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Late Quaternary lake-level fluctuations in the Mababe Depression: Middle Kalahari palaeolakes and the role of Zambezi inflows

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Abstract

A systematic drilling and optical dating programme on Middle Kalahari beach ridge (relict shoreline) sediments has enabled the identification of multiple episodes of lake high stands of an extensive palaeolake system at the terminus of the Okavango Delta, northern Botswana. This paper presents 23 ages from the Mababe Depression and establishes four shoreline construction phases in the late Quaternary coeval with other sub-basin lake high stands (Lake Ngami). These synchronous lake phases result from a coalescence of the sub-basins into a unified palaeolake, Lake Thamalakane, covering an area of ~32,000 km^2. Six additional ages are also presented from the Chobe enclave to the north of the basin where shoreline ridges were emplaced at the same time as Lake Thamalakane phases. This suggests that increased flow in the Chobe and Zambezi system significantly contributed to the Middle Kalahari lake phases in both the post-glacial and Holocene periods. The integration of these new data and their compatibility with other regional and tropical palaeo-archives is discussed in the light of understanding Quaternary climate drivers within the Kalahari.

Keywords: Palaeolake Thamalakane; Kalahari; Mababe Depression; OSL dating

Introduction

The Kalahari region of central southern Africa is today an extensive, largely semi-arid, depositional environment that preserves a complex history of Quaternary environmental change (Thomas and Shaw, 1991, 2002). Lacking the abundance of organic based proxy records that benefit more tropical zones of Africa, the record of environmental change, together with the resultant palaeoclimatic interpretations, has principally been based on geomorphological proxies. The middle Kalahari is fed by the tropically sourced Cubango and Cuito rivers, which are the major tributaries of the endoreic Okavango River, the Kwando/Chobe drainage system and, prior to its Pliocene (Lister 1979) or early-mid Pleistocene (Bond, 1975; Thomas and Shaw, 1988) capture and coastalward reorientation, the Upper Zambezi. The propensity for fluvio-lacustrine deposition has been enhanced by the existence of a large structural depression, a southwesterly propating extension of the east African rift system (Tiercelin and Lezzar, 2002; Ringrose et al., 2005), in which a large alluvial fan (the Okavango Delta), and the structural sub-basins of Lake Ngami and the Mababe depression now lie. This depression now forms the terminal sump of the Okavango and Kwando fluvial systems.

The Kwando is connected to the Okavango system via the Makwegana (Selinda Spillway) but today diverts east to the Zambezi, forming ephemeral connections between these three substantial river systems that have contributed significantly to sedimentation in the Middle Kalahari (*sensu* Passarge, 1904). These rivers have provided a sediment rich environment and together with lacustrine sedimentation and aeolian reworking have given rise to a suite of landforms that have been central to Quaternary palaeoenvironmental reconstructions in the region, supplemented by the analysis of inselberg cave precipitates (Cooke and Verhagen, 1977; Cooke, 1984; Shaw and Cooke, 1986; Brook et al., 1996), and localised pollen accumulations (Nash et al., 2006) from a limited number of locations.

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Presently the region has a highly seasonal climatic regime with considerable inter-annual variability in precipitation. Rains predominantly occur between October and May, associated with penetration of the easterly monsoon linked to movement of the ITCZ. For the remainder of the year dry descending air associated with high pressure conditions dominates. Today, there is relatively little geomorphic activity occurring in the region outside the confines of the Okavango Delta. Extensive dune systems are largely stabilised by vegetation (Stokes et al., 1998; Thomas et al., 2000) and lake basins are, at most, shallow and ephemeral (Shaw, 1988). The scale and extent of these landform suites, however, is testament to an environment that has been subject to considerable geomorphic activity and climatic contrasts, both wetter and drier than present, at times during the Quaternary. Establishing a secure chronology for the formation of the major landforms of the Middle Kalahari provides the fundamental framework for understanding the major environmental changes that have occurred in the Quaternary. To this end, initial lake phase chronologies have been constructed, primarily based on the application of ^{14}C measurements to basin carbonates associated with shoreline and river terraces, but also through a limited application of OSL (Optically Stimulated Luminescence) and TL (Thermoluminescence) dating to lake basin shoreline sediments themselves (Shaw et al., 2003; Ringrose et al., 2005). This technique has also given rise to the chronologies of late Quaternary dune building episodes that have been produced in recent years (e.g. Stokes et al., 1997; Thomas and Shaw, 2002). It is now being applied through a systematic and detailed research programme to the marginal sediments of the lake basins of the Middle Kalahari. This paper reports and interprets the chronology that has been produced for the Mababe Depression, and analyses the palaeoenvironmental and palaeoclimatic significance of these data in the context of OSL-derived lake stage chronologies already reported for Lake Ngami (Burrough et al., 2007).

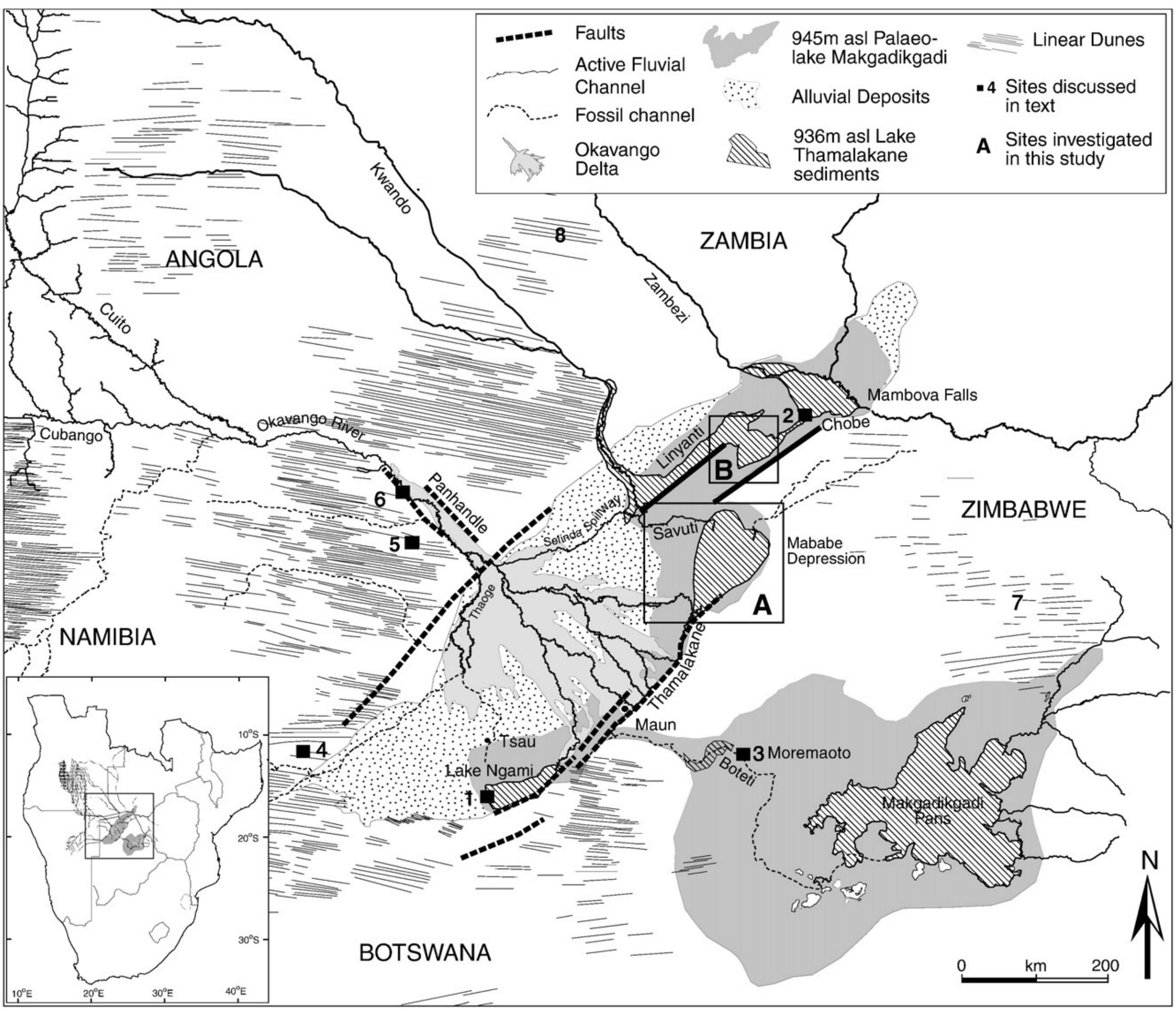

Figure 1. Map of the Lake Thamalakane region (partly constructed from 'shapefiles' courtesy of the Sharing Water Project (RAISON, 2004)). The location of the catchment of the Okavango–Kwando–Zambezi system is shown in the inset. Sampling sites are indicated by box A and box B and shown in more detail in Figures 2 (A) and 3 (B). Sites discussed in text are marked as numbers: 1) Lake Ngami; 2) Serondella and Ngwezumba Terrace shell deposits; 3) Moremaoto diatom bed; 4) Drotsky's cave; 5) Tsodilo Hills; 6) Delta Panhandle 7) Zimbabwe dunes; 8) Zambian dunes.

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Lake basins of the Middle Kalahari

The terminal sump of the Middle Kalahari endoreic drainage system is composed of three discreet sub-basins: Lake Ngami, the Mababe Depression and the Makgadikgadi basin (Fig. 1). Ngami and Mababe lie respectively at the western and eastern ends of the Thamalakane axis, the faultline that forms the distal end of the Okavango Delta and along which flows the seasonal Thamalakane River. This sub-system is linked to the Makgadikgadi basin by the Boteti River channel.

Of these three component basins, it is only parts of the Makgadikgadi basin that today hold regular but shallow (<1 m deep), seasonal standing water. At least some of this water is sourced not from the Okavango system but from runoff from the Hardveld region to the east. The occurrence and magnitude of very high lake stands within these basins in the past is directly inferred by the presence and altitude of relict shoreline, or beach, ridges. To date, the lacustrine features of the Middle Kalahari have been the principal evidence used to identify Quaternary wet phases in the region (e.g. Grove, 1969) with shoreline altitudes above sea level (Table 1) used to infer the relationships between basin water bodies (Cooke, 1980; Shaw, 1985; Shaw and Cooke, 1986), including extensions to the east in the vicinity of the present day Chobe–Zambezi confluence (Shaw and Thomas, 1988).

Beach ridges

The term "beach ridge" applies to stabilized, relict wave-built shoreline features that may consist of either siliclastic or calcareous clastic matter (Otvos, 2000). Although the Middle Kalahari shore ridges are well studied, few investigations have considered the actual processes of their development and how preserved ridges might relate to hydrological processes within the basins. Terminal lakes will develop shorelines whenever the hydrological balance between inflow and evaporation loss results in a significant stillstand (DeVogel et al., 2004). Major elevational thresholds or sills are initially the product of sediment aggradation at these stabilised levels and once formed, amplify shoreline development by dissipating wave energy and slowing the rate of progradation or retrogradation. Major positive or negative hydrological budgets will tend however, to cause a basinward or landward migration of ridges as water levels and sediment supply fluctuate. Present-day beach ridge configuration therefore represents the most recent phase of stable lake conditions at these threshold levels with their underlying stratigraphy providing a discontinuous record of deposition on the ridge flanks. In an environment such as the Kalahari, a paucity of organic preservation and a strong tendency for deflation of material from lake bed surfaces (e.g. Bryant et al., 2007; Washington et al., 2003) has rendered conventional lake coring approaches of less utility than when applied to undessicated lake floors. Beach ridges are therefore critical archives of high lake stands in this context (e.g. Magee and Miller, 1998; Drake and Bristow, 2006).

Extensive investigations based on field levelling from established bench marks and barometer surveys with an estimated accuracy of ±1 m (Shaw, 1985; SMEC, 1987), as well as newly available Shuttle Radar Topography Mission (SRTM) data, have demonstrated the consistency of prominent beach ridges within the sub-basin system (Table 1). Together with alluvial, diatomite and shell deposits, the altitudinal consistency of shorelines in individual basins indicates that water levels were once high enough to form a coalescence of sub-basin lakes and a continuous water body with a maximum area of 60,000 km^2 (Cooke, 1980) or 74,000 km^2 (White and Eckardt, 2006).

It has even been postulated that this maximum extent may increase to 120,000 km^2 if linkages and continuity with fluvio-lacustrine deposits extending as far west as the Kafue system in Zambia can be confirmed (Thomas and Shaw, 1991). This extension would have included today's Chobe–Zambezi mudflats, where Shaw and Thomas (1988) suggest the existence of a basalt bar-dammed late Quaternary 'Lake Caprivi', coeval in height and timing with the Lake Thamalakane stage of the Middle Kalahari lake system. Evidence for a water body in this location is in the form of relict sand ridge bars and terraces on the southern escarpment of the eastern-most parts of the Chobe

Table 1
Comparative landform altitudes in the Mababe and Ngami basins (adapted from Shaw and Thomas, 1991 p.127)

Altitude (m asl)	Lacustrine features	Fluvial features
Mababe Basin		
940–945	Magikwe Ridge + shorelines	
936	Magikwe Ridge	Ngwezumba and Gautumbi Bars Ngwezumba Estuary Savuti Overflow
930	Strandline	Ngwezumba Delta Mababe Bar and Terrace Savuti Terrace 1
929		Savuti Terrace 2
927		Savuti Terrace 3
926		Savuti Marsh Tsatsarra Delta
923	Strandline	Mababe Marsh
919	Sump	
Lake Caprivi		
936	Chobe enclave beach ridges	
935		Notches eroded along Mambova Fault
932–4		Terraces on Chobe
Ngami Basin		
938–945	Shoreline — Kerang Ridge	
936	Dautsa and Magotlawanen Ridges	Maximum Thalweg of Thamalakane
934	Dautsa and Magotlawanen Ridges	Terrace on upper Thamalakane
930–932	Ridges in series	Flood plain–Boteti Junction (932) Thalweg–Boteti Junction (930) Thaoge Inflow (930)
928	Strandline	Flood plain: Kunyere/ Nhabe confluence
926	Strandline	Thalweg: Kunyere/Nhabe confluence
923	Strandline — max. contemporary lake	
919	Sump	

River. These features have altitudes in the 936–932 m asl range, consistent with the shoreline sequences preserved in Ngami and Mababe.

Beach ridge chronologies

Like many Quaternary African lake records, the timing of lake high stands in the Kalahari has relied heavily on the limited timescale of a radiocarbon chronology. Unlike lake basins in the tropics however, where significant scrutiny has emerged relating to the relevance and condition of the dated organic material, the semi-arid subtropics present a highly oxidising environment that is severely lacking in datable organic material. This has led to the development of a Kalahari lake phase chronology principally constructed from ^{14}C measurements made on surficial calcretes associated with shoreline or terrace deposits. Radiocarbon measurements made on inorganic carbonates can however be problematic: calcrete can evolve over a range of timescales often unrelated to a single definable event (Shaw et al., 1997) and this multiphase dissolution and precipitation can lead to contamination by older or younger carbon. More significantly the complex controls on duricrust formation make the palaeoenvironmental interpretation of calcrete highly problematic (Nash and McLaren, 2003). The meaning of a radiocarbon age from calcretised material associated with lake shorelines is thus particularly unclear.

OSL dating has now proved an alternative and more robust mechanism for dating lake stages, primarily through applications to shoreline sediments (Shaw et al., 2003) but also including lake basin floor material (Shaw et al., 2003; Huntsman-Mapila et al.,

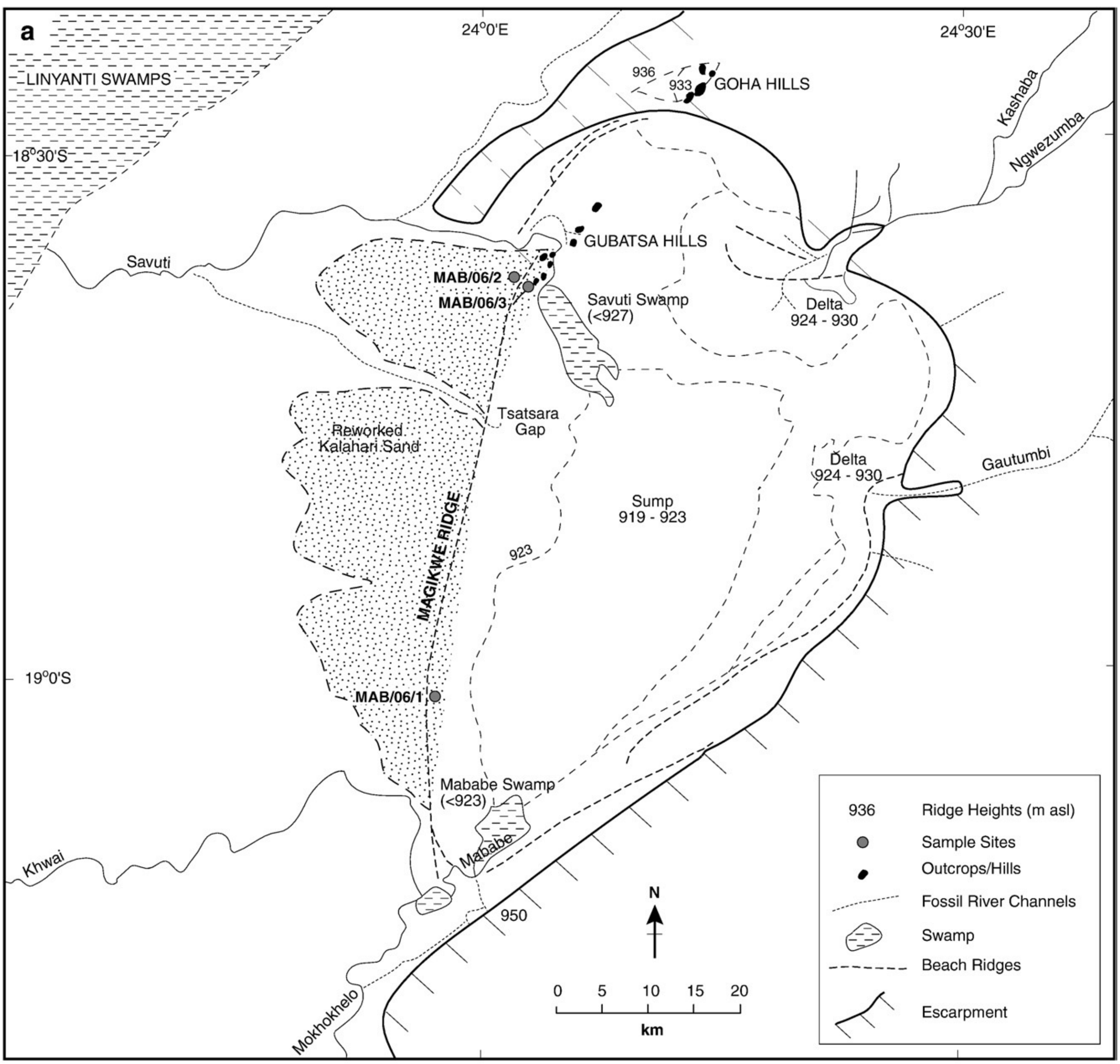

Figure 2. a.) Geomorphology of the Mababe basin (adapted from Thomas and Shaw, 1991); b) Geomorphology of the Chobe enclave (adapted from Shaw and Thomas, 1988). The location of sites sampled in this study are indicated. Also shown are the heights above sea level for significant geomorphological features.

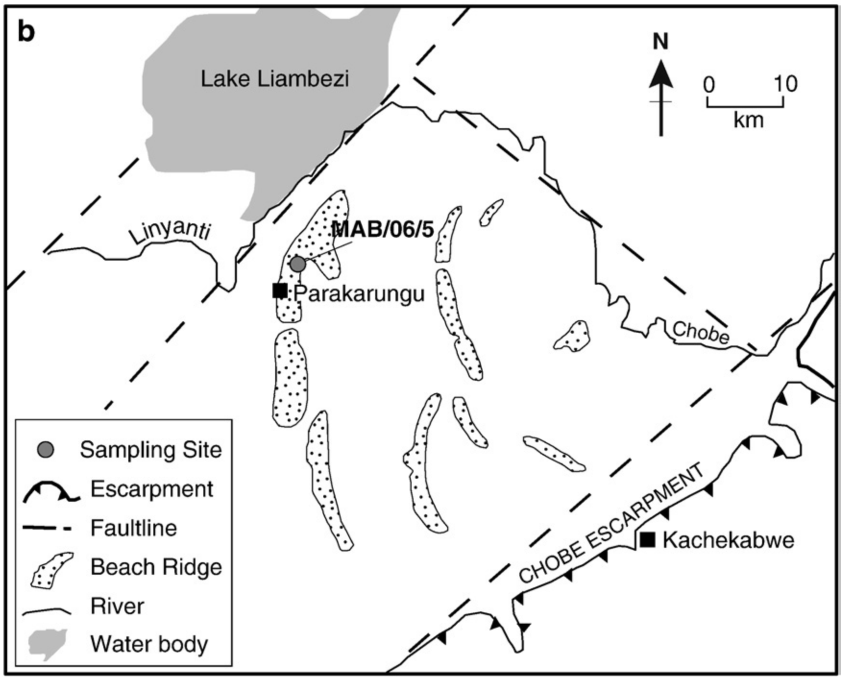

Figure 2 (*continued*).

2006). These initial studies, both conducted in the Ngami basin, have now been supplemented by a systematic and intensive study using the application of OSL to samples derived from the deep-coring of beach ridges (Burrough et al., 2007). This approach has enabled both the style and continuity of shoreline emplacement to be investigated and has identified multiple lake high stands within the Ngami basin during the late Quaternary (~0.3 ka to ~140 ka).

The Mababe basin

At the crux of the connection between the middle Kalahari's major river systems (the Okavango, Kwando/Chobe and upper Zambezi) lies the Mababe Depression, one of the three sub-basins at the terminus of the Okavango drainage system. The basin now receives little inflow and, with the exception of the Mababe swamp in the south and the Savuti marsh in the north, has no historical record of retaining any standing water.

The Mababe Depression is a 50 km by 90 km heart-shaped basin (Fig. 2). Although it receives little water in its present day dryland context, the large compound beach ridges bounding its margins, reaching over 945 m asl, are evidence of the former existence of a large wave-dominated water body within the basin. The Mababe Swamp, located at the southern end of the basin with its lowest point at <923 m asl, is intermittently fed by the Khwai River. This leads from the eastern limb of the Okavango Delta and flows into the depression after its confluence with the Mokhokhelo channel. In the northwestern part of the depression, the Savuti Swamps (<927 m asl), receive intermittent flow via the Savuti channel. This connects to the Linyanti Swamps which in turn are fed by both the Kwando/Chobe River and the Okavango Delta via the Magwegqana (Selinda Spillway). The Savuti, which is now inactive, breaches the western shoreline of the basin at the Gubatsa Hills in the northeast of the depression and terminates in the Savuti swamps. A southerly distributary of the Savuti, existing only in a very degraded form, also breaches the ridge at the Tsatsarra Gap, 25 km south of the Gubatsa hills.

On the south-eastern side of the depression a sand mantled escarpment at 950 m asl, related to the gentle up-throw of the Thamalakane fault, forms the basin rim. This escarpment is breached by the Ngwezumba and Gautumbi inflows which drain the Kalahari–Zimbabwe watershed. The Gautumbi is a poorly defined, heavily vegetated channel and only the Ngwezumba, a steep sided, coarse bedload river, has been recorded as carrying water into the basin in years of exceptionally high rainfall (Thomas and Shaw, 1991).

Although much larger in size, the Mababe Depression bears many affinities to its western counterpart, the Ngami basin. It is similarly fault-bounded on its south-eastern side and is dominated by a compound beach ridge system, the Magikwe ridge, which forms its western shoreline at maximum fetch. This wave-built beach ridge stretches for 75 km from the southern tip of the depression to the Savuti channel. At its northern end, where a linear bifurcation of the ridge is evident, it attaches to the Gubatsa Hills in "a tombolo-like feature" (Thomas and Shaw, 1991) before curving east below the Goha hills. In places, it is distinctively mantled by summit dunes up to 950 m asl in altitude. West of these ridges, reworked sand forms east–west aeolian lineations before merging with relict Okavango–Linyanti swamp sediments (Shaw, 1985). To the east of the Magikwe ridge, the sump level is marked by a low (923 m asl) ridge and a replacement of Mopane scrub by Acacia-dominated vegetation. The entire basin is tilted (possibly in relation to neo-tectonic activity in the Okavango Delta) so that the Magikwe ridge varies in elevation from a low of 930 m in the south to 954 m asl at the northern end (Gumbricht et al., 2001), though in fact the ridge crest is markedly undulating in places, probably as a function of the ridge being dune-topped.

The existing palaeoenvironmental chronology for the Mababe and Chobe systems is based on a limited number of radiocarbon dates derived from gastropod shells and calcrete material sampled from pans and associated drainage lines (Table 2). These include samples taken from the Serondella Terrace, on the south bank of the Chobe River and interpreted as the southern margin of Late Quaternary Lake Caprivi (Shaw and Thomas, 1988). Shell ages have been interpreted as representing wet phases, while calcretes are assumed to have been formed subaerially, thereby pre-dating sediments lying unconformably above them (Shaw, 1985). Given the problems associated with interpreting dates from these materials, there is to date no robust or reliable chronology for the timing of lake stages within the Mababe Depression. It was with this in mind that a programme to date the beach ridges using OSL was conducted.

Research design and methods

Field sites and sampling

SRTM (Shuttle Radar Topography Mission) data, aerial photography and published field-survey height data (Shaw, 1985) were used to identify and locate three drill sites on the western shoreline of the Mababe Depression where ridge orientation and elevation corresponded to threshold levels previously investigated in the Ngami basin (Burrough et al., 2007). Samples from within shorelines were obtained using lightweight portable Dormer hydraulic drill equipment, employing a light-tight sample head for OSL dating (Telfer and Thomas, 2006). The depths reached at individual sample sites were dependent on drill hole stability and efficiency. Drilling was carried out 2–4 m downslope on the basin-side of the ridge in order to avoid localised aeolian reworking of the crest zone. MAB/06/1 was located in the southern part of the Magikwe ridge with MAB/06/2 and MAB/06/3 close to the Gubatsa Hills, just South of the Savuti inlet (Fig. 2a). Here the ridge bifurcates, with MAB/06/2 sampling the more clearly-defined outermost ridge, and MAB/06/3 the dune-topped basinward ridge. MAB/06/5 was located on the Parakarungu sand ridge on the Chobe–Zambezi flood plain. This and other sand ridges in the area were interpreted by Shaw and Thomas (1988) as offshore bars, formed at a time when Lake Caprivi existed due to the ponding back of Chobe and Zambezi waters at the Mambova basalt bar. Dating this sand ridge was carried out in order to test their assertion that the sand bars are of equivalent age to the beach ridge systems in Ngami and Mababe.

Sedimentology

Particle size analysis (2–2000 μm grains) was carried out using a Horiba Partical Size Analyser and statistics calculated using the Folk and Ward formula (Folk and Ward, 1957). Sequential loss on Ignition at 550°C and 950°C (Heiri et al., 2001) was used to determine percentage carbonate and organic components of the sediment. Sediment colours were determined in the field (and after drying in the laboratory) using standard Munsell colour charts.

OSL dating

Equivalent dose measurements

All sample preparations and luminescence measurements were made at the Oxford Luminescence Dating Laboratory (OLDLab) under controlled red-light conditions. Any risk of sample contamination by light was minimised by using only the inner portion of samples for age determinations. The quartz fraction was then isolated using HCl, H_2O_2, sieving to 180–250 μm and heavy liquid separation. Agitation in 60% HF for 50 min both removed feldspars and etched the alpha radiated quartz rind. Samples were then subjected to a two day HCl wash to remove fluorides and a further re-sieve to obtain the correct particle size fraction. OSL measurements were made using four automated Risø TL-DA-15 readers (Botter-Jensen, 1997; Botter-Jensen et al., 2000, 2002, 2003) operated by “Mini-sys” units (Markey et al., 1997). In situ irradiations were made using $^{90}Sr/^{90}Y$ beta sources which were calibrated individually against known γ-doses administered to samples at the National Physical Laboratory. Optical stimulation was carried out using blue LED arrays with a peak emission at 470 ± 20 nm (delivering ~35 mW cm^{-2}). Infra-red (IR) stimulation was carried out at 875 nm (~400 mW cm^{-2}) and at 830 ± 10 nm (~1 W cm^{-2}) depending on the machine used. Typically, 17–20 aliquots were used

Table 2
Ages generated from previous work in and around the Mababe Depression

Location	Method	Age (^{14}C yr BP)	Age (cal kyr BP)	Material
Ngwezumba River (935.5 m asl) [a]	^{14}C	13070 ± 140	16067 ± 554	Estuarine calcrete
Ngwezumba River (935.5 m asl) [a]	^{14}C	15570 ± 220	18879 ± 285	Mollusca
Ngwezumba River (935 m asl) [a]	^{14}C	17190 ± 210	20665 ± 557	Estuarine calcrete
Savuti River (934.5 m asl) [a]	^{14}C	11950 ± 110	13930 ± 240	Sandy lacustrine calcrete
Savuti River (928.5 m asl) [a]	^{14}C	2020 ± 60	1992 ± 74	Sandy lacustrine calcrete
Goha Pan (932 m asl) [a]	^{14}C	25850 ± 500	30627 ± 359	Pan bed calcrete
Serondella Terrace, Chobe River (934 m) [b]	^{14}C	15380 ± 140	18613 ± 276	Mollusca (Lymnaeae)
Serondella Terrace, Chobe River (934 m) [b]	^{14}C	11550 ± 110	13438 ± 141	Terrace calcrete
Chobe Game Lodge (931 m asl) [b]	^{14}C	2620 ± 140	2687 ± 186	Shell (Bellamya)

Calibration was carried out using CalPal-2007 (Weninger et al., 2007).
[a] (Shaw, 1985).
[b] (Shaw and Thomas, 1993).

to measure Equivalent Doses (D_e) using a Single Aliquot Regeneration (SAR) protocol (Wintle and Murray, 2006). Some samples were more intensively measured (up to 87 aliquots). Preheats (PH_1 — 260°C, 10 s and PH_2 — 220°C, 10 s) were chosen following preheat plateau tests on both natural signals and recovered doses. OSL measurements were made at 130°C for 50 s and test dose cycles were followed by a 280°C, 100 second optical wash. Sensitivity corrections were monitored using two recycled dose points at low (RR_1) and high doses (RR_2). The measurement procedure included a subset of six aliquots within each sample on which a Dose Recovery Test (DRT) at the expected D_e value was carried out. DRT's were performed following two room temperature bleaches each with an associated 10,000 s pause.

Dose rate measurements

i) Beta and gamma dose determinations

Dose rates were obtained from radionuclide (^{232}Th, ^{238}U and ^{40}K) concentrations measured using ICP-MS and ICP-AES and converted to radioactive activities using the conversion factors of Adamiec and Aitken (1998). A cross-check on these measurements (and a crude test of secular equilibrium within the radioisotope decay chains) was carried out on samples from MAB/06/1 using high resolution gamma spectrometry at the geochronology laboratories, University of Gloucestershire, Cheltenham. Radiation attenuation corrections associated with grain size, HF etching and moisture content were made. The moisture corrections were estimated independently for each sample using an estimated mean saturation period of 150 yr for each beach ridge building event in conjunction with a measured saturation water content and an estimated "normal" water content based on its as found depth and the degree of sorting characteristic of the sediment.

ii) Cosmic dose determination

Very low ^{232}Th, ^{238}U and ^{40}K concentrations within sediment from this region lead to a particularly large relative contribution of cosmic dose to the total dose rate. It was therefore necessary to estimate cosmic dose over the duration of the burial period for each sample. Following the method of Munyikwa et al. (2000), the overburden history of each sample was modelled based on a near-surface sample from the drill site and calculated iteratively in sequence down core. Dose rates at each sample depth were calculated following the algorithm of Prescott and Hutton (1994). Within this down-core reconstruction, and using the initial unadjusted depositional ages, two time slice models were used. The first assumes the accumulation of sediment between one unit and the next has taken place gradually; the second uses an episodic overburden accumulation model assuming overlying the sediment unit is deposited in an instantaneous depositional event. Episodic accumulation was assumed unless adjacent samples returned ages within errors. No account was taken of potential erosional events.

This procedure can at best only generate estimates of the cosmic dose received by each sample. With up to 60% of the total dose in the Mababe sediments contributed by the cosmic component, this approach does provide a substantially more realistic scenario than would be achieved using the conventional cosmic dose estimation method, which is based only on the depth at the time of sampling. Failing to account for this attenuated portion of the dose rate can lead to age overestimates of up to 35% in samples from the Mababe beach ridges.

Results

Sedimentology

Both qualitative and quantitative characteristics of each drill site are summarized in Figure 3 and presented in Table 3. Samples were consistently dominated by medium to fine sand-sized particles with mean grain sizes in the range 180–280 μm. Mean grain size generally decreases northwards along the Magikwe Ridge. It is possible that this is a function of a northwards longshore drift process acting over the length of the ridge although if this process was integral to the mechanism of ridge formation, it is not possible to discern a significant chronological difference between ridge depositional phases in the north and south of the basin implying this was a subsidiary process. There is some variation in particle sorting both within and between drill sites. Most samples are well sorted with the exception of MAB/06/1/10; MAB/06/1/11 and MAB/06/1/6 in the Mababe basin and MAB/06/5/4 at Parakarungu. The degree of sorting seems to be strongly related to the degree of carbonate and organic content. Most of the samples from MAB/06/5, the Parakarungu sand ridge site, show a lesser degree of sorting, and a lower mean grain size, than those from the Mababe basin (Fig. 4). This may be because the beach ridge sediments from the west of the Mababe basin would have experienced greater wave energy, generated over a longer fetch, than samples from the shallower water body in the backflooding zone to the north. Carbonate and organic content are less than 1% for all samples within the Mababe basin and less than 4% in the Parakarungu site.

Chronology

While some sample D_e distributions showed evidence of skew, this would be entirely expected in samples subject to microdosimetric variability within the sediment matrix (Nathan, pers comm) and there is little reason or additional evidence to infer partial bleaching. Overdispersion values were generally less than 20% and in many cases much lower. Greater overdispersion was found for samples that lay nearer to the present day surface and is possibly the result of a moderate degree of bioturbation, the relative impact of which would diminish with age. However, while bioturbation is a factor that offers an inherent limitation to establishing ages (e.g. Bateman et al., 2007), especially at the single-aliquot scale, its impacts are difficult to differentiate from microdosimetry in low dose-rate environments. For this reason, the central dose (Galbraith et al., 1999) was considered to be the most appropriate estimate of true sample D_e and was used in the final calculation of sample ages (Table 4).

Dose rates were found to be extremely low (0.25–0.42 Gy ka^{-1}). Radio-isotope concentrations obtained using High

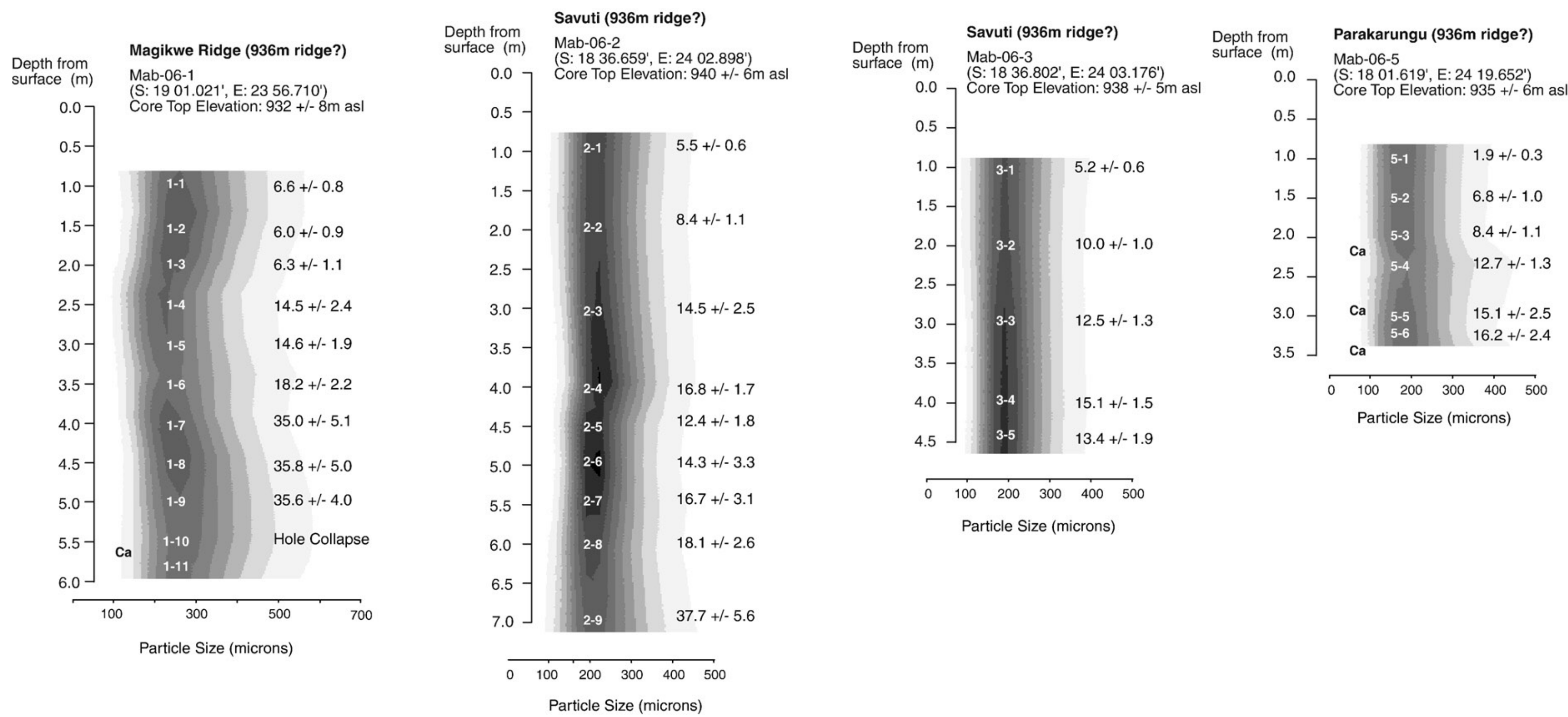

Figure 3. OSL ages for sampled drill sites. Particle size distributions (PSD) are plotted against sample depth and presented as surface plots. Particle size data is derived from point sample locations, extrapolated between points to show inferred down-column changes in sediment characteristics. Grayscale tones indicate the % particles by mass across the distribution. Sampling localities are indicated by sample labels (marked in white) and the presence of calcrete is indicated to the left of each PSD column.

Table 3
Particle size statistics: percentage sand (coarse, medium and fine), silt and clay, mean grain size and sorting

Sample code	Depth (m) ±0.2	Munsell colour	Mean particle size (μm)	Sorting (s.d)	Coarse sand %	Medium sand %	Fine sand %	Silt %	Notes
MAB/06/1/1	0.5	10YR 6/3	264	1.6	0.1	0.5	0.4	0.0	
MAB/06/1/2	1.0	10YR 7/3	278	1.5	6.1	56.0	36.9	1.0	
MAB/06/1/3	1.5	10 YR 7/5	264	1.5	5.0	51.0	43.3	0.8	
MAB/06/1/4	2.0	10YR 6/3	234	1.5	3.4	40.0	55.4	1.2	
MAB/06/1/5	2.5	10YR 6/3	234	1.6	3.6	40.6	52.2	3.7	
MAB/06/1/6	3.0	10YR 6/3	236	2.2	5.7	42.6	42.9	8.9	Small calcrete flecks
MAB/06/1/7	3.5	10YR 6/3	250	1.5	4.3	46.0	46.1	3.7	
MAB/06/1/8	4.0	10YR 6/3	272	1.5	5.6	53.9	37.6	2.9	
MAB/06/1/9	4.5	10YR 6/3	272	1.7	6.8	52.6	35.6	4.9	
MAB/06/1/10	5.0	10YR 5/3	263	2.0	7.3	51.3	34.4	7.0	Very friable — calcrete present (possible hole collapse)
MAB/06/1/11	5.5	10YR 6/3	232	2.3	5.7	46.9	35.1	12.2	Fine and dusty — calcrete (possible hole collapse)
MAB/06/2/1	1.0	10YR 5/3	241	1.4	2.1	43.1	54.5	0.2	
MAB/06/2/2	2.0	10YR 6/3	234	1.4	1.7	40.1	57.4	0.8	
MAB/06/2/3	3.0	10YR 6/3	245	1.4	2.4	43.8	53.7	0.1	
MAB/06/2/4	4.0	10YR 7/3	257	1.3	2.1	51.1	46.8	0.0	Contains abundant seeds
MAB/06/2/5	4.5	10YR 7/2	238	1.4	1.6	40.5	57.9	0.0	
MAB/06/2/6	5.0	10YR 7/2	239	1.3	1.3	40.6	58.1	0.0	
MAB/06/2/7	5.5	10YR 7/2	237	1.4	1.8	39.6	58.6	0.0	
MAB/06/2/8	6.0	10YR 7/2	223	1.5	1.5	35.5	59.7	3.2	Small calcrete flecks
MAB/06/2/9	7.0	10YR 7/2	231	1.5	2.8	38.9	57.9	0.5	Calcrete, rhizoliths and shell flecks
MAB/06/3/1	1.0	10YR 4/2	208	1.5	1.2	29.8	65.3	3.7	
MAB/06/3/2	2.0	10YR 5/3	205	1.5	0.8	28.2	66.9	4.1	
MAB/06/3/3	3.0	10YR 7/3	213	1.4	0.8	29.4	66.4	3.4	Calcrete present
MAB/06/3/4	4.0	10YR 7/2	217	1.4	1.2	30.6	66.8	1.4	Increasing calcrete, shell and rhizoliths
MAB/06/3/5	4.5	10YR 7/2	214	1.4	0.8	29.5	68.6	1.2	Powdery calcrete
MAB/06/5/1	1.0	10YR 4/3	189	1.9	1.4	24.5	67.5	6.7	
MAB/06/5/2	1.5	10YR 4/3	182	2.0	1.2	23.2	67.1	8.5	
MAB/06/5/3	2.0	10YR 5/4	181	2.0	1.1	23.0	67.0	8.9	
MAB/06/5/4	2.3	10YR 7/3	187	2.2	3.1	28.2	57.9	10.6	Calcrete present
MAB/06/5/5	3.0	10YR 7/3	193	1.7	1.6	25.8	67.0	5.7	Calcrete present
MAB/06/5/6	3.2	10YR 7/3	204	1.6	2.7	28.5	64.6	4.2	

Munsell colours for each sample are also indicated as well as qualitative sediment properties.

Resolution Gamma Spectrometry (HRGS) showed broad agreement with ICP-MS derived concentrations. The very low count rate from samples measured using HRGS however, resulted in a poor signal to noise ratio and gave little insight (e.g. through the comparison of $^{226}Ra/^{238}U$ ratios) into the present day existence of disequilibrium within the decay chain.

Sample ages are shown stratigraphically in Figure 3. With few exceptions the 29 ages that were determined were found to be chronostratigraphically sensible within 1 sigma errors, and consistent in terms of depositional phases recorded at the different sites. Ages range from 37.7+/−5.6 ka at 7 m depth at site MAB/06/2, to 1.9+/−0.3 ka at 1 m depth at MAB/06/5, from the Parakarungu sand ridge. Minor inversions were found within core MAB/06/2, with MAB/06/2/4 possessing notable chronostratigraphic discrepancies with both overlying and underlying sample ages. Large numbers of seeds found within this sample during laboratory preparations may have been responsible for an underestimated dose rate producing an anomalously old age. The deepest samples from core MAB/06/1 may have been affected by hole collapse during sampling. Initial processing revealed anomalously young ages for samples MAB06/1/10 and 11 and therefore data for these samples are not included in Figure 3 nor in the subsequent interpretation and discussion of the chronology of beach ridge construction in the Mababe Depression.

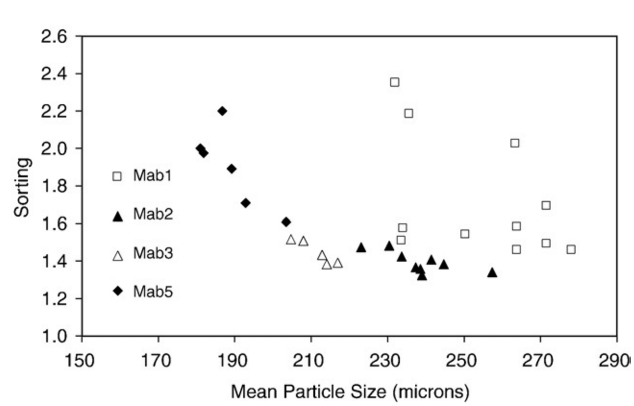

Figure 4. Relationship between mean particle size and sorting for all samples dated within this study.

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Discussion

The Mababe depression shorelines

The ages presented here suggest beach ridges were not constructed in a single transgression event, but are composite landforms constructed from stacked depositional events during multiple lake high stands. Broadly, these high stand phases are identified at 6.6±0.8 to 5.2±0.6; 9.95±1.03 to 8.4±1.14; 18.2±2.1 to 12.4±1.8 and 37.7±5.6 to 35.0±5.1 ka. The persistence of lake transgression during the beach construction phases recorded here is impossible to determine. The precision of the OSL chronology for this period is, as yet, unable to adequately distinguish between prolonged periods of high lake levels, and punctuated extreme events resulting in an overall mean positive hydrological balance within high stand phases. It should be stressed that, due to the nature of terrestrial deposits and the possibility of erosion or non-preservation of the shoreline sediments, the 'gaps' in the record do not necessarily indicate lake absence, in constrast to the dated units which unequivocally infer lake presence. Despite these limitations in the dataset, the existence of an extensive lake body in the Mababe depression implies a significant deviation from the conditions of the present day hydrological system in the middle Kalahari.

Potential avulsion mechanisms operating in the Okavango Delta and the sensitivity of the system to minor changes in flow distribution, for example caused by subtle tectonic movements (Modisi et al., 2000) can affect flow into the basin. It is therefore vitally important to examine the causes and significance of transgression phases identified in the Mababe basin in the context of previously identified lake high stands at lake Ngami which lies at the terminus of a separate distributary in the south west. of the Okavango Delta.

Lake Thamalakane

The consistency of shoreline altitudes within the Ngami, Mababe and Makgadikgadi basins has led many researchers to infer a mega-lake system formed from the unification of these sub-basins into a single system during periods of increased precipitation or fluvial input in the late Quaternary (e.g. Heine, 1978; Cooke and Verstappen, 1984; Shaw et al., 1988). The 936 m and 945 m asl ridges are common to the western and northern margins of these sub-basins and have been inferred to represent the Lake Thamalakane (Shaw, 1988) and Lake Palaeo-Makgadikgadi (Grey and Cooke, 1977) configurations respectively (Fig. 2).

Identification, both in the Mababe Depression and the Ngami basin, of beach ridges as composite stacked landforms, renders

Table 4
Mababe Depression and Chobe Enclave OSL data

Site Location	Sample	Depth (m) ±0.2	K (%) ±0.01	Th (ppm) ±0.1	U (ppm) ±0.05	Mean cosmic dose (Gy/ka)	Water content (%) ±20%	Total dose rate (Gy/ka)	De (Gy)± 1 σ	Overdispersion± 1 σ	Final age (ka)
Southern Magikwe Ridge (936–940 m asl)	Mab-06-1-1	1.00	0.09	0.63	0.20	0.21	0.04	0.38±0.21	1.01±0.54	0.43±0.06	6.6±0.8
	Mab-06-1-2	1.50	0.08	0.61	0.16	0.21	0.07	0.35±0.05	2.16±0.13	0.28±0.05	6.0±0.9
	Mab-06-1-3	2.00	0.07	0.48	0.16	0.20	0.08	0.32±0.04	2.10±0.08	0.35±0.03	6.3±1.1
	Mab-06-1-4	2.50	0.07	0.53	0.19	0.20	0.09	0.33±0.05	4.93±0.35	0.29±0.05	14.5±2.4
	Mab-06-1-5	3.00	0.08	0.61	0.18	0.19	0.05	0.35±0.04	5.18±0.24	0.18±0.03	14.6±1.9
	Mab-06-1-6	3.50	0.10	1.53	0.24	0.18	0.08	0.42±0.05	7.70±0.38	0.18±0.04	18.2±2.2
	Mab-06-1-7	4.00	0.06	0.60	0.13	0.19	0.05	0.31±0.05	11.05±0.25	0.07±0.02	35.0±5.1
	Mab-06-1-8	4.50	0.06	0.57	0.15	0.18	0.02	0.31±0.04	11.30±0.22	0.05±0.02	35.8±5.0
	Mab-06-1-9	5.00	0.08	0.65	0.18	0.17	0.04	0.33±0.04	11.96±0.24	0.08±0.02	35.6±4.0
Savuti Outer Magikwe Ridge (940 m asl)	Mab-06-2-1	1.00	0.04	0.53	0.15	0.21	0.04	0.31±0.05	1.73±0.09	0.18±0.04	5.5±0.6
	Mab-06-2-2	2.00	0.07	0.56	0.18	0.20	0.05	0.34±0.05	2.83±0.15	0.22±0.04	8.4±1.1
	Mab-06-2-3	3.00	0.03	0.49	0.17	0.19	0.04	0.29±0.05	4.21±0.13	0.14±0.02	14.5±2.5
	Mab-06-2-4	4.00	0.03	0.34	0.12	0.17	0.02	0.25±0.06	4.17±0.10	0.10±0.02	16.8±1.7
	Mab-06-2-5	4.50	0.06	0.58	0.14	0.21	0.02	0.34±0.05	4.16±0.08	0.08±0.02	12.4±1.8
	Mab-06-2-6	5.00	0.03	0.38	0.13	0.19	0.05	0.28±0.06	3.97±0.09	0.07±0.02	14.3±3.3
	Mab-06-2-7	5.50	0.04	0.45	0.19	0.19	0.05	0.29±0.05	4.89±0.17	0.14±0.03	16.7±3.1
	Mab-06-2-8	6.00	0.07	0.53	0.20	0.18	0.07	0.32±0.05	5.76±0.18	0.12±0.03	18.1±2.6
	Mab-06-2-9	7.00	0.05	0.51	0.19	0.19	0.03	0.31±0.05	11.73±0.32	0.10±0.02	37.7±5.6
Inner Magikwe Ridge (936 m asl)	Mab-06-3-1	1.00	0.08	0.86	0.22	0.21	0.05	0.39±0.05	2.00±0.16	0.31±0.06	5.2±0.6
	Mab-06-3-2	2.00	0.10	0.73	0.25	0.20	0.07	0.39±0.04	3.84±0.16	0.18±0.03	10.0±1.0
	Mab-06-3-3	3.00	0.09	0.81	0.23	0.18	0.08	0.36±0.04	4.53±0.14	0.15±0.02	12.5±1.3
	Mab-06-3-4	4.00	0.06	0.49	0.21	0.17	0.06	0.30±0.04	4.52±0.09	0.06±0.02	15.1±1.5
	Mab-06-3-5	4.50	0.08	0.49	0.25	0.17	0.06	0.33±0.04	4.53±0.14	0.11±0.03	13.4±1.9
Parakarungu Ridge (936 m asl)	Mab-06-5-1	1.00	0.06	0.63	0.18	0.21	0.05	0.35±0.06	0.65±0.49	0.43±0.07	1.9±0.3
	Mab-06-5-2	1.50	0.04	0.62	0.20	0.21	0.06	0.32±0.05	2.21±0.08	0.19±0.04	6.8±1.0
	Mab-06-5-3	2.00	0.06	0.78	0.20	0.20	0.08	0.34±0.04	2.86±0.09	0.11±0.03	8.4±1.1
	Mab-06-5-4	2.30	0.06	0.42	0.29	0.20	0.08	0.33±0.04	4.21±0.11	0.09±0.02	12.7±1.3
	Mab-06-5-5	3.00	0.03	0.40	0.24	0.19	0.08	0.29±0.05	4.43±0.10	0.02±0.01	15.1±2.5
	Mab-06-5-6	3.20	0.03	0.58	0.25	0.18	0.08	0.29±0.04	4.77±0.13	0.03±0.07	16.2±2.4

D_e values were calculated using a central age model (Galbraith et al., 1999). All uncertainty values are given as one standard error and combined for age calculations using standard error propagation methods (Taylor and Kuyatt, 1994).

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the altitude of ridges of less importance than previously envisaged. Instead, the extent of water bodies confined by the ridges is of more importance. The general inter-basin consistency of shoreline altitudes suggests that though tectonic movements (Cooke, 1980; Gumbricht et al., 2001) have been widely reported including in association with subsidence within the Okavango graben, their impacts on the hydrology of the interconnected lake system have been either minimal or uniform between basins. The consistency of ages across the basins suggest that the altitudinal variation in the Magikwe ridge (Gumbricht et al., 2001), if due to tectonic movement, is likely to postdate the last major basin-full phase (6.6±0.8 to 5.2±0.6 ka). However there may well be other explanations for altitudinal variation along the ridge, including aeolian deposition, and postdepositional denudation.

At the extent of the 936 m ridge in the Mababe Depression, the lake would have been an open basin system connected to Lake Ngami and at a level controlled by outflow through the Boteti River to the Makgadikgadi basin. Shaw et al.(1988) postulated, on hydrological grounds and on not identifying a 936 m ridge in Makgadikgadi, that the 936 m level in Lake Thamalakane would have been coincident with a lake at 920 m in Makgadikgadi. The extent of the lake in Makgadikgadi is unknown but other estimates using SRTM data have suggested a higher and more extensive lake level in Makgadikgadi and a total surface area of the 936 m lake of ~32,000 km^2 (White and Eckardt, 2006). The concurrence of these ridge-building phases requires rigorous direct dating of the Makgadikgadi shorelines before it can be confirmed or refuted. Using geomorphological evidence, Shaw (1985) suggested that the 936 m level was reached on at least two occasions in Mababe, based principally on the existence of terraces on the Ngwezumba, Savuti, and Mababe rivers (the inlet to the Mababe swaps in the south of the basin) which would have cut through the eastern and western shorelines as lake levels receded. Some of these levels are associated with ^{14}C ages on calcrete or molluscs (Table 2).

Secure dating of the beach ridges in Makgadikgadi has not yet been achieved, but an intensive drilling and OSL dating programme in Ngami has recently established a reliable chronology for shoreline building events in that basin, extending the record of lake high stand phases back to 140 ka (Burrough et al., 2007). Inter-basin comparisons of lake high stands, made possible by the ages presented here, facilitate a classification of ridge building episodes into those that represent a response to a significant palaeoclimatic shift, and those that have been recorded only within an individual basin. While single-basin identification might be a product of sampling in the field, this has been to some extent mitigated against given the full beach ridge-profile sampling and dating strategy employed. More likely is that these effects are a product of upstream flow redistribution within the Okavango Delta channel distributary system (*sensu* McCarthy et al., 1992).

While the record of beach ridge construction at Lake Ngami shows greater antiquity than that of the Mababe Depression, there is a high level of consistency in the lake high-stand chronologies of the two basins over the last 40 ka (Fig. 5). During the late Pleistocene, wave-built ridges were emplaced in the western Mababe basin between 38±6 ka and 35–36±5 ka consistent with the construction of Ngami's Dautsa Ridge between 38±3 ka and 30±3 ka (Burrough et al., 2007) and the presence of diatom rich sediments laid down at 35.6±3.85 ka and 40.5±3.2 ka (Huntsman-Mapila et al., 2006). Shoreline emplacement at 32±2 ka was also found in the Kareng Ridge on the western limits of the Ngami basin suggesting this high lake phase was particularly extensive in the Ngami basin. This phase is also concurrent with the ponding back of water in the Boteti River channel, which links the Thamalakane system with the Makgadikgadi basin. Diatom beds at Moremaoto, indicative of the presence of a shallow water body, are bracketed by OSL dates at 32±2 ka and 28±2 ka (Shaw et al., 1997). These deposits may indicate a period of backflooding up the Boteti due to the presence of a lake in Makgadikgadi at this time, though confirmatory dating of lake stages in that basin is required to verify this.

Intensive shoreline emplacement is recorded in both basins during the post-glacial period 18–13 ka suggesting a greatly increased hydrological budget at this time. Evidence of activity within the Ngwezumba River and Savuti Channel is also provided by mollusc ^{14}C ages (Table 2). It again suggests that while lake high stands and a positive hydrological budget dominated the post-glacial period, there was considerable variability in inflow and the basin is likely to have been subject to substantial fluctuations in lake level. However, the Kerang Ridge in Ngami, at 938–940 m asl, has been OSL dated to 12.4±1.1 ka (Burrough et al., 2007), an age consistent with ridge aggradation in the Mababe basin. Furthermore, the recording of sand-ridge construction at site MAB/06/5 at 16.2±2.4 ka, 15.1±2.5 ka, and 12.7±1.3 ka confirms the extent of a substantial body of water including Ngami in the west to the Zambezi–Chobe confluence in the east during this late-glacial period.

A transgression of palaeolake Thamalakane also seems to have occurred during the early-mid Holocene. Phases of ridge building occurred on the western shoreline of Mababe at 8.4±1.1 ka, 6.6–6.3±1.1 ka, 5.5 –5.2±0.6 ka consistent with high lake stands found in the Ngami basin and with increased inflow through the Okavango panhandle (Nash et al., 2006). Interestingly, high lake stands at this time have also been found as far west as Etosha where shorelines indicate high lake stands at 6.4±1.0 ka as well as later periods at 4.0±1.4 ka and 2.1±1.0 ka (Brook et al., 2007).

The role of the Zambezi in Lake Thamalakane high stands

130 km to the north east of the Mababe Depression, the Mambova Falls marks the Chobe–Zambezi confluence where the rivers flow east across a Karoo basalt ridge along a north–south oriented fault line. During present-day peak flows, the impediment of the ridge produces annual backflooding up to 20 km westwards along the Chobe during peak flow in the Zambezi (Thomas and Shaw, 1991). Covering an estimated surface area of 2000 km^2, the backflooded zone must have been stable enough to significantly impact upon the geomorphology of the floodplain and it is thus referred to in the literature as “Lake Caprivi.” Higher levels of flooding during the Quaternary are evident at the Mambova fault from erosional notches along

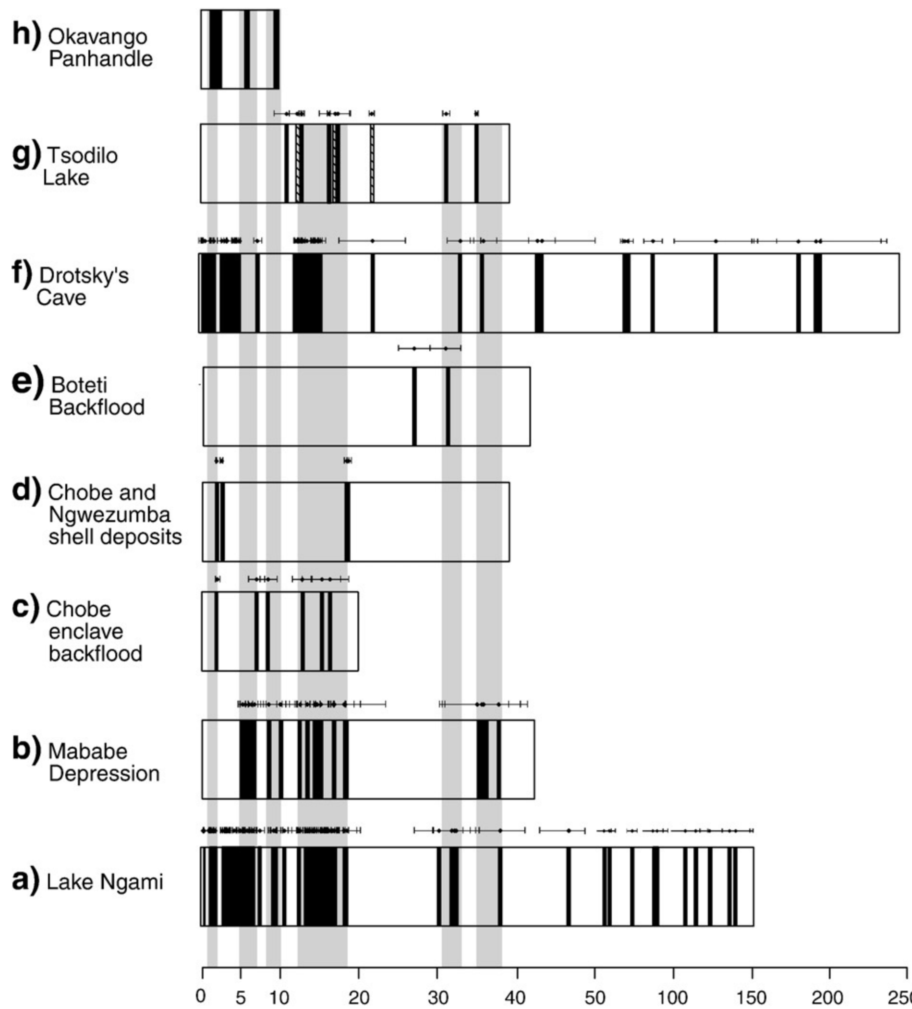

Figure 5. Wet-phase chronologies for geomorphological features in the Middle Kalahari (Lake Thamalakane phases shaded in grey) Black bars within columns refer to dated wet phase proxies. Actual dates and their associated errors are plotted adjacent to these columns. a) Lake Ngami high stands (Burrough et al., 2007) b) Mababe Depression lake high stands (this study); c) Chobe Enclave backfloods (this study); d) Lake Caprivi: Serondella and Ngwezumba terrace shell deposits (Shaw and Thomas, 1988) e) Boteti backflood (Shaw et al., 1997) f) Drotsky's Cave Speleothems (Cooke, 1975; Cooke and Verhagen, 1977; Shaw and Cooke, 1986; Brook et al., 1996; Robbins et al., 1996.) g) Tsodilo Hills (Robbins et al., 1994; Thomas et al., 2003), h) Panhandle Pollen Record (Nash et al., 2006).

the hillslope at 935 m asl, and calcretised alluvial terraces at 932–4 m asl (Shaw and Thomas, 1988).

At 936 m asl, the sand ridges on the Chobe enclave mudflats have equivalent altitude, orientation and granulometric characteristics (Fig. 3), to the Magikwe, Dautsa and Kerang ridges of Palaeolake Thamalakane. These floodplain beach ridges are likely to have been formed as either offshore bars or shorelines during stabilised periods of backflooding within the Chobe–Zambezi confluence that caused water to back up along the Chobe and become impounded between the channel and the Escarpment (see Fig. 2b). OSL ages from the most prominent of the 936 m asl ridges at Parakarungu (MAB06/5) confirms that phases of ridge building were consistent with those of the Mababe Depression and Lake Ngami. Ridge construction at 1.9±0.3 ka, 6.8±1.1 ka, 8.4±1.1 ka, 12.7±1.3 ka, 15.1±2.5 ka and 16.2±2.4 ka have corollaries in both Ngami and Mababe (see Fig. 5). Gastropods from the 934 m asl terrace at Serodella have been dated by ^{14}C to 18.6±0.28 cal kyrs BP (Shaw and Thomas, 1988), concordant with the onset of the post-glacial lake Thamalakane phase. Together, these ages confirm that 'Lake Caprivi' and the Chobe Enclave were an additional component to the unified lake system along the Thamalakane axis, and provide further evidence for the role of backflooding from the Zambezi–Chobe confluence at Mambova as an amplifying or causal role in high lake stages along the Thamalakane axis. The common catchment region of the Zambezi, Kwando and Okavango mean that similar hydrological shifts in all three rivers are likely to have contributed to high lake stands within the sub-basin sumps. The Okavango and Kwando flow would have been directed via the Okavango Delta distributaries and Linyanti swamps respectively but in addition, the backing up of water behind the Zambezi–Chobe confluence described above provides a plausible and likely mechanism of directing Zambezi flow towards these basins.

Hydrological factors affecting Palaeolake Thamalakane

The volume of water required to sustain a lake along the Thamalakane axis to the Mambova Falls to the extent of the

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936 m asl ridges would be substantial. At its present day configuration, even if no allowance is made for likely outflows via the Boteti (and the possibility of a contemporaneous lake in the Makgadikgadi) then a basin inflow of $\sim 7\times10^9$ m^3 yr^{-1} under present climatic conditions (60% of the today's Okavango–Linyanti inflow prior to evapo-transpiration losses) would be required to maintain such a lake (Shaw, 1985). Little is known about the source of this significantly increased hydrological budget or whether it is derived from climatic changes in the upper Okavango and Kwando/Chobe catchments of central Angola or from local shifts in climate or as a response to the combination of both. Unravelling these different roles, plus potential feedback-effects of a large water body on local rainfall, is complex (Burrough et al., 2007). The presence of Lake Caprivi in the lee of the Chobe–Zambezi confluence and its associated Chobe enclave backflood is informative in that it may suggest that increased flow (compared to present) in the Zambezi system also contributed to the Middle Kalahari lake phases in both the post-glacial and Holocene periods. However, the initial forcing of this increased hydrological input is difficult to decipher: backflooding from the Chobe–Zambezi confluence zone could have been either caused by increased flow in the Zambezi or a result of enhanced outflow from Lake Thamalakane along the lower course of the Chobe.

Like many large palaeolakes including comparable subtropical basins in the northern hemisphere such as palaeolake Chad, the catchment of palaeolake Thamalakane spans several degrees of latitude covering a wide climatic gradient. A comparison of the timing of Lake Thamalakane high phases with both records from tropical latitudes equivalent to the catchment zone of the contributory river systems and local archives of direct rainfall increases is required in order to better understand the causal factors of such a greatly increased hydrological budget.

Tropical records

The amplitude and phase relationship between the characteristically humid tropics and the dry subtropical zone is likely to have varied significantly during the Quaternary in response to the average position of the Inter Tropical Convergence Zone (ITCZ) on which summer rains are dependent. The location of the ITCZ is influenced by several climate drivers including fluctuations in precessional insolation and sea surface temperatures (SSTs) both within and between the Atlantic and Indian Oceans (e.g. Pokras and Mix, 1987; Stokes et al., 1997; Barker and Gasse, 2003; Dupont and Behling, 2006). A significant body of literature has focused on establishing wet and dry phases by examining depositional records within tropical lake basins, particularly within east Africa. Many of these records lack a robust chronology beyond the Last Glacial Maximum (LGM). However, within the post-glacial period there is now consistent evidence for the onset of a positive hydrological balance between 18 and 15 ka (Gasse, 2000 and references therein). Particularly pertinent is the record of Lake Malawi which lies in the tropics at a similar latitude to the upper catchment of the Okavango, Kwando and Zambezi. Filippi and Talbot (2005) have shown, through the use of geochemical and lithological data in combination with earlier interpretations of diatom assemblages (Gasse et al., 2002), that high lake levels existed here between 18 and 12 ka with a fall to a low lake level stand at 11.7 ka that persisted until 10 ka. This shift to more humid conditions following an arid LGM is consistent with the record of the south west African tropics where pollen spores derived from a zone between 13°S and 21°S (including the Angolan highlands) suggest an amelioration in LGM aridity at 17.5 ka cal BP (Shi et al., 1998; Dupont and Behling, 2006). A tropical wet phase in the upper catchments of the Okavango, Kwando and Zambezi channels is thus a very likely driver of the Lake Thamalakane post-glacial high stand phase.

Lake Tritrivakely in the Madagascan highlands is 2500 km to the east of the Mababe Depression, but at a similar latitude (19°47’S). A 40 ka multi-proxy record that includes the analysis of organic matter, mineral magnetic properties, pollen and diatoms suggests Lake Tritrivakely experienced stages of positive mean annual hydrological balance leading to a permanent water body in the intervals 38,000–32,000 and 17,500–7000 cal yrs BP (Gasse and Van Campo, 1998). Since Lake Tritrivakely is a crater lake, which is almost entirely fed by local precipitation and runoff, the strong correlation of high stand timings with Lake Thamalakane is potentially indicative of a significant increase in precipitation at this latitude, though its presence within the Indian Ocean is likely to have resulted in a stronger forcing of precipitation by a more effective monsoon than in central southern Africa.

The occurrence of large scale changes in the late glacial, over spatially diverse sites, implies a major reorganisation of climate at this time rather than merely a localised hydrological shift. Climatic reorganisation does not necessarily invoke a single rain-bearing system but could involve both westerly and easterly incursions, a shift in the mean position of the ITCZ and the affect of a significant number of biophysical feedbacks following an initial triggering mechanism. Without accurate regional scale modelling, the configurations of reorganisations would be mere conjecture. Nevertheless, it seems increasingly evident that the regional increase in effective precipitation occurs consistently earlier in the southern hemisphere (even within errors) relative to the records of equatorial and northeast African lake basins where the onset of wetter conditions is typically placed two to three thousand years later at ~15 ka (e.g. Williams et al., 2006).

Local records

Shaw (1985) has estimated that a 160–225% increase in local precipitation above present levels would be required in order to maintain Lake Thamalakane. There is a significant volume of evidence within local late Quaternary records to suggest a coherence between high lake phases and local precipitation (Fig. 5). At Tsodilo, an important archaeological site with a localised catchment to the west of the Okavango Delta, a deep lake phase has been identified from mollusc and diatom deposits and dated using ^{14}C measurements on shells to between 36 and 32 cal kyrs BP. A subsequent shallow phase between 17 and 13 ka during which time a low lake shoreline was built is also concurrent with the presence of Lake Thamalakane (Thomas et al., 2003).

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Close to Tsodilo, a unique pollen, sediment and stable carbon isotope record from tributaries associated with Okavango Delta Panhandle flow has been investigated. This record suggests a wet phase or period of enhanced Okavango flooding at ~9 cal kyrs BP on the basis of increased accumulation of organic matter within floodplain sediments. This is consistent with the deposition of shorelines between 9.95±1.0 and 8.4±1.1 ka at Mababe and 9.4±0.6 and 9.2±0.5 at Ngami. Nash et al. (2006) report relatively dry conditions, from 7 to 4 cal kyrs BP, punctuated by a short wet phase at around 6 cal kyrs BP. This wet phase is recorded as a high lake stand in the Mababe depression between 6.6±0.8 and 5.2±0.6 ka although it appears to persist for much longer (at least until 4.9±0.4 ka) in the record at Lake Ngami (Burrough et al., 2007). In a review of other southern African Holocene sites, Nash et al. (2006) point out the relatively wet conditions reported in other middle Kalahari records at this time (i.e. Drotksys and Bone Caves (Brook et al., 1996), Stampriet–Auob aquifer (Heaton et al., 1983; Stute and Talma, 1998), Tsodilo Hills (Thomas et al., 2003) and Kathu Pan (Beaumont et al., 1984) as well wider records from the southern Kalahari at Equus Cave (Scott, 1987) and Wonderwerk cave (Butzer, 1984)). They infer that the 7–4 cal kyrs BP drier period evident in the Panhandle represents a wetland ecosystem response to reduced rainfall over the Okavango headwaters in Angola, and thus lower flood levels in the Okavango River, rather than a regional dry phase. The record of Lake Thamalakane supports this assertion: while the individual record from Lake Ngami alone suggests low flow periods at this time may well have caused flow redistribution within the Delta that favoured the westernmost feeder distributaries to this sub-basin sump.

Drotsky's Cave in the Gchwihaba Hills to the east of the Okavango Delta contains large relict speleothems. The length of this record renders it a unique and important independent record of effective precipitation in the middle Kalahari. Sinter growth here is highly dependent on rainfall and depositional phases can thus be related to phases wetter than the present day conditions. A sequence of ages, comprising 15 ^{14}C dates (Cooke and Verhagen, 1977), 15 U/Th dates (Brook et al., 1996) and an additional eight dates measured on paired samples using both methods (Shaw and Cooke, 1986), have been used to identify localised wet phases (Fig. 5). Speleothem growth at 37±1.7 ka and 34±1.7 ka, between 16.2±0.2 and 13±0.2 ka and at 8.2±0.5 ka is consistent with Lake Thamalakane high stands. In addition to this, faunal and archaeological evidence within the cave, dated using ^{14}C measurements suggest the interval between 17,500 and 11,000 cal yr BP may have been particularly moist (Robbins et al., 1996). Wet phases at Drotsky's Cave however, are not exclusively correlated with lake phases in the middle Kalahari which supports the assertion that local rainfall can be, at times, decoupled from the positive hydrological balance of the Okavango basins. It may also be that the shoreline deposition records exhibit a level of discontinuity that means significant lake phases have not yet been sampled or identified.

To the south east of the lake system in Zimbabwe, dune building phases, identified from OSL ages taken from pit samples, occurred in antiphase to high lake stands at 115–95, 46–41 and 26–20 ka (Stokes et al., 1997, 1998). In contrast, dune construction in western Zambia, occurred in-phase with periods of high lake levels at 32–27, 16–13 and 10–8 ka (O'Connor and Thomas, 1999). These dunes lie to the west of the Zambezi River and their formation, as source-bordering dunes, might be coincident with high-flow phases especially if a more active easterly monsoon led to higher wind velocities. However, these entire dune chronologies are based on OSL ages constructed using old laboratory protocols, especially the use of multiple aliquot additive dose (MAAD) techniques to obtain D_e values. Few studies have re-measured earlier age determinations but in other regions of the world, re-dated samples using a Single Aliquot Regeneration (SAR) protocol have found discrepancies of up to 84% with old MAAD generated ages (Duller and Augustinus, 2006). It is therefore presently advisable to treat these chronologies of dune construction with caution, until samples are reprocessed and ages revalidated or revised.

Conclusion

High-resolution OSL dating in conjunction with penetrative sampling techniques has demonstrated the extent and nature of high lake stands within the Mababe and Ngami basins. The intermittent existence of a large unified lake body, Lake Thamalakane, produced by the coalescence of two sub-basins subject to phases of high lake stands at the distal end of the Okavango drainage system now seems beyond doubt. Multiple phases of lake high stands have been identified at 38–35 ka; 18–13 ka; and between 10 and 8.4 ka and 6.6 and 5.2 ka. Beach ridges from Parakarungu in the Chobe enclave were also emplaced synchronously with Lake Thamalakane phases suggesting that increased flow in the Chobe and Zambezi system also contributed to the Middle Kalahari lake phases in both the post-glacial and Holocene periods. These episodes of positive hydrological balance show incomplete but consistent correlations with both tropical and local rainfall records and suggest that both played a role in contributing to Lake Thamalakane high stands. Both Thamalakane high stands and its possible desiccation phases add a level of complexity to interpreting the emplacement of other localised geomorphological features, such as dunes, over the Late Quaternary. The full extent of palaeolake phases in the Middle Kalahari has not yet been tested and a systematic dating programme of the Makgadikgadi shorelines is currently underway.

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