ratios of 0 – 0.20 represent higher intertidal mangroves.

Therefore, the pollen biostratigraphy as used in this study allows correlation between horizons using the S/BC and S/R ratios of the surface samples within the eighteen vegetation plots that were calculated and used to characterise the mangrove position of the reconstructed past mangrove ecosystems. This information is applied to the dated samples (Figure 2b).

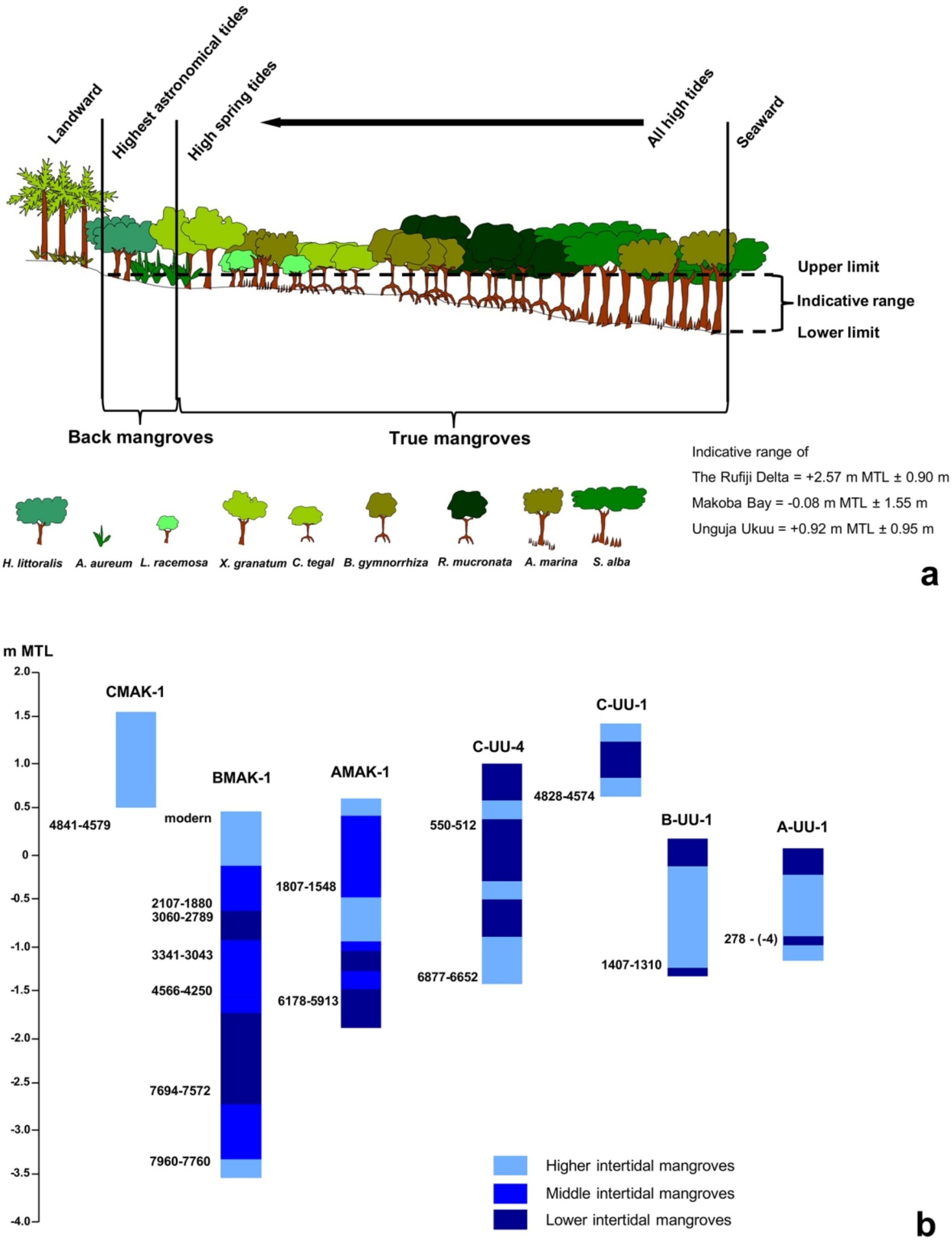

Figure 2. (a) Summary cross section showing typical mangrove zonation and response of this to RSL change in Tanzania developed from Watson's (1928) and Santisuk's (1983) inundation classes and field observations with its indicative range. Figure 2. (b) Biostratigraphy of core sites from Makoba Bay and Unguja Ukuu showing paleoenvironmental interpretation in terms of mangrove position

as lower, middle, higher inferred from the ratios of S/BC and S/R. All ages are in cal yr BP developed from Punwong et al. (2013a; 2013b).

Site	Core	Altitude (m MTL)	^{14}C yr BP	(2σ) Calibrated age range yr BP	Indicative meaning (m MTL) derived from full range of mangrove	RSL (m MTL) derived from full range of mangroves	Mangrove classes with altitudinal range (interpolated from Fig. 2b)	Indicative meaning (m MTL) derived from pollen ratios	RSL (m MTL) derived from pollen ratios	Decompaction correction	Sea-level tendency
Northern Rufiji Delta	ANR	1.61	392 ± 30	493-324							
	BNR	3.22	> 1950 A.D.								
		2.95	Failure to make graphite								
		2.34	4167 ± 30	4821-4453	2.57 ± 0.9	-0.23 ± 0.9	n/a	n/a	n/a	1.03	rise
		0.61	4751 ± 30	5579-5318	2.57 ± 0.9	-1.96 ± 0.9	n/a	n/a	n/a	0.51	rise
		-0.96	4931 ± 30	5711-5486	2.57 ± 0.9	-3.59 ± 0.9	n/a	n/a	n/a	0.02	rise
	CNR	2.33	> 1950 A.D.								
		1.06	884 ± 31	799-680	2.57 ± 0.9	-1.51 ± 0.9	n/a	n/a	n/a	0.62	fall
		-0.97	1292 ± 30	1264-1071	2.57 ± 0.9	-3.54 ± 0.9	n/a	n/a	n/a	0.02	fall
Makoba Bay	AMAK-1	-0.37*	1803 ± 36	1807-1548	-0.08 ± 1.55	-0.29 ± 1.55	Middle intertidal (-1.14)-0.57	-0.08 ± 0.86	-0.29 ± 0.86	0.46	rise
		-0.41	1615 ± 24	1525-1385							
		-1.55*	5290 ± 38	6178-5913	-0.08 ± 1.55	-1.47 ± 1.55	Lower intertidal (-1.61) - (-1.14)	-0.08 ± 0.23	-1.47 ± 0.23	0.11	fall
		-1.56	5078 ± 26	5892-5659							
	BMAK-1	0.39*	Modern		-0.08 ± 1.55	0.47 ± 1.55	Higher intertidal 0.57-1.51	-0.08 ± 0.47	0.47 ± 0.47	1.19	fall
		-0.54	3111 ± 24	3362-3167							
		-0.55*	2072 ± 35	2107-1880	-0.08 ± 1.55	-0.47 ± 1.55	Middle intertidal (-1.14)-0.57	-0.08 ± 0.86	-0.47 ± 0.86	0.91	fall
		-0.64	1543 + 25	1477-1305							
	BMAK-1	-1.16	1695 ± 50	1692-1408							
		-1.17*	3053 ± 37	3341-3043	-0.08 ± 1.55	-1.09 ± 1.55	Middle intertidal (-1.14)-0.57	-0.08 ± 0.86	-1.09 ± 0.86	0.73	rise
		-1.53	309 ± 23	443-289							
		-1.54*	4024 ± 40	4566-4250	-0.08 ± 1.55	-1.46 ± 1.55	Middle intertidal (-1.14)-0.57	-0.08 ± 0.86	-1.46 ± 0.86	0.61	rise
		-2.78	6878 ± 36	7735-7582							
		-2.79*	6847 ± 39	7694-7572	-0.08 ± 1.55	-2.7 ± 1.55	Low intertidal (-1.61) - (-1.14)	-0.08 ± 0.23	-2.70 ± 0.23	0.24	rise
		-3.52*	7092 ± 38	7960-7760	-0.08 ± 1.55	-3.46 ± 1.55	Middle intertidal (-1.14)-0.57	-0.08 ± 0.86	-3.46 ± 0.86	0.01	rise
		-3.54	7202 ± 30	8025-7872							
	CMAK-1	0.41	5200 ± 35	5991-5751							
		0.18	4239 ± 37	4841-4579							
		-0.24	3117 ± 35	3376-3162							
Unguja Ukuu	A-UU-1	-0.84	169 ± 22	278-(-4)	0.92 ± 0.95	-1.76 ± 0.95	Lower intertidal 0.01-0.21	0.92 ± 0.10	-1.76 ± 0.10	0.17	fall
	B-UU-1	-1.24	1534 ± 23	1407-1310	0.92 ± 0.95	-2.16 ± 0.95	Higher intertidal 0.21-1.91	0.92 ± 0.85	-2.16 ± 0.85	0.04	fall
	C-UU-1	0.57	4211 ± 25	4828-4574	0.92 ± 0.95	-0.35 ± 0.95	Lower intertidal 0.01-0.21	0.92 ± 0.10	-0.35 ± 0.10	0.09	rise
	C-UU-4	0.59	>1950 AD								
		0.39	560 ± 19	550-512	0.92 ± 0.95	-0.53 ± 0.95	Lower intertidal 0.01-0.21	0.92 ± 0.10	-0.53 ± 0.10	0.47	fall
		-1.29	5973 ± 36	6877-6652	0.92 ± 0.95	-2.21 ± 0.95	Higher intertidal 0.21-1.91	0.92 ± 0.85	-2.21 ± 0.85	0.02	rise

Table 1. List of radiocarbon dates derived from bulk samples and organic concentrates (marked with asterisks) from three sites. The calibrated ages are shown using the Shcal04 curve (McCormac et al., 2004) within the software

OxCal v4.10 Bronk-Ramsey (2009). RSL dates are also depicted using the indicative range derived from the upper and lower limits of modern mangrove vegetation and altitudinal error derived from the full range of mangroves for the Rufiji Delta and from the pollen ratios for Makoba and Unguja Ukuu.

Site	Plot	Altitude of plot MTL (m)	Altitudinal range of mangrove classes	S/BC ratio	Range of S/BC ratios	S/R ratio	Range of S/R ratios	Mangrove classes
Makoba Bay	AMAK-3	-1.61	(-1.61) - (-1.14)	22.8	5.4-22.8	2.29	0.37-2.29	Lower intertidal
	AMAK-2	-1.14		5.4		0.37		
	BMAK-3	-0.55	(-1.14) - 0.57	1.3	0.2-5.4	0.07	0.04-2.29	Middle intertidal
	BMAK-2	-0.05		0.2		0.04		
	BMAK-1	0.42		0.2		0.05		
	AMAK-1	0.57		0.2		0.09		
	CMAK-3	1.01	0.57-1.51	0	0-0.2	0	0-0.04	Higher intertidal
	CMAK-1	1.48		0		0		
	CMAK-2	1.51		0		0		
Unguja Ukuu	A-UU-3	0.01	0.01-0.21	2.23	0.17-2.23	0.59	0.20-0.59	Lower intertidal
	A-UU-1	0.07		0.88		0.20		
	B-UU-1	0.14		0.72		0.25		
	A-UU-2	0.21		0.17		0.33		
	B-UU-2	0.86	0.21-1.91	0.04	0-0.17	0.16	0-0.20	Higher intertidal
	B-UU-3	0.99		0.04		0.08		
	C-UU-1	1.35		0.02		0.05		
	C-UU-3	1.89		0		0		
	C-UU-2	1.91		0		0		

Table 2. Vegetation plots of Makoba Bay and Unguja Ukuu showing *Sonneratia*/(*Bruguiera*/*Ceriops*) (S/BC) and *Sonneratia*/*Rhizophora* (S/R) ratios of surface samples developed from Punwong et al. (2013a; 2013b). The ranges of ratios show the modern altitudinal range and are applied to infer the mangrove position of sediment in core as modern analogue of lower intertidal, middle intertidal, higher intertidal mangrove classes of the area with respect to altitude.

4.3. Chronology

Nine radiocarbon dates were obtained from the northern Rufiji Delta (Table 1). The radiocarbon dates indicate sedimentary hiatuses in the upper part of BNR between 46 cm (4821- 4453 cal yr BP) and 19 cm (modern deposition) and between 242 cm (799 - 680 cal yr BP) and 115 cm (modern deposition) in CNR. The dates from 19 cm (BNR) and 115 cm (CNR) are therefore rejected for RSL reconstruction. In ANR there is no pollen record between the depths of 115-150 cm. The date from 128 cm of ANR is therefore not applicable for RSL reconstruction.

Eleven radiocarbon dates on bulk sediment were obtained from Makoba Bay (Table 1). The radiocarbon dates from cores BMAK-1 (96 and 195 cm) and CMAK-1 (107 and 172 cm) demonstrate age reversals. Despite their potential, mangrove peats are notoriously difficult to date with age reversals common in radiocarbon dated sequences, and modern ages often being reported from samples collected several decimeters below the ground surface (e.g. Woodroffe and Horton, 2005). The likely causes of these dating problems are reworking of mangrove sediments through root penetration introducing younger carbon lower down in the sediment profile and mixing of older sediments within the upper unit (Punwong et al., 2013b; Woodroffe et al., 2015a). The nine dates obtained from the organic concentrates reveal a coherent chronology and logical age-depth relationship suggesting reliable dates for AMAK-1 and BMAK-1 (Woodroffe et al., 2015a). It would therefore appear that the source of contamination, such as the penetration of mangrove roots into the sediment matrix and bioturbation at depth, taking younger carbon down the core (Punwong et al., 2013b; Woodroffe et al., 2015a). We therefore reject the dates on bulk sediments from the cores AMAK-1, BMAK-1 and the two reversed dates (at 107 and 172 cm) of CMAK-1 and use the organic concentrate dates for RSL reconstruction. In CMAK-1, there is no pollen record between the depths of 105-174 cm. The date from 130 cm of CMAK-1 is therefore not used for RSL reconstruction.

Six radiocarbon dates were obtained from Unguja Ukuu (Table 1). The radiocarbon date from core C-UU-4 (42 cm) records modern age deposition, probably due to contamination (as described above) and this date is therefore rejected for RSL reconstruction.

4.4. RSL and compaction

In order to reconstruct RSL changes using mangrove sediments, the upper and lower limits of mangrove vegetation with reference to the mean tide level (MTL) is used in order to establish an indicative range for mangroves following the approach of Woodroffe et al. (2015b) and Hijma et al. (2015). The indicative ranges for mangrove sediments are +2.57 m MTL ± 0.90 m in the northern Rufiji Delta, -0.08 m MTL ± 1.55 m in Makoba Bay and +0.92 m MTL ± 0.95 m in Unguja Ukuu (Table 1; Figure 2a). To reduce the vertical error, where detailed contemporary vegetation pollen studies were undertaken in Makoba Bay and Unguja Ukuu, we use the pollen ratios of S/BC and S/R to calculate the altitudinal ranges of RSL (as described in 4.2 Pollen analysis and vegetation survey). For example, the radiocarbon date of 1807-1548 cal yr BP occurs at the depth of 0.94 m in AMAK-1 from Makoba Bay; using the pollen ratios of S/BC and S/R derived from contemporary pollen studies, it is possible that the vegetation at the depth of 0.94 m represent a middle-intertidal mangrove association (Figure 2b). If this is related to MTL using the vegetation plot data, the vertical error of the date becomes ± 0.86 m derived from the vertical range of the middle-intertidal mangrove that is -1.14 m MTL and +0.57 m MTL (Table 1 and 2). The indicative range derived from the upper and lower limit of mangrove vegetation in Makoba Bay is -0.08 m MTL and therefore the indicative range of RSL from the date is -0.08 m MTL ± 0.86 m (Table 1).

Sediments are susceptible to post-depositional compaction (Bird et al., 2004; Horton and Shennan, 2009). A compaction factor for the mangrove sediment was estimated by comparing the dry bulk density of a compacted sample with the modern sediment sample and found to range from 17-31% (Bird et al., 2004). As this geotechnical technique is beyond the scope of study, the worst-case compaction scenario of Bird et al. (2004) of 31% was adopted for the decompaction correction below the depth dated (Table 1). For example, at the depth 1.07 m of BNR that is 4.50 m in total length, the compaction of mangrove sediment below this depth would be 1.0633 m (31% of 4.50 – 1.07 m) and would be applied to the vertical error in an upward direction. This approach has also been used in mangrove sea-level reconstructions from mangrove deposits in the Seychelles (Woodroffe et al., 2015b).

Vertical errors also include compaction caused by the coring equipment (± 0.04 m) (Woodroffe, 2006), levelling errors (± 0.051 m), and the vertical range of the radiocarbon date (± 0.005 m). Sea-level tendency for each RSL reconstruction is determined (Table 1) by using a combination of stratigraphy and the trend of mangrove pollen-based interpretation from each coring site (Figure 2b).

5. Interpretation and discussion

Age-depth plots of the cores indicated that the basal age for each core ranged from ~ 7900 cal yr BP (BMAK-1 of Makoba Bay) to ~100 cal yr BP (A-UU-1 of Unguja Ukuu). A comparison of sedimentation rates showed great variation between the Rufiji Delta and Zanzibar sites (Figure 3). Although the chronology is problematic, it would appear that the sedimentation rate of between 2.1-10.9 mm cal yr^{-1} for the Rufiji Delta was considerably higher than that for

Makoba Bay and Unguja Ukuu (0.3-6.6 mm cal yr^{-1}). This enhanced sedimentation rate is probably due to the nature of the deltaic mangrove setting with river discharge transporting sediment from the wider Rufiji catchment to be deposited into the Rufiji Delta (Semesi, 1992; Fisher et al., 1994). The variation in sedimentation rates results in different altitudinal ranges of the mangrove areas at the three locations with freshwater input, sediment supply and progradation having significantly more effect in the Rufiji Delta than at the Zanzibar sites. However, given site-specific responses of mangroves relative to sea level, when sites are combined, they provide regional RSL reconstruction.

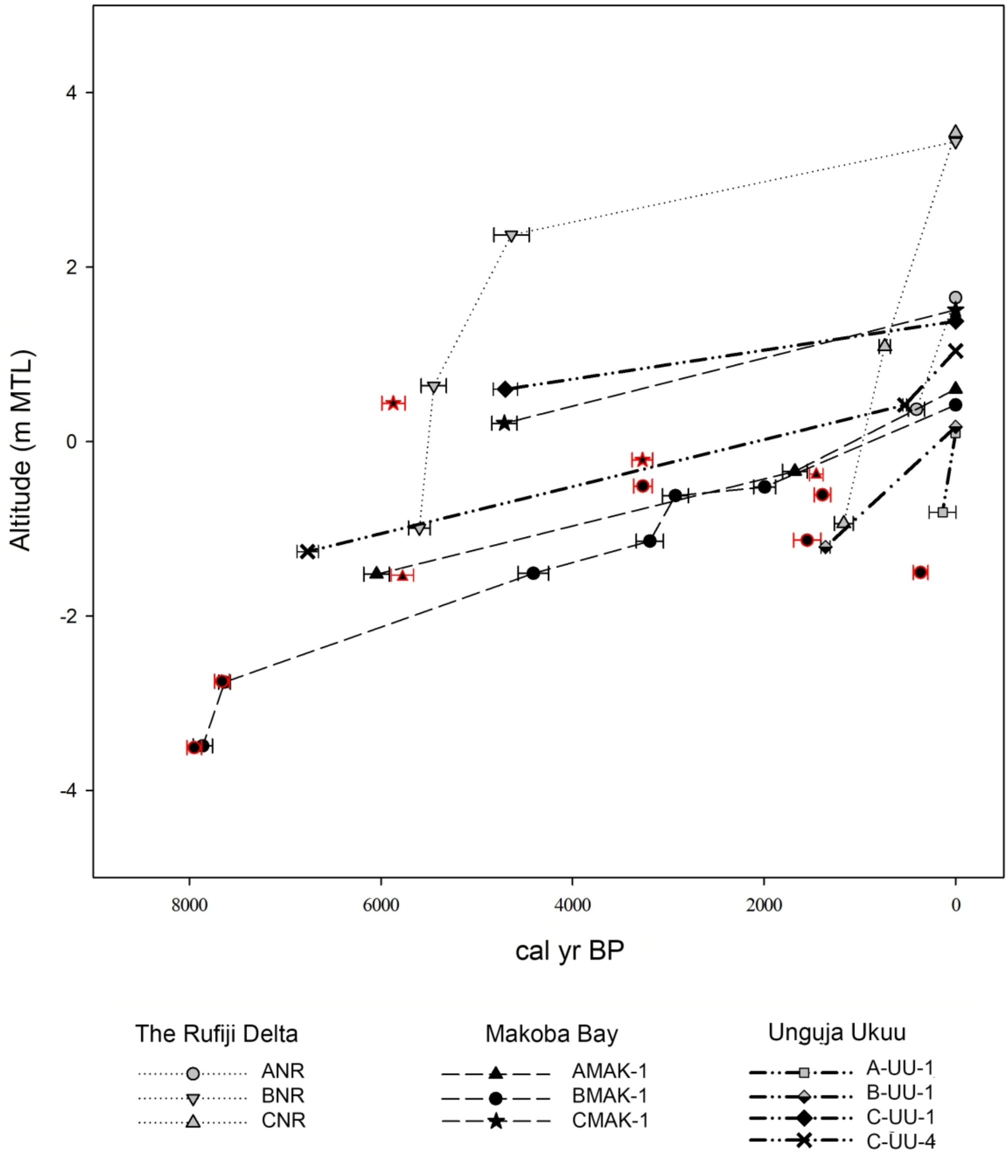

Figure 3. Comparative age-depth plots including rejected dates (in red edge) for the cores analysed in this study. Comparative age-depth (altitude) models for the cores analysed in this study. The top value against the zero origin (cal yr BP) on all such graphs except BMAK-1 does not necessarily represent present day deposition because of potential surface erosion.

5.1. Holocene mangrove dynamics

Combined palaeoecological records from the three locations provide a new palaeoenvironmental sea-level synthesis from Tanzania where relatively little is known about the Holocene mangrove dynamics. The records reveal that mangrove ecosystems have not remained stable as they responded to wide scale environmental changes and there are some site-specific responses to environmental shifts. The results further our understanding of how mangrove ecosystems reflect environmental variables, and shifts in these, that could help assess resilience of coastal ecosystems under future climatic scenarios, particularly sea-level rise (Ellison, 2015).

Early to mid Holocene

The pollen record of BMAK-1 indicates that mangroves have been present at Makoba Bay at -3.6 m below MTL since at least ~7900 cal yr BP (Figure 2b). The ratios of S/BC and S/R suggest that the central core (BMAK-1) location was colonised by higher intertidal mangroves (Figures 1f, 2b; Table 2) suggesting an early Holocene RSL rise. A higher RSL rise was then recorded after this period for a relatively short duration until ~7600 cal yr BP, as mangroves migrated landward and this area supported middle intertidal mangrove taxa. RSL 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 taxa at these two coring locations to migrate further landwards and allowed mangroves to establish on the headland of Unguja Ukuu at -1.3 m MTL as recorded ~6800 cal yr BP in C-UU-4. After this time, higher intertidal mangroves recorded in C-UU-4 were replaced by lower intertidal mangrove taxa; thus contributing to a body of evidence indicating that RSL continued to rise during the mid Holocene (Camoin et al., 1997; 2004; Zinke et al., 2003; Norström et al., 2012). It should be noted that the pollen records from both sites in Zanzibar reveals a similar age determination of 5600 cal yr BP and a similar pollen record, lending support to the chronological and sea-level interpretation from BNR in the northern Rufiji Delta (Punwong et al., 2012). The predominance of *R. mucronata* pollen suggests that BNR was located in a low intertidal environment, a further indication of a higher sea level relative to the present day. A mid Holocene RSL rise possibly attained a higher altitude after 4700 cal yr BP resulting in higher intertidal mangroves establishment at 0.5 m above MTL in CMAK-1 and higher intertidal mangrove establishment at 0.6 m MTL in C-UU-1. This mid Holocene RSL rise occurred until prior to ~4400 cal yr BP, when RSL started to fall as indicated by the transition from lower intertidal to middle intertidal mangroves in BMAK-1.

Mid Holocene to the present day

After ~4400 cal yr BP mangrove ecosystem character varied between the sites reflecting different RSL changes. A lower RSL is recorded in Makoba Bay from ~4400 cal yr BP, as indicated by the change in mangrove composition from lower to middle intertidal mangroves in BMAK-1 until ~3200 cal yr BP. This period coincides with a regionally arid phase recorded across East Africa commencing around 4500–4100 cal yr BP (Hassan, 1997; Bonnefille and Chalie, 2000; Thompson et al., 2002; Marchant and Hooghiemstra, 2004; Kiage and Liu, 2006; Rijsdijk et al., 2011; de Boer et al., 2015). After 3200 cal yr BP, and prior to 2900 cal yr BP, a RSL rise occurred indicative of a change from middle to lower intertidal mangroves. Mangrove composition subsequently changed to middle intertidal mangroves in AMAK-1 and BMAK-1 (Figure 2b) suggesting a lower RSL as mangroves retreated seaward until the late Holocene ~2000-1700 cal yr BP. However, a sea-level rise is recorded at Unguja Ukuu as lower intertidal mangroves occupied C-UU-1 and C-UU-4 after the mid Holocene until ~500 cal yr BP. The apparent discrepancy in RSL between these two sites at Unguja after 4400 to 1700 cal yr BP is probably due to local processes including mangrove composition response to sediment input and/or erosion at the sites, resulting in localised RSL changes.

The late Holocene RSL fall is recorded at all three sites. In Makoba Bay, RSL fell until the present day, as suggested by the change of middle intertidal mangroves to higher intertidal mangroves in AMAK-1 and BMAK-1. At Unguja Ukuu, lower intertidal mangroves changed to higher intertidal mangroves after 1400 cal yr BP in B-UU-1. RSL probably continued falling in Unguja Ukuu, as represented by the change from lower intertidal mangroves to higher intertidal mangroves after ~500 cal yr BP in C-UU-4, and the presence of more intertidal mangroves after ~100 cal yr BP in A-UU-1. In the Rufiji Delta, a reduction in mangrove pollen and increase in back-mangrove and terrestrial grasses in the landward site (CNR) after 1200 cal yr BP resulted in a shift of mangroves seaward. RSL then fluctuated, as suggested by changes in the proportions of mangroves, back-mangrove and terrestrial grasses until prior to 700 cal yr BP. After 700 cal yr BP, RSL started to fall, as recorded by a gradual change from mangroves characterised by *R. mucronata* to terrestrial vegetation, and a replacement of mangroves by recent herbaceous taxa. However, changes from higher intertidal mangroves to lower intertidal mangroves in A-UU-1, B-UU-1 and C-UU4 at Unguja Ukuu, corresponding to an increase in *A. marina* at the top of ANR, are likely to represent a signal of sea-level rise during the last few hundred years.

5.2. Sea-level reconstruction

The pollen evidence from the Rufiji Delta, Makoba Bay and Unguja Ukuu can be used to reconstruct the Holocene RSL from Tanzania using the upper and lower limits of mangrove vegetation and shift in recognisable salinity tolerance zones of the mangrove ecosystem. The RSL derived from the pollen ratios within the vegetation plots can refine vertical errors (Figure 4). Regardless of site-specific characteristics, it should be noted that all three sites provide evidence for a phase of early-mid Holocene RSL rise and late Holocene RSL fluctuation. The composite RSL curve shows that RSL rise occurred from around 7900 cal yr BP. It is possible that RSL rose and was potentially higher than present at ~4700-4600 cal yr BP. However, when the sites are compared (Figure 4), variations in the rate of sea level rise are noted. In the northern Rufiji Delta, the higher sedimentation rates are probably due to the large freshwater and terrestrial inputs to the system.

The general trend of the early to mid Holocene RSL rise (Figure 4) appears to be in agreement with RSL trends from other locations such as the mainland coast and offshore islands in the Southwest Indian Ocean (Colonna et al., 1996; Camoin et al., 1997; 2004; Zinke et al., 2000; Compton, 2001; Ramsay and Cooper, 2002; Zinke et al., 2003).

The proposed higher than present sea level at around 4700-4600 cal yr BP recorded in Tanzania indicates a similar trend to that recorded from South Africa (Compton, 2001; Ramsay and Cooper, 2002) (Figure 4). The mid Holocene RSL rise in Tanzania is also comparable to a marine transgression phase in

Mozambique (Norström et al., 2012) where a highstand is recorded ~6600-6300 cal yr BP. The mid Holocene transgression is well represented from the Southern Hemisphere in far-field locations (Isla, 1989) relating to three possible causes including meltwater from late glacial ice sheets (Lambeck and Nakada, 1990; Fleming et al., 1998) and/or the Holocene melting of ice sheets from Antarctica, Greenland and mountain glaciers during the early Holocene until 5000 cal yr BP (Milne et al., 2005).

Evidence from Mauritius, Mayotte and Réunion Island (Camoin et al., 1997; 2004; Zinke et al., 2003) suggest no mid Holocene highstand occurred at these locations. The differences between the records from the islands and Tanzania may result from hydro-isostatic influences relating to the differences in the geographical locations of the Tanzanian coast and the islands (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, the highstand recorded from South Africa is likely to be higher than the potential maximum transgression at ~4700 cal yr BP and 4600 cal yr BP in Tanzania (Compton, 2001; Ramsay and Cooper, 2002). In addition to eustatic changes, a combination of various factors such as hydro-isostasy, thermal expansion of sea water caused by warmer ocean temperatures in subtropical latitudes (Ramsay, 1995, Woodroffe and Horton, 2005), and the steric expansion of sea water (Ramsay, 1995; Compton, 2001) may also be considered as factors enhancing the highstand altitude in South Africa.

RSL fell from 4600 cal yr BP to 4400 cal yr BP. After 4400 cal yr BP, RSL slightly rose until ~2000 cal yr BP. The RSL record at this time from

Tanzania correlates well with records from South Africa (Ramsay and Cooper, 2002) and also corresponds with a possible marine transgression with a highstand from Macassa Bay (Mozambique) between 4000 - 1100 cal yr BP (Norström et al., 2012). The pollen records from Makoba Bay and C-UU-1 and C-UU-4 of Unguja Ukuu indicate that mangrove development continued after the mid Holocene RSL rise indicating a sustained higher level that did not fall until the late Holocene ~2000 cal yr BP. This may have allowed suitable conditions for mangroves to establish at A-UU-1 and B-UU-1 and may correspond to the progradation of beach plains that is recorded in Zanzibar (Arthurton, 2003).

The late Holocene RSL record after 2000 cal yr BP until 100 cal yr BP correlates well with the RSL records from South Africa (Compton, 2001; Ramsay and Cooper, 2002) and Mozambique (Norström et al., 2012) (Figure 4). A lower sea level occurred in Tanzania until 1400 - 1200 cal yr BP; this RSL fall is also recorded in northeastern South Africa ~1400 cal yr BP to the present (Ramsay and Cooper, 2002). We acknowledged that potential sea-level fall would correspond to climatically cold phases and sea-level rise to warm phases, as a result of the glacial eustasy (Oerlemans, 2001). Changes in rainfall can also cause local eustatic sea-level changes (Mörner, 1996). However, easternmost East Africa experienced drought during the Medieval Warm Period (MWP) (900 - 700 cal yr BP) and wet conditions during the Little Ice Age (LIA) (700 - 100 cal yr BP) (Verchuren et al., 2000). These phases are contrast with our records of sea-level transgression after 1200 - 500 cal yr BP and sea-level regression from 500 - 100 cal yr BP. Archaeological sites in Unguja Ukuu indicate that RSL was approximately -0.5 m below the present level between ~1300 - 1000 cal yr BP (Mörner, 1992). This is in good agreement with the reconstruction from the three sites studied suggesting RSL did not attain present sea level between 1400-1200 cal yr BP (Figure 4).

A further RSL rise occurred after 1200 to ~700 - 500 cal yr BP and it is likely that RSL was below the present sea level. This concurs with records from ruins in southeastern Tanzania (Kilwa) suggesting RSL was about -1 m below the present level between 800- 600 cal yr BP (Mörner, 1992). After this period, RSL fell until ~100 cal yr BP when sea level was lower than the present day. This is in good agreement with a study of raised terraces along the Kenyan coast indicating that RSL started to fall 500 years ago (Åse, 1978; 1981). In contrast, data from Mozambique (Norström et al., 2012) and southern Langebaan Lagoon in South Africa (Compton, 2001) show somewhat conflicting results from the Tanzanian data indicating RSL fell after 1200 cal yr BP. After 100 cal yr BP, RSL rose until the present day corresponding to the onset of recent sea-level rise from the 19th century (Stocker et al., 2013) as recorded in Kenya between 1986-2002 (Kibue, 2006). However, a recent sea-level fall was observed in Zanzibar between 1985-2001 (Permanent Service for Mean Sea Level) before rising trend was observed to the present day. In addition, it should be noted that Makoba and Unguja Ukuu which all are on the west cost of Unguja Island and separated by 40 km shows different RSL especially during the last 2000 years probably due to local processes, such as changes in sediment input and/or erosion at the sites.

Difficulties encountered in dating suggest additional records and chronological control using dating of pollen concentrates is required to determine a high-resolution record of mid Holocene sea level and environmental changes. Although the evidence from Tanzania demonstrates the site-specific nature of responses of mangroves to RSL changes, it does provide a valuable contribution to patterns of Holocene RSL from "far-field" locations. There is great potential to scale up the type of investigation presented here to other coastal mangrove sites across East Africa, as well as offshore islands. Such an extension to this study would provide an unprecedented regional record of environmental and sea-level changes from a far-field region and allow us to distinguish large and meso-scale regional signals against site-specific responses across East Africa.

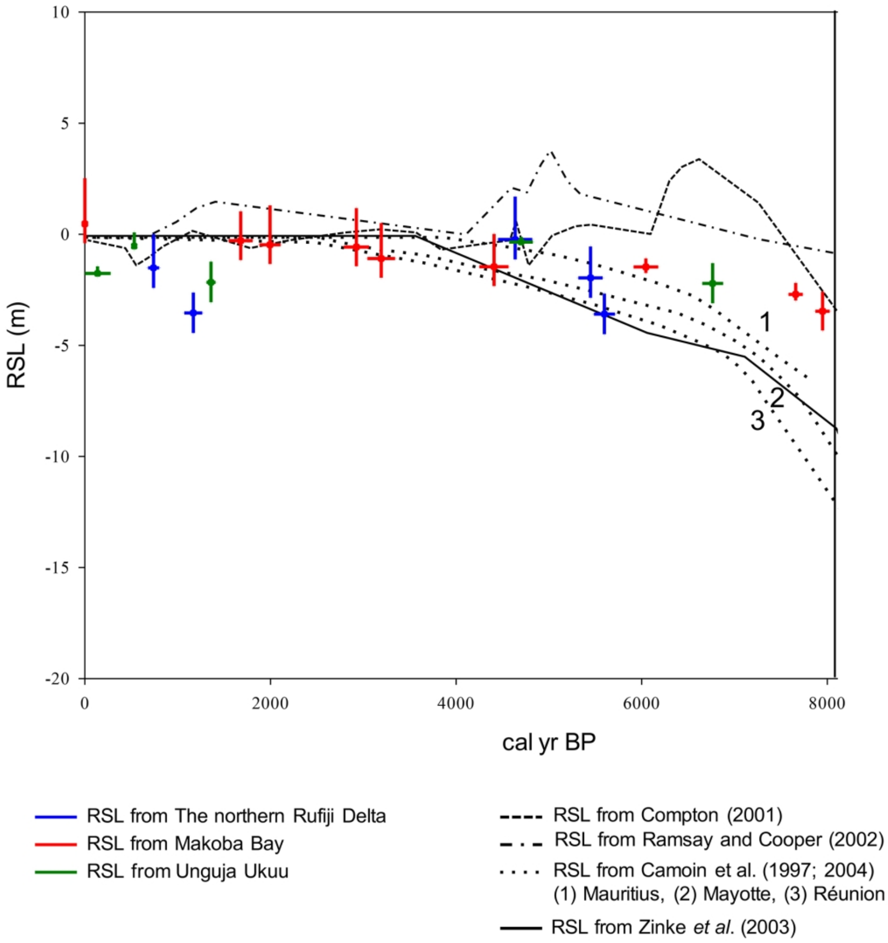

Figure 4. RSL reconstructions from this study along the Tanzanian coast plotted alongside RSL curves from the southwest Indian Ocean region

6. Conclusions

A reconstruction of Holocene RSL has been derived for coastal Tanzania from mangrove ecosystem changes from three sites. The ratios of *Sonneratia*:(*Bruguiera*/*Ceriops*) and *Sonneratia*:*Rhizophora* derived from the pollen-vegetation-altitude realtionships can be used to interpret mangrove dynamics and refine the vertical errors of RSL changes derived from mangrove sediments. Although the results in part demonstrate the site-specific shifts in the upper and lower limits of mangroves relative to sea level, due to responses of sediment input and/or erosion at the three sites, they do provide evidence for Holocene RSL fluctuations coherent across coastal Tanzania. An early-mid to mid Holocene RSL rise occurred from ~ 7900 cal yr BP prior to ~4700-4600 cal yr BP when RSL was potentially higher than the present. This period is followed by a lower RSL until 4400 cal yr BP when RSL rose until ~2000 cal yr BP. Subsequently, late Holocene RSL fluctuations were characterised by RSL rise recorded at ~700 - 500 cal yr BP before falling below the present level at ~100 cal yr BP. There is evidence of a more recent RSL rise during the last centuries. The Tanzanian RSL curve indicates a similar trend to the mid Holocene RSL record from South Africa, probably related to similar hydro-isostatic conditions representing the apparent Holocene highstand at continental margins due to the effects of continental levering. The RSL fall recorded during the last 500 years is in good agreement with the records from the Kenyan coast, although data from Mozambique and the Langebaan Lagoon in South Africa indicate RSL fell after 1200 cal yr BP. The difficulties of developing a reliable chronology from mangrove environments have previously precluded extensive use of these sediment archives for reconstructing RSL changes. Organic concentrate dating applied on some of the samples presented here can provide a reliable chronology allowing these far-field locations to be fully investigated and used as a proxy for reconstructing eustatic sea-level changes. Site-specific signals of RSL change, mangrove response to this and the need to further constrain the pollen-vegetation-environmental relationships all emphasise the need for further research along the East African coast, as well as other "far-field" locations, so that the full potential of the mangrove sedimentary sea-level archive can be fully realised.

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References

Admiralty Tide Tables, 2014. NP203 Admiralty Tide Tables (ATT) Volume 3, Indian Ocean and South China Sea (including Tidal Stream Tables). Hydrographer to the Navy. Admiralty Hydrography Department. 365 pp.

Arthurton, R.S., Brampton, A.H., Kaaya, C.Z., Mohamed, S.K., 1999. Late Quaternary coastal stratigraphy on a platform-fringed tropical coast- a case study from Zanzibar, Tanzania. Journal of Coastal Research 15, 635-644.

Arthurton, R., 2003. The fringing reef coasts of eastern Africa-present processes in their long-term context. Western Indian Ocean Journal Marine Science 2 (1), 1-13.

Åse, L.E., 1978. Preliminary Report on Studies of Shore Displacement at the Southern Coast of Kenya. Geografiska Annaler, Series A, Physical Geography, 60, 3/4, 209-221.

Åse, L.E., 1981. Studies of Shores and Shore Displacement on the Southern Coast of Kenya. Especially in the Kilifi District. Geografiska Annaler, Series A, Physical Geography, 63, 3/4, 303-310.

Baker, R.G., Haworth, R., Flood, P., 2001. Inter-tidal fixed indicators of former Holocene sea levels in Australia: a summary of sites and a review of methods and models. Quaternary International 83–85, 257–273.

Banerjee, P.K., 2000. Holocene and Late Pleistocene relative sea level fluctuations along the east coast of India. Marine Geology 167, 243–260.

Bird, M. I., L. K. Fifield, S. Chua, Goh, B., 2004. Calculating sediment compaction for radiocarbon dating of intertidal sediments. Radiocarbon 46(1), 421–435.

Bird, M.I., Fifield, L.K., Teh, T.S., Chang, C.H., Shirlaw, N., Lambeck, K., 2007. An inflection in the rate of early-mid Holocene eustatic sea-level rise: A new sea-level curve from Singapore. Estuarine, Coastal and Shelf Science 71, 523–536.

Blasco, F., Saenger, P., Janodet, E. 1996. Mangroves as indicators of coastal change. Catena 27, 167–178.

Bonnefille, R., Chalie, F., 2000. Pollen-inferred precipitation time-series from equatorial mountains, Africa, the last 40 kyr BP. Global Planet Change 26, 25–50.

Bronk-Ramsey, C., 2009. OxCal Program v4.10. Oxford Radiocarbon Accelerator Unit, Oxford.

Camoin, G.F., Colonna, M., Montaggioni, L.F., Casanova, J., Faure, G., Thomassin, B.A., 1997. Holocene sea level changes and reef development in the southwestern Indian Ocean. Coral Reefs 16 (4), 247–259.

Camoin, G.F., Montaggioni, L.F., Braithwaite, C.J.R., 2004. Late glacial to post glacial sea levels in the Western Indian Ocean. Marine Geology 206, 119–146.

Clark, J.A., Farrell, W.E., Peltier, W.R., 1978. Global changes in post glacial sea level: a numerical calculation. Quaternary Research 9, 265–287.

Cohen, M.C.L., Behling, H., Lara, R.J., 2005. Amazonian mangrove dynamics during the last millennium: The relative sea-level and the Little Ice Age. Review of Palaeobotany and Palynology 136, 93-108.

Colonna, M., Casanova, J., Dullo, W.C., Camoin, G., 1997. Sea-level changes and $\delta^{18}O$ record for the past 34,000 yr from Mayotte Reef, Indian Ocean. Oceanographic Literature Review 44(7), 693–693.

Compton, J.S., 2001. Holocene sea-level fluctuations inferred from the evolution of depositional environments of the southern Langebaan Lagoon salt marsh, South Africa. The Holocene 11(4), 395–405.

Davis, O.K., 1984. Pollen frequencies reflect vegetation patterns in a Great Basin (U.S.A.) mountain range. Review of Palaeobotany and Palynology 40, 295–315.

de Boer, E.J., Vélez, M.I., Rijsdijk, K.F., de Louw, P.G., Vernimmen, T.J., Visser, P.M., Tjallingii, R. and Hooghiemstra, H., 2015. A deadly cocktail: How a drought around 4200 cal. yr BP caused mass mortality events at the infamous 'dodo swamp' in Mauritius. The Holocene, 25(5), 758–771.

Ellison, A.M., Farnsworth, E.J., 2001. Mangrove communities. In: Bertness, M.D., Gaines, S.D., Hay, M.E. (Eds.). Marine Community Ecology. Sinauer Associates, Sunderland, MA. pp. 423–442.

Ellison, J.C., 1989. Pollen analysis of mangrove sediments as a sea level indicator: assessment from Tongatapu, Tonga. Palaeogeography, Palaeoclimatology, Palaeoecology 74: 327–341.

Ellison, J.C., 2005. Holocene palynology and sea-level change in two estuaries in Southern Irian Jaya. Palaeogeography and Palaeoclimatology. 220, 291–309.

Ellison, J.C., 2008. Long-term retrospection on mangrove development using sediment cores and pollen analysis: A review. Aquatic Botany 89, 93–104.

Ellison, J.C., 2015. Vulnerability assessment of mangroves to climate change and sea-level rise impacts. Wetlands Ecology and Management, 23(2), 115–137.

Engelhart, S.E., Horton, B.P., Roberts, D.H., Bryant, C.L., Corbett, D.R., 2007. Mangrove pollen of Indonesia and its suitability as a sea level indicator. Marine Geology 242, 65-81.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep- ocean circulation. Nature 342, 639–642.

Fisher, P. R., Dyer, K., Semesi, A. 1994. Rufiji Delta hydrodynamics research program, Final report: Characteristic circulation and sedimentation in the Rufiji delta, Tanzania. Frontier-Tanzania Technical report No. 13. The Society for Environment Exploration. U.K.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far-and intermediate-field sites. Earth and Planetary Science Letters 163, 327–342.

Francis, J. 1992. Physical processes in the Rufiji delta and their possible implications on the mangrove ecosystem. Hydrobiologia 247, 173–179.

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. Quaternary Science Reviews 19, 189–211.

Gehrels, R., Long, A., 2008. Sea level is not level: the case for a new approach to predicting UK sea-level rise. Geography 93(1), 11–16.

Gilman, E.L., Ellison, J., Duke, N.C. and Field, C., 2008. Threats to mangroves from climate change and adaptation options: A review. Aquatic Botany 89(2), 237–250.

Goudie, A. S., 1996. Climate: past and present. In: Adams, W.A., Goudie, A.S., Orme, A.R. (eds) The physical geography of Africa. Oxford University Press, New York, pp 34–59

Hait, A. K., Behling, H., 2009. Holocene mangrove and coastal environmental changes in the western Ganga–Brahmaputra Delta, India. Vegetation History and Archaeobotany 18, 159–169.

Hanebuth, T., Stattegger, K., Grootes, P.M., 2000. Rapid Flooding of the Sunda Shelf: A Late-Glacial Sea-Level Record. Science 288, 1033–1035.

Hassan, F.A., 1997. Holocene Palaeoclimates of Africa. African Archaeological Review 14(4), 213–230.

Hijma, M., Engelhart, S.E., Törnqvist, T.E., Horton, B.P., Hu, P. and Hill, D.F., 2015. A protocol for a geological sea-level database. Handbook of Sea-Level Research, edited by: Shennan, I., Long, AJ, and Horton, BP, Wiley Blackwell, pp. 536–553.

Horton, B.P., Benjamin, P., Gibbard, L.G., Milne, M., Morley, R.J., Purintavaragul, C. and Stargardt, J.M., 2005. Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, Southeast Asia. The Holocene 15, 1199–1213.

Isla, F.I., 1989. Holocene sea-level fluctuation in the Southern Hemisphere. Quaternary Science Reviews 8, 359–368.

Jaritz, W., Ruder, J., B, Schlenker, B., 1977. Das Quartar im Kustengebiet von Mocambique und seine Schwermineralfuhrung. Geologisches Jahrbuch, B, 26: 3–93.

Katupotha, J., Fujiwara, K., 1988. Holocene sea level change on the southwest and south coasts of Sri Lanka. Palaeogeography, Palaeoclimatology, Palaeoecology 68, 189–203.

Kiage, L.M., Liu, K., 2006. Late Quaternary paleoenvironmental changes in East Africa: areview of multiproxy evidence from palynology, lake sediments, and associated records. Progress in Physical Geography 30 (5), 633–658.

Kibue, A. M., 2006. Sea level measurement and analysis in the Western Indian Ocean. National Report, Kenya.

Knopp, S., Mohammed, K.A., Simba Khamis, I., Mgeni, A.F., Stothard, J.R., Rollinson, D., Marti, H., Utzinger, J., 2008. Spatial distribution of soil-transmitted helminths, including *Strongyloides stercoralis*, among children in Zanzibar. Geospatial Health 3 (1), 47–56.

Lambeck, K., Nakada, M., 1990. Late Pleistocene and Holocene sea-level change along the Australian coast. Palaeogeography, Palaeoclimatology, Palaeoecology 89, 143–176.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. P Natl. Acad. Sci. U. S. A. 111, 15296–15303.

Larcombe, P., Carter, R.M., Dye, J., Gagan, M.K., Johnson, D.P., 1995. New evidence for episodic post-glacial sea-level rise, central Great Barrier Reef, Australia. Marine Geology 127, 1–44.

Lewis, S.E., Sloss, C.R., Murray-Wallace, C.V., Woodroffe, C.D. and Smithers, S.G., 2013. Post-glacial sea-level changes around the Australian margin: a review. Quaternary Science Reviews, 74, pp. 115–138.

Machiwa, J.F., Hallberg, R.O., 1995. Flora and crabs in a mangrove forest partly distorted by human activities. Zanzibar Ambio 24 (7–8), 492–496.

Mangora, M.M., Shalli, M.S., Semesi, I.S., Njana, M.A., Mwainunu, E.J., Otieno, J.E., Ntibasubile, E., Mallya, H.C., Mukama, K., Wambura, M. and Chamuya, N.A., 2016, January. Designing a mangrove research and demonstration forest in the rufiji delta, Tanzania. In Proceedings of the 5th Interagency Conference on Research in the Watersheds, pp. 190-192. US Department of Agriculture Forest Service, Southern Research Station.

Marchant, R.A., Hooghiemstra, H., 2004. Rapid environmental change in Africa and South American tropics around 4000 years before present. Earth Science Reviews 66, 217–260.

Masalu, D.C.P., 2003. Challenges of coastal area management in coastal developing countries—lessons from the proposed Rufiji Delta prawn farming project, Tanzania. Ocean Coastal Management 46, 175–188.

McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere Calibration, 0–11.0 cal kyr BP. Radiocarbon 46(3), 1087–1092.

McIvor, A.L., Spencer, T., Möller, I. and Spalding. M., 2013. The response of mangrove soil surface elevation to sea level rise. Natural Coastal Protection Series: Report 3. Cambridge Coastal Research Unit Working Paper 42. The Nature Conservancy and Wetlands International. 59 pp.

Milne, G., Long, A., Bassett, S., 2005. Modelling Holocene relative sea-level observations from the Caribbean and South America. Quaternary Science Reviews 24, 1183–1202.

Milne, G.A., Mitrovica, J.X., 2008. Searching for eustasy in deglacial sea-level histories. Quaternary Science Reviews 27, 2292–2302.

Mitrovica, J.X., Peltier, W.R., 1991. On postglacial geoid subsidence over the equatorial oceans. Journal of Geophysical Research 96, 20053–20071.

Mitrovica, J.X., Milne, G.A., 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. Quaternary Science Reviews 21, 2179–2190.

Mörner, N., 1992. Ocean circulation, sea level changes and east African coastal settlements. In Sinclair, P.J.J., and Juma, A., (Eds.). Urban Origins in Eastern Africa: Proceedings of the 1991 Workshop in Zanzibar. Stockholm: Swedish Central Board of National Antiquities, pp. 256–266.

Mörner, N.A., 1996. Global change and interaction of earth rotation, ocean circulation and paleoclimate. Anais da Academia Brasileira de Ciências, 68, 77-94.

Mwandya, A.W., Gullstrom, M., Andersson, M.H., Ohman, M.C., Mgaya, Y.D., Bryceson, I., 2010. Spatial and seasonal variations of fish assemblages in mangrove creek systems in Zanzibar (Tanzania). Estuarine, Coastal and Shelf Science 89(4), 277–286.

Nicholson, S.E., 2001. Climatic and environmental change in Africa during the last two centuries. Climate research, 17(2), 123-144.

Nshubemuki, L., 1993. Forestry resources in Tanzania's wetlands: concepts and potentials. Wetlands of Tanzania, 37–48.

Norström, E., Risberg, J., Gröndahl, H., Holmgren, K., Snowball, I., Mugabe, J.A. Sitoe, S.R, 2012. Coastal Paleo-environment and Sea-level Change at Macassa Bay, Southern Mozambique, Since c 6600 Cal BP. Quaternary International 260, 153–163.

Oerlemans, J., 2001. Glaciers and climate change. Library of Congress Cataloging-in-Publication Data.

Pirazzoli, P. A., Montaggioni, L. F., Salvat, B., & Faure, G., 1988. Late Holocene sea level indicators from twelve atolls in the central and eastern Tuamotus (Pacific Ocean). Coral Reefs, 7(2), 57–68.

Pirazzoli, P.A., 1991: World Atlas of Holocene sea level changes. Elsevier, Amsterdam, 300 pp.

Prendergast, M.E., Rouby, H., Punnwong, P., Marchant, R., Crowther, A., Kourampas, N., Shipton, C., Walsh, M., Lambeck, K. and Boivin, N.L., 2016.

Continental island formation and the archaeology of defaunation on Zanzibar, eastern Africa. PLoS ONE 11(2): e0149565.

Punwong, P., Marchant, R., Selby, K., 2012. Holocene mangrove dynamics and environmental change in the Rufiji Delta, Tanzania. Vegetation History and Archaeobotany 22(5), 381–396.

Punwong, P., Marchant, R., Selby, K., 2013a. Holocene mangrove dynamics from Unguja Ukuu, Zanzibar. Quaternary International 298, 4–19.

Punwong, P., Marchant, R., Selby, K., 2013b. Holocene mangrove dynamics in Makoba Bay, Zanzibar. Palaeogeography Palaeoclimatology Palaeoecology 379–380, 54–67.

Ramsay, P.J, 1995. 9000 years of sea-level change along the southern African coastline. Quaternary International 31, 71–75.

Ramsay, P.J., Cooper, J. A. G., 2002. Late Quaternary Sea-Level Change in South Africa. Quaternary Research 57, 82–90.

Richmond, M. D., Wilson, J. D. K., Mgaya, Y. D., Le Vay, L. 2002. An analysis of smallholder opportunities in fisheries, coastal and related enterprises in the floodplain and delta areas of the Rufiji River, Tanzania. Rufiji Environment Management Project Technical report (25), 89 pp.

Rijsdijk, K.F., Zinke, J., de Loux, P.G.B., Hume, J.P., van der Plicht, H., Hooghiemstra, H., Meijer, H.J.M., Vonhof, H., Porch, N., Florens, V., Baider, C., van Geel, B., Brinkkemper. J., Vernimmen, T., Janoo, A., 2011. Mid-Holocene (4200 kyr BP) mass mortalities in Mauritius (Mascarenes): Insular vertebrates resilient to climatic extremes but vulnerable to human impact. The Holocene, 1–16.

Santisuk, T., 1983. Taxonomy and distribution of terrestrial trees and shrubs in the mangrove formations in Thailand. The Natural History Bulletin of the Siam Society. 5 (1), 63–91.

Schlüter, T., 1997. Geology of East Africa. Gebrüder Borntraeger, Berlin, 484 pp.

Semesi, A. K., 1992. The mangrove resource of the Rufiji delta, Tanzania. In: Matiza T, Chabwela HN (Eds.) Wetlands conservation conference for southern Africa. Proceedings of the southern African development coordination conference held in Gaborono, Botswana, 3–5 June 1991. Union Internationale pour la Conservation de la Nature et de ses Ressources, Switzerland (UICN), Gland, pp 157–172.

Shennan, I., Innes, J. B., Long, A. J., & Zong, Y. 1995. Late Devensian and Holocene relative sea-level changes in northwestern Scotland: new data to test existing models. Quaternary International, 26, 97–123.

Shunula, J.P., 2002. Public awareness, key to mangrove management and conservation: the case of Zanzibar. Trees 16, 209–212.

Sloss, C. R., Murray-Wallace, C. V., & Jones, B. G., 2007. Holocene sea-level change on the southeast coast of Australia: a review. The Holocene, 17(7), 999–1014.

Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, B. and Midgley, B.M., 2013. IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P., Mikhalenko, V.N., Hardy, D.R., Beer, J., 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. Science 298, 589–593.

Tossou, M.G., Akoègninoua, A., Balloucheb, A., Sowunmic, M.A., Akpagana, K., 2008. The history of the mangrove vegetation in Bénin during the Holocene: A palynological study. Journal of African Earth Sciences 52, 167–174.

Vedel, V., Behling, H., Cohen, M., Lara, R., 2006. Holocene mangrove dynamics and sea-level changes in northern Brazil, inferences from the Taperebal core in northeastern Pará State. Vegetation History and Archaeobotany 15, 115–123.

Verschuren, D., Laird, K.R. and Cumming, B.F., 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. Nature, 403(6768), 410-414.

Watson, J. G. 1928. Mangrove forests of the Malay Peninsula. Malayan Forest Records 6, 275 pp.

Woodroffe, C.D., Grindrod, J., 1991. Mangrove Biogeography: The Role of Quaternary Environmental and Sea-Level Change. Journal of Biogeography 18, 479.

Woodroffe, S.A., Horton, BP, 2005. Holocene sea-level changes in the Indo-Pacific. Journal of Asian Earth Sciences 25, 29–43.

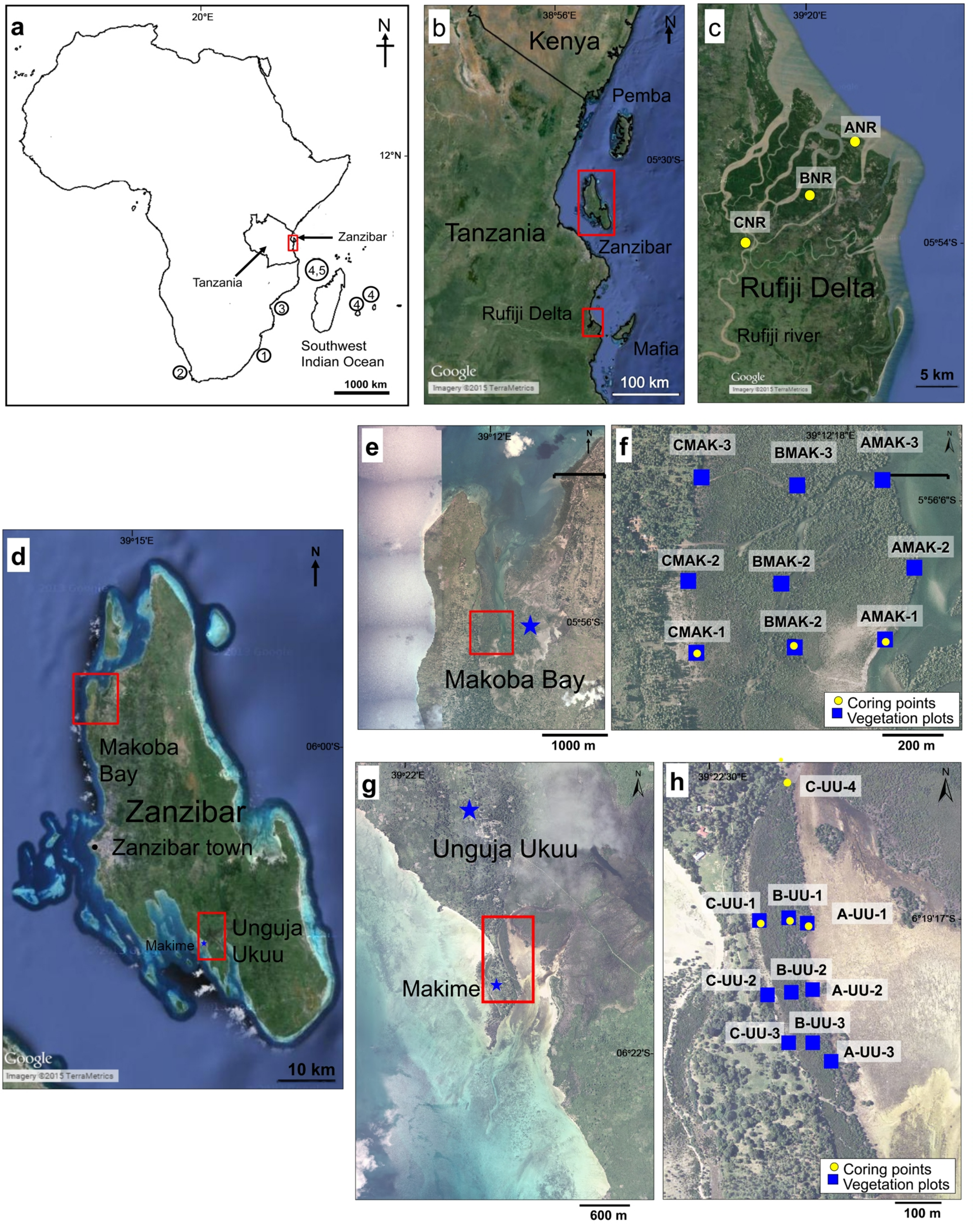
Woodroffe, S.A., 2006. Holocene relative sea-level changes in Cleveland Bay, North Queensland, Australia. PhD thesis, University of Durham, 155 pp.

Woodroffe, S. A., Long, A.J., Punwong, P., Selby, K., Bryant, C.L., Marchant, R., 2015a. Radiocarbon dating of mangrove sediments to constrain Holocene sea-level change on Zanzibar in the Southwest Indian Ocean. The Holocene 25(5), 820-831.

Woodroffe, S. A., Long, A. J., Milne, G. A., Bryant, C. L., & Thomas, A. L. 2015b. New constraints on late Holocene eustatic sea-level changes from Mahé, Seychelles. Quaternary Science Reviews 115, 1–16.

Zinke, J., Reijmer, J.J.G., Dullo, W. C., Thomassin, B.A., 2000. Paleoenvironmental changes in the lagoon of Mayotte associated with the Holocene transgression. Geolines 11, 150–153.

Zinke, J., Reijemer, J.J.G., Thomassin, B.A., Dullo, W. C., Grootes, P.M. and Erienkeuser, H., 2003. Postglacial flooding history of Mayotte Lagoon (Comoro Archipelago, southwest Indian Ocean). Marine Geology, 194 (3-4), 181–196.



a
20°E
N
12°N
Zanzibar
Tanzania
4,5
3
4
4
1
2
Southwest
Indian Ocean
1000 km
b
38°56'E
N
Kenya
Pemba
05°30'S
Tanzania
Zanzibar
Rufiji Delta
Mafia
Google
100 km
c
39°20'E
ANR
BNR
CNR
05°54'S
Rufiji Delta
Rufiji river
Google
5 km
d
39°15'E
N
Makoba
Bay
06°00'S
Zanzibar
Zanzibar town
Unguja
Ukuu
Makime
Google
10 km
e
39°12'E
N
05°56'S
Makoba Bay
1000 m
f
39°12'18"E
CMAK-3
BMAK-3
AMAK-3
5°56'6"S
CMAK-2
BMAK-2
AMAK-2
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Coring points
Vegetation plots
200 m
g
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Unguja Ukuu
Makime
06°22'S
600 m
h
39°22'30"E
N
C-UU-4
C-UU-1
B-UU-1
A-UU-1
6°19'17"S
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B-UU-2
A-UU-2
C-UU-3
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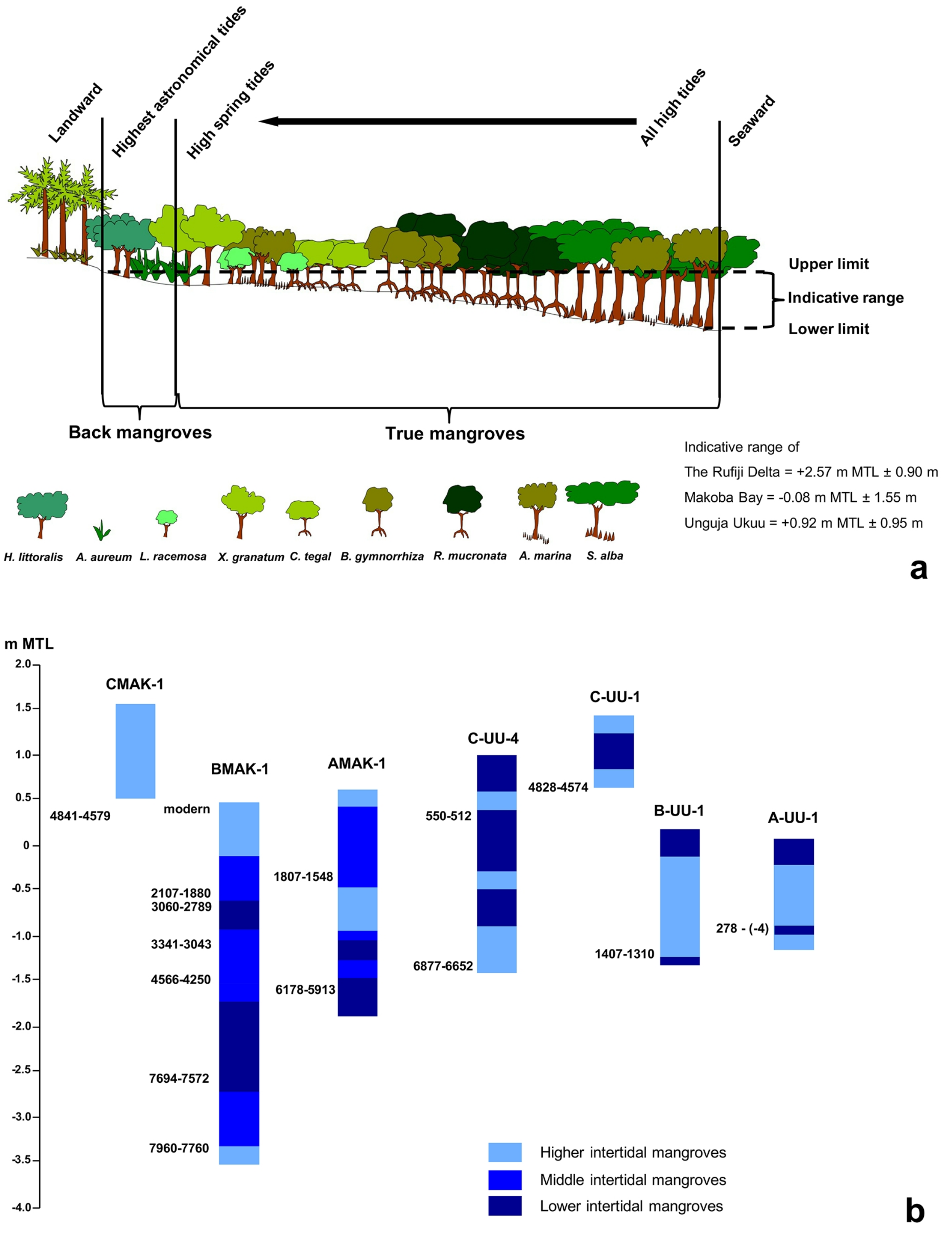
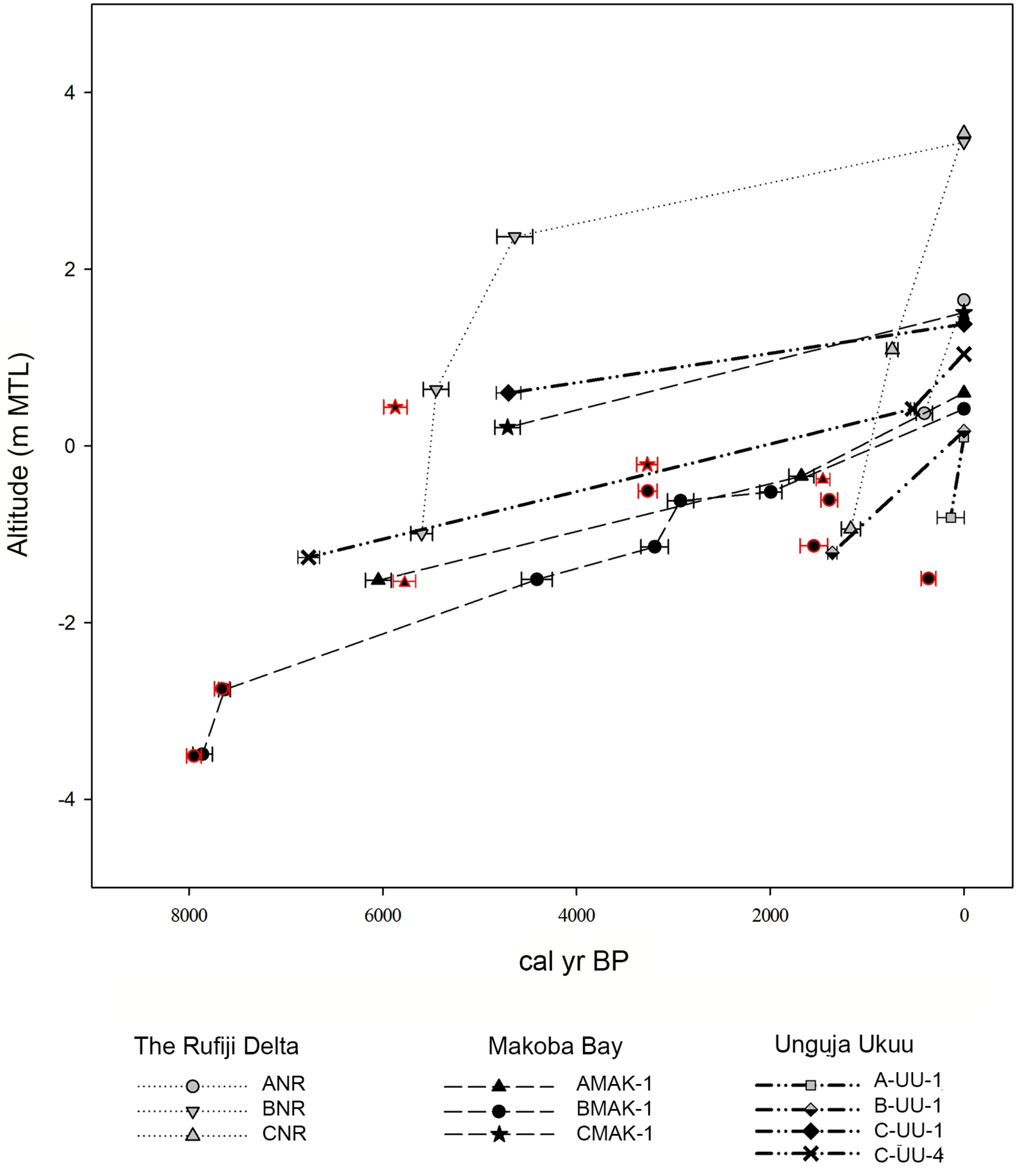
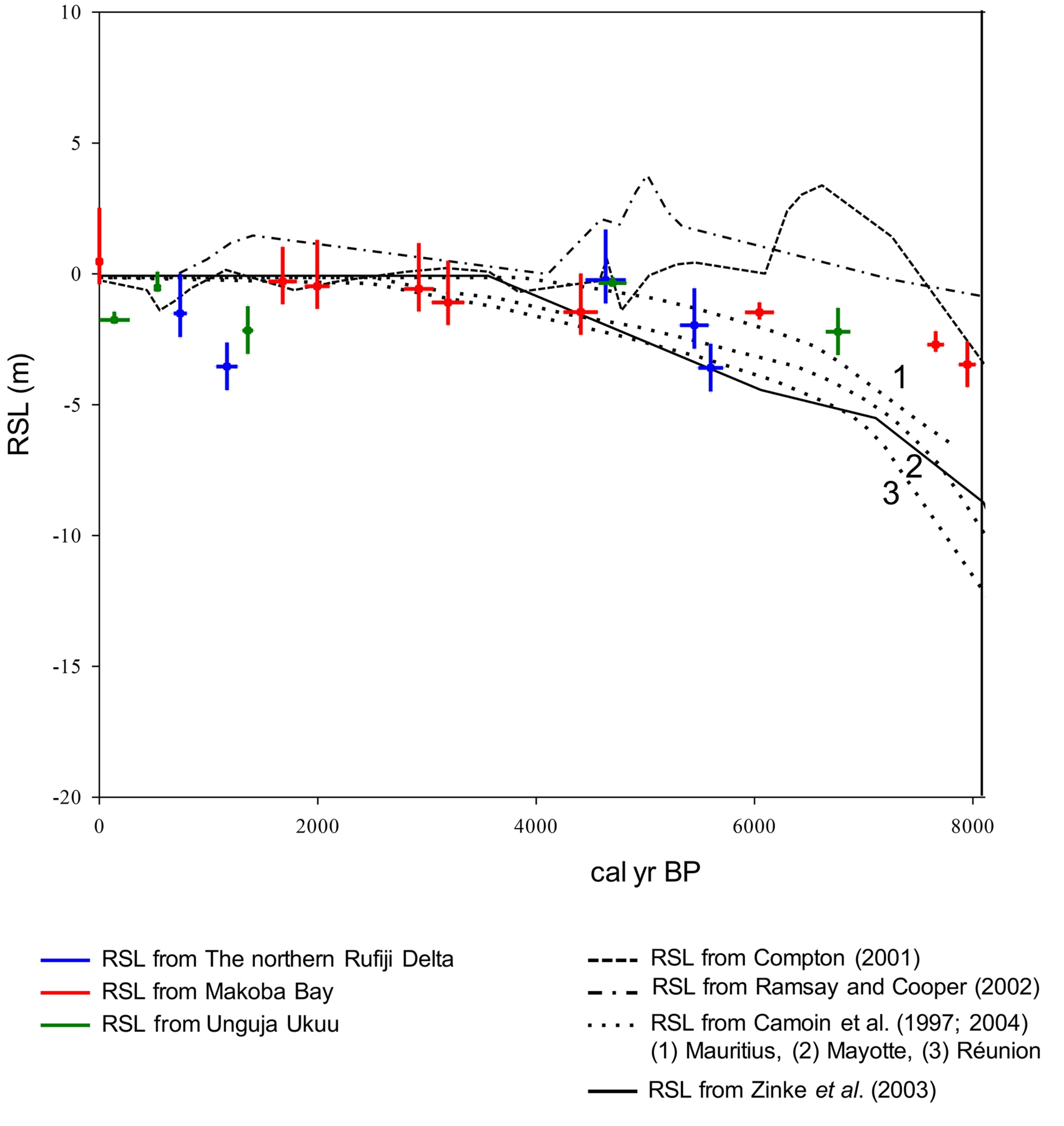
A-UU-3
Coring points
Vegetation plots
100 m



Landward
Highest astronomical tides
High spring tides
All high tides
Seaward
Upper limit
Indicative range
Lower limit
Back mangroves
True mangroves
Indicative range of
The Rufiji Delta = +2.57 m MTL ± 0.90 m
Makoba Bay = -0.08 m MTL ± 1.55 m
Unguja Ukuu = +0.92 m MTL ± 0.95 m
H. littoralis
A. aureum
L. racemosa
X. granatum
C. tegal
B. gymnorrhiza
R. mucronata
A. marina
S. alba
a
m MTL
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
CMAK-1
4841-4579
BMAK-1
modern
2107-1880
3060-2789
3341-3043
4566-4250
7694-7572
7960-7760
AMAK-1
1807-1548
6178-5913
C-UU-4
550-512
6877-6652
C-UU-1
4828-4574
B-UU-1
1407-1310
A-UU-1
278 - (-4)
Higher intertidal mangroves
Middle intertidal mangroves
Lower intertidal mangroves
b



Altitude (m MTL)
4
2
0
-2
-4
8000
6000
4000
2000
0
cal yr BP
The Rufiji Delta
ANR
BNR
CNR
Makoba Bay
AMAK-1
BMAK-1
CMAK-1
Unguja Ukuu
A-UU-1
B-UU-1
C-UU-1
C-UU-4


10
5
0
-5
-10
-15
-20
RSL (m)
0
2000
4000
6000
8000
cal yr BP
1
2
3
RSL from The northern Rufiji Delta
RSL from Makoba Bay
RSL from Unguja Ukuu
RSL from Compton (2001)
RSL from Ramsay and Cooper (2002)
RSL from Camoin et al. (1997; 2004)
(1) Mauritius, (2) Mayotte, (3) Réunion
RSL from Zinke *et al.* (2003)