

THE EVOLUTION AND AGES OF MAKGADIKGADI PALAEO-LAKES: CONSILIENT EVIDENCE FROM KALAHARI DRAINAGE EVOLUTION

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ABSTRACT

The Makgadikgadi Pans in northern Botswana are the desiccated relicts of a former major inland lake system, with fossil shorelines preserved at five distinct elevations (~995 m, 945 m, 936 m, 920 m and 912 m). These lakes persisted in the Makgadikgadi Basin, which evolved in the Okavango-Makgadikgadi Rift Zone: the south-western extension of the East African Rift System (EARS) into northern Botswana. This paper synthesizes cross-disciplinary evidence, which reveals that the antiquity of this lake complex has been widely underestimated. It presents a Regional Drainage Evolution Model that invokes tectonically initiated drainage reorganizations as the underlying control over lake evolution. Lake formation was initiated by rift-flank uplift along the Chobe Fault, across the course of the Zambezi River, which diverted the regional drainage net into the Makgadikgadi Basin. Filling of the basin initiated a major climatic feedback mechanism that locally increased rainfall and lowered evaporation rates. This progressively enhanced water input to the basin, and most likely led to overtopping of the Chobe Horst barrier during the three highest lake stands, with outflow into the Zambezi River. During this period, the hydrology of the basin would have been closely analogous to modern, shallow Lake Victoria. Fragmentation of the regional drainage network by successive river captures resulted in sequential contractions of the lake to lower elevation shorelines. In turn, resultant decreases in areas of these successive lakes modulated the magnitude of the feedback mechanism. Thus, loss of the Upper Chambeshi catchment caused the lake to drop from the 990 to the 945 m level. Severance of the former link between the Kafue and Zambezi resulted in a further drop to the 936 m shoreline. Inflow declined further after the impoundment of a major lake (Palaeo-Lake Bulozzi) on the Upper Zambezi River, causing contraction to the 920 m shoreline. Continued incision of the Zambezi channel into the Chobe horst barrier ultimately terminated input from this river to the Makgadikgadi depression, causing contraction of the lake below 920 m, sustained by the Cuando and Okavango prior to final desiccation. This Regional Drainage Evolution Model contradicts previous proposals that have invoked Late Pleistocene climatic forcing to explain inferred fluctuations in lake levels. The timeframe developed for the drainage reorganizations requires that the lake was initiated by ~1.40 to 0.51 Ma at the most recent (Early – Mid-Pleistocene), while archaeological evidence shows that it had contracted below the 936 m shoreline before 500 ka. This contrasts with ¹⁴C and quartz luminescence dates (generally <100 ka), which require that the 945 m lake stage was extant during much of the Upper Pleistocene. The calcareous radiocarbon dates reflect multiple episodes of calcrete formation, while the young luminescence dates are ascribed to the extensive bioturbation of older Kalahari landforms.

Introduction

The landscape of northern Botswana is a complex mosaic of fossil landforms. Degraded eastwest oriented linear dunes indicate former episodes of extreme aridity, while fossil drainage lines provide evidence of a once well-watered environment, and the desiccated Makgadikgadi Pans are relicts of a former major inland sea (Figures 1 to 3).

Recent literature reflects an upsurge of interest in the origin and temporal links between these landforms, and their importance for understanding Plio-Pleistocene palaeo-environments of south-central Africa (Ringrose et al., 2005; 2009; Huntsman-Mapila et al., 2006; Moore et al., 2007; Burrough and Thomas, 2008; 2009; Burrough et al., 2007; 2009a; b; Moore and Cotterill, 2010).

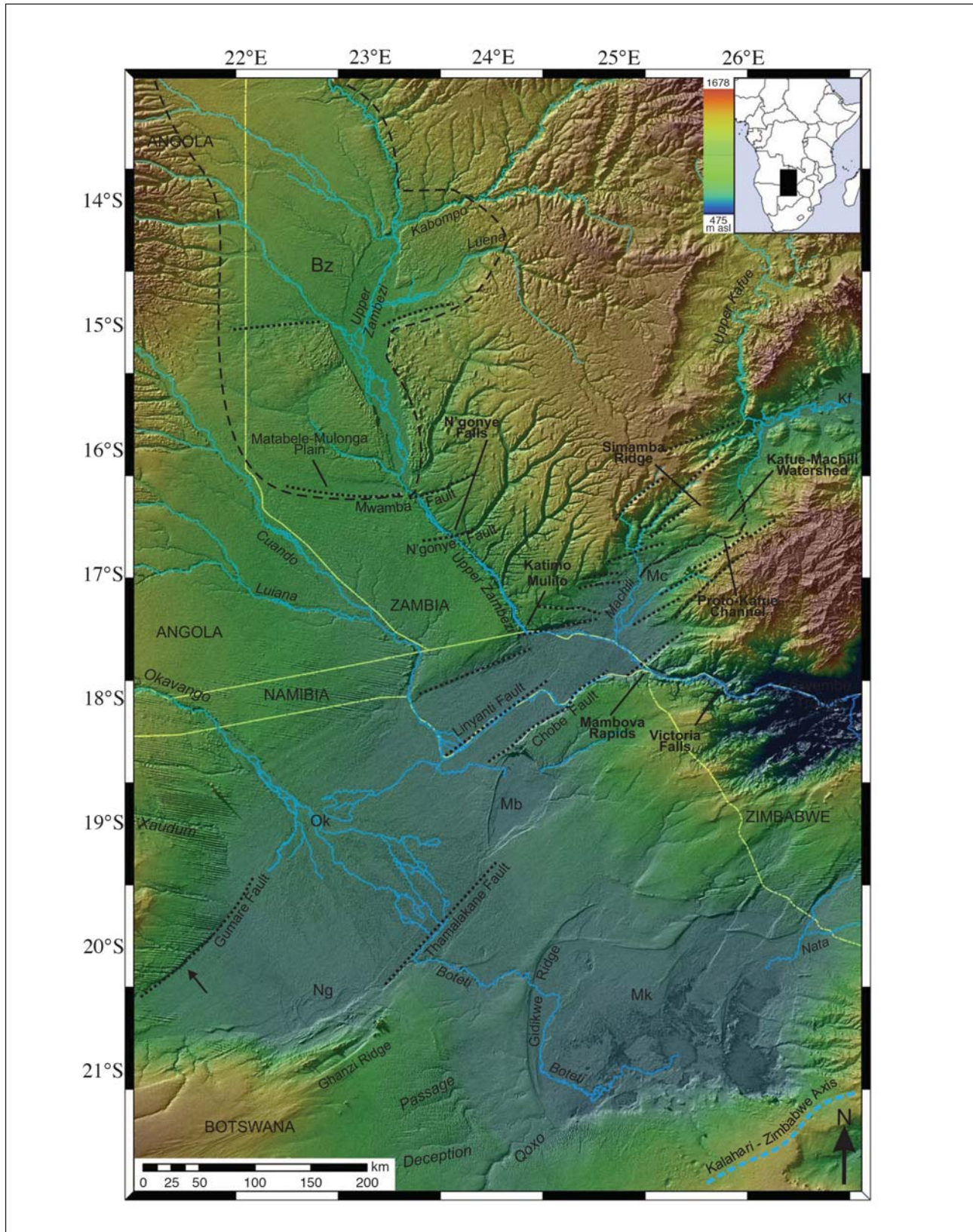


Figure 1. The subtle topographic relief of the Kalahari Plateau, using side-shaded SRTM-4 imagery, reveals widespread fault control (dotted lines) across the Buluzi, Machili and Okavango graben (arrow denotes truncated dunes along the Gumare Fault). Extending southeast of the Simamba Ridge as a topographic low: the shallow Kafue-Machili watershed dividing the Kafue (Kf) and Machili graben is straddled by an abandoned drainage channel (bold, dashed line) attributed to the Proto-Kafue River, when it was a major north bank tributary of the Zambezi. Bz = Palaeo-Lake Buluzi (dashed line approximates its extent) occupied in part today by the Barotse Floodplain; Mb = Mababe Depression; Mc = Machili graben; Mk = Makgadikgadi Pans; Ng = Lake Ngami; Ok = Okavango Delta.

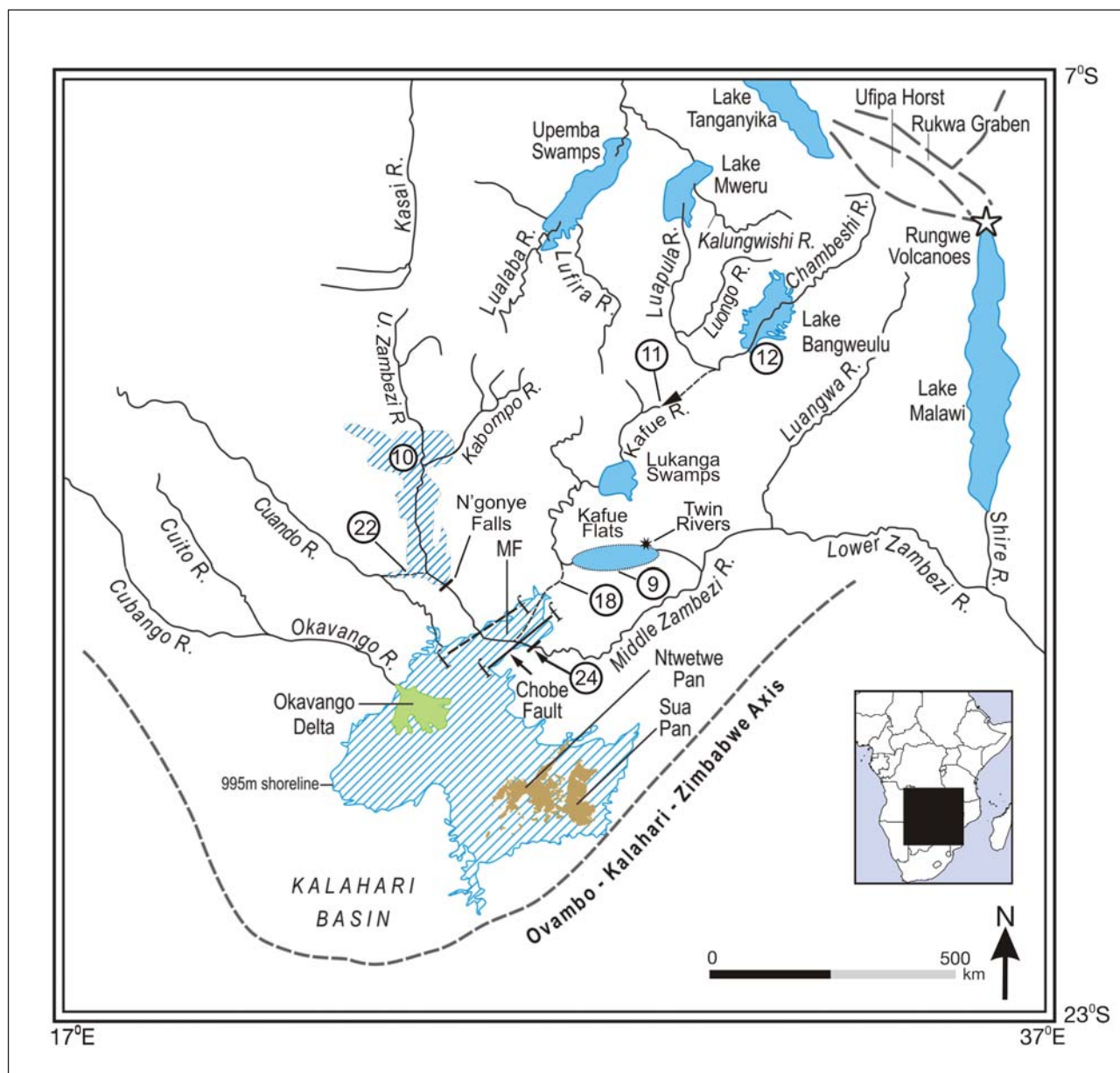


Figure 2. The modern drainage systems of south-central Africa depicting landforms and formative events discussed in the Regional Drainage Model. Numbered landforms (Table 1) include: Palaeo-Lake Bulozzi (PLB) (10); the former link between the Upper Chambeshi and Upper Kafue Rivers (11); the former link between the Kafue and Upper Zambezi Rivers (18); Palaeo-Lake Patrick (PLP) (9); Matabele-Mulonga Floodplain; (22); and Victoria Falls (24).

This paper re-evaluates the antiquity, and historical relationships among principal landforms of the portion of the high plateau of south-central Africa (designated the Kalahari Plateau; de Wit, 2007; Cotterill and de Wit, 2011) centred on the Makgadikgadi Basin. Our aim is to integrate independent lines of evidence for tectonics, and the evolution of the regional drainage and key arid landforms. We focus on the Plio-Pleistocene history of rivers that today comprise the Zambezi and Upper Congo systems (Moore and Larkin, 2001; Goudie, 2005; Cotterill and de Wit, 2011), with particular emphasis on the Victoria Falls and downstream Batoka Gorges (Cotterill, 2006; Moore and Cotterill, 2010). This synthesis structures a Regional Drainage

Evolution Model (hereafter termed the Regional Model) focused on the Makgadikgadi palaeo-lakes (Tables 1 and 2, Figures 1 and 2). It links sequential configurations of the regional drainage net (and their respective inflows) to tenures of discrete lake stands, and invokes a climatic feedback mechanism, which modulated rainfall and evaporation over the largest lakes.

The main body of evidence synthesizes published geomorphological data, supported by SRTM-4 imagery (Shuttle Radar Telemetry Mission, Kobrick, 2006). Structured by details of landform evolution, climatological, archaeological, and biological evidence inform key aspects of its synthesis:

Table 1. Plio-Pleistocene context of principal lacustrine and fluvial landforms, and their associations with geomorphological events on the Kalahari Plateau, south-central Africa. Inferred formative events and evidence correspond to respective landforms; their numbering follows a chronological sequence, corresponding to mapping of their geographical context in Figures 2 and 7. Abbreviations: Early Stone Age (ESA); Middle Stone Age (MSA); Late Stone Age (LSA); Kalahari Plateau (KP); Lake Bangweulu including Upper Chambeshi River (Bw); Okavango Delta and Cubango River (Ok); Palaeo-Chambeshi River (PC); Palaeo-Lake Deception (PLD); Palaeo-Lake Makgadikgadi (PLM); Palaeo-Lake Patrick (PLP); Palaeo-Lake Thamalakane (PLT); Palaeo-Lake Buluzi (PLB); Proto-Kafue River (PK); Upper Kafue River (UK); and Upper Zambezi River (UZ). Data Sources are ordered chronologically: ¹Dixey (1944); ²Clark (1950); ³Grove (1969); ⁴Grey (1976); ⁵Grey and Cooke (1977); ⁶Cooke and Verstappen (1984); ⁷Mallick et al. (1981); ⁸Jackson (1986); ⁹Skelton (1994); ¹⁰Simms (2000); ¹¹McFarlane and Segadika (2001); ¹²Moore and Larkin (2001); ¹³Cotterill (2006); ¹⁴Motapa Diamonds Ltd. (2006); ¹⁵Bishop et al. (2007); ¹⁶McFarlane and Eckardt (2008); ¹⁷Miller (2008); ¹⁸Day et al. (2009); ¹⁹Riedel et al. (2009); ²⁰Moore and Cotterill (2010); ²¹Cotterill and de Wit (2011); ²²Goodier et al. (2011); ²³Cotterill et al unpublished data; ²⁴This Study.

Lacustrine landform	Age (Ma)	Evidence	Geomorphological interpretation
1. Alab dune fields	Late Pliocene Early Pleistocene (minimum age)	Linear dunes are the oldest fossil landforms ¹⁷ truncated by the Gomare Fault, coinciding with 995 m PLD shoreline ²⁴	Older than PLD, absolute minimum age constrained by ESA artefacts ¹⁷
2. Palaeo-Lake Deception (PLD)	Minimum age 2.2 to 1.8 Ma	Predates PLM ¹⁶ Molecular dating for initiation of PLB constrains PC inflow ^{21,22,23}	Late Pliocene dune field ¹⁷ predates PLD ^{16,24} until formation of PLB sustained by PC inflow ^{21,22,23} . Approximate extent of PLD = ~175 000 km ² (Table 4)
3. Deception Ridge		Offshore bar related to PLD ^{16,24}	
4. 945 m shoreline of Palaeo-Lake Makgadikgadi (PLM)	Minimum age 1.5 to 0.8 to 0.5 Ma	Molecular dating of demographic expansion in <i>Crocodylus</i> ¹⁵ Adaptive radiation of <i>Synodontis</i> catfishes ^{18,21}	Younger than PLD with estimated area of ~65 000 km ² , but formerly estimated ³ as ~34 000 km ² (Table 4)
5. Gidikwe Ridge		Offshore bar linked to the 945 m PLM ^{4-7,12,24}	Formed within PLD and PLM ¹²
6. Transverse Dunes		Reworked and repositioned sands across abandoned lake floor	Coeval with PLM ²⁴
7. 936 m shoreline of Palaeo-Lake Thamalakane (PLT)	Minimum age of 500 ka but likely Early Pleistocene,	ESA factory site, ~6 km to the north of Gweta ¹¹ , dated older than 0.5 Ma ^{20,24}	Postdates PLM and Transverse Dunes Tenure of PLT predates end of the ESA ^{11,20,24}
8. Fossil shorelines at 920 m and 912 m	Mid-Pleistocene minimum age	Reconstructed fossil shorelines ^{4-7,24} constrained by MSA and LSA artefacts ²⁴	MSA artefacts constrain minimum ages on 920 and 912 m shorelines, respectively ^{20,24}
9. Flowstone capping lake sediments near Twin Rivers, northeast Kafue Flats	Minimum age = 0.5 Ma	U-Series dates on flowstone above lake sediments set minimum age of 200 ka, but lake sediments are possibly older than 500 ka ^{10,13,20}	U-Series dates constrain tenure of Palaeo-Lake Patrick within Mid-Pleistocene ^{10,13,20}
10. Graben infilled by Buluzi floodplains, Barotseland, west Zambia	Mid-Pleistocene for minimum 140 ka	Faults bounding sediment-infilled graben (Figure 1). Pedogenic Ferricrete I formed under Kalahari Sands ² in river channel, downstream of N'gonye Falls when UZ was impounded upstream ^{13,20}	UZ flow (and Cuando?) impounded in Buluzi graben, upstream of N'gonye Falls, to maintain Palaeo-Lake Buluzi (PLB)

- Climatological inputs into the Regional Model reconstruct interactions between key hydrological parameters. These estimate how changes in regional drainage inflows into the Makgadikgadi Lakes interfaced with evaporation, and local precipitation over these lakes (detailed in Supplementary File 1) (*see Supplementary File 1 - pg 000). Here we revisit interesting observations by Grove (1969) on sandy ridges preserved across northern Botswana. Their context endorses consideration of all relevant hydrological factors to understand evolution of the Makgadikgadi palaeo-lakes. Grove argued that no mesic Plio-Pleistocene climate could, alone, account

for the 945 m mega-lake (later named Palaeo-Lake Makgadikgadi (PLM) by Thomas and Shaw, 1991). He concluded that significant river inflow with at least the catchment of the modern Upper Zambezi (contributing a minimum volume of 33 km³/yr) was essential to complement the precipitation and evaporation budget over the mega-lake.

- Archaeological evidence preserved on land surfaces, and in near surface sediments, across the Kalahari Plateau, comprises lithic artefacts collectively representing at least the final 2 Ma of the Late Cenozoic (Robbins and Murphy, 1998; Walker, 1998; Deacon and Deacon, 1999). (Nomenclature of

Table 1. continued

Fluvial landform	Age (Ma)	Evidence	Geomorphological interpretation
11. Congo-Zambezi watershed	2.2 to 1.8 (3.4 to 0.6) Ma	Windgap on Congo-Zambezi watershed ^{1,13} Biogeographical affinities of aquatic biodiversity ^{8,9,13,21,23}	Formation of Congo-Zambezi watershed isolated Bw that maintained PLD ^{21,22,23,24}
12. Bangweulu Depression	2.2 to 1.8 Ma (3.4 to 0.6) Ma	Molecular dating of phylogeographic events in fishes ²¹ constrains initiation of Bw	Link with PK disrupted after formation of Bw ^{13,21}
13. Eastern Batoka Gorge	3 to 2.5 Ma (minimum)	Shallow gradient and broadened channel of Zambezi; compared to western Batoka, gorge flanks are more dissected ^{2,20,23,24}	Antecedent flow of PC incised eastern Batoka with far greater flow and erosive power ^{13,20} relative to more recent incision by UZ ²⁴
14. Chimamba Rapids	1.1 to 0.65 ka	This 6 m knickpoint delimits upstream extent of abandoned terrace preserved as prominent benches along the base of eastern Batoka ^{2,20,23,24}	Geomorphological boundary ² demarcates significant break in river flow, and/or period of reduced river flow ^{13,20} ; abandoned channel of inherited gorge floor incised by underfit Zambezi River ^{23,24}
15. Western Batoka Gorge	1.1 to 0.65 Ma	Deeply incised, near vertical flanks; short, deeply entrenched tributaries have incised flanking basalt plain ² Younger Gravels ² contain MSA (Mode 3) lithic artefacts ^{13,20} constrain erosion rates over ~29 km of the western Batoka Gorge ^{20,23,24}	Gorge incised 40.7 km upstream from Chimamba Rapids (Batoka Discordance) ^{2,13,20,24}
16. Machili Flats	Minimum age = Early Pleistocene	Fault controlled structure. Fluvial gravels buried under alluvium (Kafue Flats and Machilli Flats) ² attest to southwest flow of PK into Ok and/or Upper Zambezi ^{13,20,24}	Megafan where PC debouched into Okavango Depression ¹³ ; succeeded by PK until uplift formed watershed between Kafue and Machili Flats ²⁴
17. Simamba Ridge	Mid-Pleistocene	Deposited Kalahari Sands postdate formation of Machili graben and PC flow, but predate uplift of Kafue-Machili watershed that disrupted PK ²⁴	Kalahari Sands predate formation of PLP; testifies to recurrent tectonism in Machili and Kafue graben ²⁴
18. Kafue-Machili watershed	Mid-Pleistocene	Focus of uplift along northwest-southeast axis of Simamba Ridge disrupted PK ²⁴	Post-dates ESA and deposition of Kalahari Sands, and associated with initiation of PLP ²⁴
19. Kafue Flats	Minimum age =200 ka	U-Series dates on flowstone near Twin Rivers set minimum age of 200 ka, but lake sediments are possibly older than 500 ka ^{10,13,20}	Formed after tenure of PL Patrick ¹⁰ in Kafue graben, maintained by PK inflow ^{13,20}
20. Upper Zambezi	Mid-Pleistocene	Downstream of Bulozzi, UZ incised the uplifted Sioma Horst (northwest of Machili Flats); Rapids in river channel coincide with north-northeast to south-southwest faults parallel with Chobe Fault ^{12,20,23,24}	Knick points (rapids) in river profile between Mambova and Victoria Falls represent north-south trending faults associated with Linyanti Horst; Mambova and Katombora Rapids delimit faulted blocks of Chobe horst ^{2,24}
21. Ferricretes I in Upper Zambezi channel	Mid-Pleistocene	Pedogenic ferricrete preserved unconformably in channel of UZ, between Victoria Falls and N'gonye Falls ^{2,13,20}	Impoundment of UZ upstream in PLB ^{13,20} coincided with formation of pedogenic ferricrete under Kalahari Sands ^{12,13,20}
22. Matebele-Mulonga Plain	Mid-Pleistocene(?)	Drill cores revealed diamondiferous fluvial gravels buried under alluvium ^{14,24}	Former channel of Palaeo-Cuando was a west bank Zambezi tributary ²⁴
23. Lower Kafue River	Mid-Pleistocene	Termination of Palaeo-Lake Patrick ^{10,13}	Piracy of Kafue Flats (Palaeo-Kafue River) by Mid-Zambezi headwater ^{10,12,13}
24. Victoria Falls (Mosi-wa-Tunya)	Late Pleistocene	Deepest knickpoint in Zambezi River that represents erosion of the western Batoka Gorge. Current position reflects 40.7 km of knickpoint retreat ^{2,12,13,20}	Rates of knickpoint retreat constrained by archaeological evidence (Table 4) ^{13,20,24}

Table 2. Summary of the revised drainage model for south-central Africa centred on geomorphological evolution across northern Botswana and the Batoka Gorges (Victoria Falls) over the late Cenozoic, with a focus on lake tenures in the Okavango Rift Zone (ORZ) in northern Botswana. Relationships between principal events and tenures of lacustrine landforms and main rivers on the Kalahari Plateau illustrates the relationships between estimated timings of formative events and episodes discussed in this paper. Abbreviations follow Table 1. See Table 1 for collated evidence, together with Figures 2 and 7 for locations of landforms.

	Estimated age	Tectonic/geomorphic event	Mega-Lake stage
Late Palaeogene	~25 Ma	Uplift of Okavango-Kalahari-Zimbabwe (OKZ) axis	Initiation of endoreic drainage system and deposition of Kalahari Formation in northern Botswana
Pliocene	3 to 2.5 Ma	Diversion of Palaeo-Chambeshi/ Upper Zambezi into Mid-Zambezi Incision of eastern Batoka Gorge	Dramatic decrease in sediment supply to the northern Botswana Kalahari Basin.
Early Pleistocene	Not tightly constrained, but prior to 2.5 to 1.4 to 0.6 Ma	Uplift along Chobe Fault	Palaeo-Chambeshi river diverted into northern Botswana to initiate Palaeo-Lake Deception bounded by 990 to 1000 m shoreline
Early Pleistocene	2.2 to 1.8 Ma within 95% CI of 3.4 to 0.6 Ma	Upper Chambeshi-Kafue link severed by uplift of Congo-Zambezi watershed to form Proto-Kafue River; Palaeo-Lake system sustained by Upper Zambezi, Proto-Kafue, Cuando and Okavango Rivers	Lake contracts to 945 m shoreline of Palaeo-Lake Makgadikgadi (PLM)
Early Mid-Pleistocene	1.1 to 0.649 Ma	Initiation of incision of western Batoka Gorge	Overtopping from PLM into Mid-Zambezi River
Early Mid-Pleistocene	>500 ka	Isolation of Proto-Kafue from Upper Zambezi River; Palaeo-Lake system sustained by Upper Zambezi, Cuando and Okavango Rivers	Lake contracts to 936 m shoreline of Palaeo-Lake Thamalakane (PLT)
Mid-Pleistocene	Not tightly constrained		
Mid-Pleistocene	>500 ka	Impoundment of Palaeo-Lake Bulozhi (PLB), reducing input from Upper Zambezi River	Lake contracts to 920 m shoreline
Mid-Pleistocene	>500 ka	Diversion of Upper Zambezi in Bulozhi graben	Lake contracts to 912 m shoreline, sustained by Okavango and Cuando Rivers
Mid-Pleistocene	0.6>0.3<0.06 Ma	Palaeo-Lake Bulozhi breached, and Upper Zambezi attained exoreic status, to reactivate erosion of western Batoka Gorge	Zambezi establishes modern topology
Mid-Late Pleistocene	100 ka to present	Activation of Thamalakane Fault. Formation of Okavango Delta and Boteti River	Progressive desiccation of Makgadikgadi Pans

these lithic industries follows Lahr and Foley, 2001). This archaeological record constitutes an invaluable geochronological resource (Cotterill, 2006; Moore and Cotterill, 2010), whose potential to date key landforms was appreciated early in the 20th century by pioneering researchers (Lamplugh, 1906, 1907, 1908; Clark, 1950; Bond, 1975; Derricourt, 1976). We focus on the artefacts that rim the Makgadikgadi fossil shorelines (Cotterill, 2006; Robbins and Murphy, 1998), and are preserved in river sediments across Botswana, Namibia, Zambia and Zimbabwe (du Toit, 1933; Dixey, 1944, 1950; Miller, 2008). Critical archaeological evidence is preserved in the Victoria Falls Formation (VFF), described by Clark (1950, 1975) and Moore and Cotterill (2010), along the Upper Zambezi River, especially in abandoned sediments above the Batoka Gorges.

- Biological evidence complements and consolidates the archaeological, geological and climatological data structuring the Regional Model. Severance of former drainage lines by processes linked to river piracy can result in the isolation of fish and certain

bird and mammal populations (Skelton, 1994; Cotterill, 2003; 2004; 2005; 2006). Thereafter, independent evolution of such isolated populations will accumulate genetic differences readable as spatially contained signatures. An estimated mutation rate of DNA sequences enables applications of molecular clocks to quantify times of isolation of these species by drainage disruption (Craw et al., 2008; Waters and Craw, 2008). Calibrated by molecular clocks, these phylogeographical signatures (palaeoplex) preserved in aquatic biota resolve novel details of earth history – pertinently dates of landforms for which established geochronological methods are not amenable (McDowall, 2010; Cotterill and de Wit, 2011). With their high fidelity for particular landforms, ecological specialists can provide invaluable insights into landscape evolution; exemplified by aquatic species whose phylogeographic records resolve details of drainage evolution. Phylogeography – the study of these genetic patterns of speciation – thus provides a powerful new tool to date changes in drainage

Table 3. Comparison of estimated hydrological budgets of Late Cenozoic Lake tenures in the Okavango Rift Zone (ORZ) in northern Botswana. Average annual inflows for principal rivers are obtained from Sahin (2002). Respective relationships between tenures of lacustrine landforms and regional drainage topology across the Kalahari Plateau are depicted in Figure 7. Areas of principal palaeo-lake stages in the Okavango Rift Zone (OKZ), bounded by shorelines at different elevations, calculated using the Shuttle Radar Telemetry Dataset (SRTM4). Each lake stage is related to the inflows of respective drainage nets, and associated estimates of evaporation and input from rainfall over the lake surface.

Shoreline elevation m amsl of the Makgadikgadi Basin	Area km ²	Inflow required to sustain net evaporation km ³ /yr	River	Annual flow km ³ /yr	Cumulative annual flow km ³ /yr	Net annual inflow deficit km ³ /yr	Required evaporation loss saving (mm/yr)
912	11061	15.5	Okavango Cuando	10.3	13	2.5	226
920	19984	28	Upper Zambezi -Partial?	0? / <401	13 (+)	15 (-)	750
936 (PLT)	41082	57.5	Upper Zambezi -Partial?	(<40?)1 / 40	53	4.5	110
945 (PLM)	65734	92	Upper Kafue	13	66	26	395
995 (PLD)	175400	246	Upper Chambeshi	14	80	166	946

¹Denotes loss of inflow into ORZ when the Upper Zambezi was impounded upstream of N'Gonye Falls in the Bulozzi graben, and maintained Palaeo-Lake Bulozzi (PLB).

configurations. It has been applied to refine the tempo and mode of propagation of the EARS southwest across the Kalahari Plateau (Cotterill and de Wit, 2011).

- For example, the geocodynamics of tigerfishes (genus *Hydrocynus*) across tropical Africa reveals how a molecular clock constrains estimated drainage rearrangements, which agree closely with known independent geological constraints (Goodier, 2010; Goodier et al., 2011). Of equal interest to the present paper, a second example of geocodynamics pertains to the Mid-Pleistocene radiation of the “Palaeo-Lake Makgadikgadi species flock” of cichlid fishes, which Joyce et al., (2005) postulated to have evolved in its namesake. Resolution conferred by the Regional Model reveals that these fishes more likely evolved across the palaeo-lake archipelago extant across the Kalahari Plateau in the Mid-Pleistocene. So these south-central African cichlids have been renamed the “Kalahari Palaeo-Lakes Flock” by Schwarzer et al. (2012), who applied molecular dating of evolutionary events of selected cichlid species to reveal when particular Neogene river captures reshaped the Congo-Zambezi watershed and their respective tributaries.

The Regional Model requires major downward revision of palaeo-lake ages, previously constrained by radiocarbon dates of calcretes, and Thermoluminescence (TL) and Optically Stimulated Luminescence dating of quartz grains (collated by Thomas (2012) and here collectively termed Luminescence Dating or LD). Exploring the interplay between these controls of hydrological dynamics, our model reveals how tectonic changes to river topology exercised first order control over palaeo-lake evolution (with ancillary controls of local climate over the largest lake stands). This finding concurs with evidence collated across the world's rivers, testifying to how tectonism has reshaped continental drainage (Potter and Hamlin,

2006; Vita-Finzi, 2012). This finding is not surprising considering burgeoning evidence, accumulated since the early 20th century, for active rifting across the Makgadikgadi Basin and south-central Africa (Haddon and McCarthy, 2005; Kinabo et al., 2008 and references therein). So the present study further evaluates this interplay between the tempo and mode of tectonism and drainage evolution across the Kalahari Plateau.

Regional tectonic setting

Northern Botswana is traversed by a fault system with a predominantly northeast to southwest strike, expressed as subtle topographic lineaments (Figure 1). Seismic activity recorded in northern Botswana (Reeves, 1972; Reeves and Hutchins, 1975; Scholz, et al., 1976) reflects ongoing tectonic activity. The faulting and active seismicity are interpreted to reflect incipient development of the Okavango-Makgadikgadi Rift across northeast Botswana, linked to the propagation of the East African Rift System (EARS) to the southwest (Du Toit, 1927; 1933; Mallick et al., 1981; Kinabo et al., 2007; 2008; Modisi et al., 2010) from the Upemba (Katanga) and Mweru-Tanganyika Rift Zones (Mondeguer et al., 1989; Tack et al., 2003; Chorowicz, 2005; Haddon and McCarthy, 2005) and through the Kabompo Gorge, western Zambia (Key et al., 2001, Figure 1). This tectonism has been invoked as the primary driver of major topological reorganizations of regional drainage nets across the low relief Kalahari Plateau (details in Moore and Larkin, 2001; Cotterill 2003; 2004; 2005; 2006; Moore et al., 2007; Cotterill and de Wit, 2011, Tables 1-3). These observations echo the prescient appreciation that:

“In all the cases described above the axes of uplift and the longer diameters of the areas of depression, including auxiliary warpings, lie directed between northeast and east-northeast [across southern and central Africa], which indicates that *they owe their origin to one and the same controlling set of tectonic forces*”

(du Toit, 1933: 17, *italics his*).

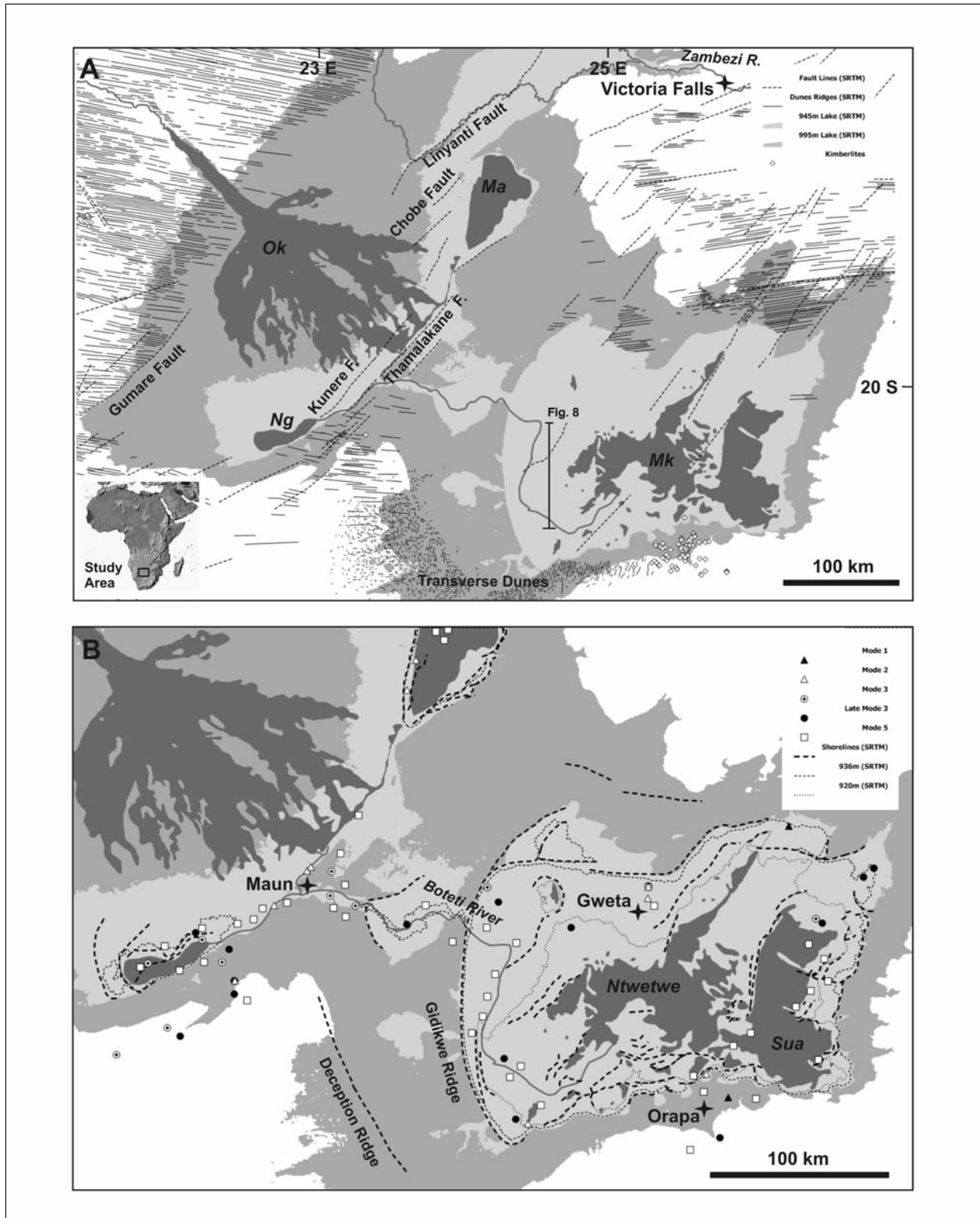


Figure 3. (A) Overview of the Makgadikgadi Basin illustrating major landforms and faults, interpreted from the SRTM-4 digital elevation model. Grey-shading depicting the approximate extent of the principal lake stands, discussed in main text. Ma= Mababe Depression; Mk = Makgadikgadi Pans complex; Ng = Lake Ngami; Ok = Okavango Fan. Line marked Fig. 8 denotes the approximate location of the sediment profile shown in Figure 8. (B) Detail of the Makgadikgadi Pans Complex, showing the location of major sand ridges and the distribution of documented Stone Age localities. The Ntwetwe and Sowa Pans together comprise the Makgadikgadi Pans. Grey tones as for Figure 3A. Archaeological data collated from Bond and Summers (1954); Clark (1950); Cooke (1979); Ebert et al (1976); Helgren (1984); McFarlane and Segadika (2001); Robbins (1988) and Robbins and Murphy (1998).

Subtle faulting related to the southwest propagation of the EARS has modified landforms across Zambia into eastern Angola, the Caprivi and northern Botswana: exemplified in the Okavango graben, bounded by the Thamalakane and Gumare Faults (Figure 1). A structural analysis by Ballieul (1979) demonstrated how recurrent faulting has shaped the geometry of the Makgadikgadi Basin. This faulting extends southeast from the Kafue Flats into the Makgadikgadi Basin across the Machili Flats (hereafter designated the Machili graben). The Machili graben is bounded by the Chobe Fault to the south, and to the north by a topographic linear (an inferred fault trace) exhibiting close structural relationships with the Kafue and Okavango graben. To the northwest, the inferred eastwest trending Mwamba and N'gonye Faults testify to a zone of pronounced faulting across western Zambia, bounding the sediment-infilled Bulozzi (Barotse) graben (Cotterill, 2006, Figure 1).

Fossil landforms

Fossil linear dunes

Major relict linear dunes in northern Botswana, with a roughly east-west orientation, reflect episodes of pronounced aridity across the Mega-Kalahari sand sea (Figures 1 and 3A), presumably when annual rainfall was well below 250 mm, significantly lower than average modern precipitation (~400 to 500 mm/annum, Grove, 1969; Thomas and Shaw, 1991; Shaw and Goudie, 2002). Their former crest heights approximated ~90 m – estimated from the average “straat” width of 1.75 +/-0.3 km separating adjacent dunes (Grove, 1969). Today these dunes are highly degraded, in places only diagnosable by vegetation contrasts between the crests, which support tall trees separated by grassy intervening “straten” (Grove, 1969; McFarlane and Eckardt, 2007). Faulting has truncated the dunes in places (Mallick et al., 1981; McFarlane and Eckardt, 2007), indicating that their formation pre-dated the southwest propagation of the EARS. This is well illustrated by the dunes truncated against the Gumare Fault (Figure 1).

Lacustrine landforms

Grove (1969) was the first to recognize the geomorphic significance of an arcuate fossil sand ridge (the Gidikwe Ridge), crest elevation ~945 m, fringing the western edge of Makgadikgadi Pans (Figure 1). He inferred that the ridge marked a shoreline of a former inland sea (its area then estimated at ~34 000 km²), and that the Ntwetwe and Sowa Pans (collectively termed the Makgadikgadi Pans), are desiccated relics of this former body of water. North of the Makgadikgadi Basin, Grove (1969) recognized that sand ridges with crest elevations ~945 m also bounded Lake Ngami and the Mababe Depression (Figures 1 and 3B).

Grey (1976) subsequently interpreted boulder beds along the southern margin of the Makgadikgadi Pans at an elevation of ~945 m as shoreline relics of this fossil lake. On the evidence of detailed levelling, Grey (1976)

argued that the 945 m contour would have also enclosed the Ngami and Mababe Depressions to form a major north-easterly oriented body of water, linked to the larger Makgadikgadi Basin via a narrow neck along the Boteti River (Figure 3A). The arcuate ridges which Grove (1969) had interpreted as the lake shoreline, were reinterpreted to represent off-shore bars; so the actual shoreline was located further west, separated from the Gidikwe Ridge by a shallow lagoon (Grey, 1976; Cooke and Verstappen, 1984). This lake bounded by the 945 m shoreline, its area re-estimated at ~65 000 km², was designated Palaeo-Lake Makgadikgadi (PLM) (Thomas and Shaw, 1991; Burrough et al., 2009a; b).

Thomas and Shaw (1991) argued that shoreline features at the 936 m level represented Palaeo-Lake Thamalakane (PLT). Fossil evidence for this lake stage is represented in all major basins (M.J. McFarlane, personal communications, 2009). Additional well developed shorelines are preserved at the 920 m and 912 m elevations (Grey, 1976; Grey and Cooke, 1977; Cooke and Verstappen, 1984).

McFarlane and Eckardt (2008) recently documented a relict sand ridge at the ~995 m elevation (named the Deception Ridge, Figures 4A and 4B), which represented a hitherto unrecognized lake stand, designated Palaeo-Lake Deception (PLD) (Figures 3A and 3B). Its inundated area (over 175 000 km², Tables 1 and 3) dwarfed modern Lake Victoria (68 800 km²).

West and southwest of the Makgadikgadi Basin, transverse dunes (i.e. transverse to the prevailing easterly winds) are now stabilized by vegetation (Figures 3A and 3B). Mallick et al., (1981) inferred these formed when the 945 m lake (PLM) was extant. These transverse dunes cap the Deception Ridge (Figure 4) and extend further west to cover the linear dunes (Mallick et al., 1981).

Fossil drainage lines

Northern Botswana is traversed by a number of fossil drainage lines which formerly emptied into the Makgadikgadi Basin (e.g the Xaudum, Qoxo and Deception palaeo-drainages, Figure 1).

Chronological evidence for ages of northern Botswana fossil landforms

Recognition of a major fossil dune field juxtapositioned against fossil shorelines, across northern Botswana, raises intriguing questions about what processes formed these contrasting landforms, and their respective ages. Despite a general absence of age-diagnostic fossils and material suitable for radiometric dating, several lines of evidence set relative and/or absolute ages on these fossil landforms.

Relative ages of landforms

Several observations point to the linear dunes being the oldest of the fossil landforms in the Kalahari landscape. The lineament of their truncation by the Gumare Fault coincides with the 995 m shoreline (Figures 1 and 3A).

So these dunes (and equally fault initiation) predate Palaeo-Lake Deception (PLD). The transverse dunes, inferred to be shoreline features associated with the 945 m lake shoreline, cover linear dunes to the west (Mallick et al., 1981). Transverse dunes capping the ~995 m Deception Ridge (Figure 4) demonstrably post-date formation of this offshore bar. Clearly, the 945 m PLM coincided with formation of the transverse dunes, and both landforms post-date PLD.

The east-west orientated palaeo-drainage across northwest Botswana parallel the linear dunes, suggesting the latter determined river orientations. The dunes never cover the drainage lines, consistent with observations from southern Namibia (Miller, 2008).

A similar relationship characterises northwest Zimbabwe, where east-west tributaries of the Gwayi River flow parallel to the crests of highly degraded linear dunes (Thomas and Shaw, 1991). Collectively, this evidence requires that drainage incision post-dated the linear dunes.

The palaeo-drainages (e.g. Qoxo and Deception) emptied into the Makgadikgadi Basin. Significantly, between the Deception and Gidikwe Ridges these channels can be traced across the shallow lagoon formed in the 945 m PLM (Figure 1). The Xaudum drainage exhibits a similar relationship (Moore, 2011). Clearly, these drainage lines were active during the tenures of PLD and PLM, and flow persisted after lake contraction to lower shorelines.

In summary, the well-defined succession of landforms centred in northern Botswana reveals the following relative ages:

- Linear Dunes > initiation of Gumare Fault > PLD (995 m lake) = active Kalahari River flow > PLM (945 m lake) = formation of transverse dunes > desiccation of Kalahari rivers to form palaeo-drainages > progressive decrease in flow of Boteti River.

¹⁴C dates of carbonates and quartz luminescence dates
Based on ¹⁴C ages for calcretes and shell fragments of aquatic gastropods, Thomas and Shaw (1991) inferred that Palaeo-Lake Makgadikgadi filled to the 945 m level on several occasions during the last 50 ka (the upper limit of the ¹⁴C dating method). However, the geological credibility of this chronology is questionable, because calcretes characteristically reflect several generations of formation, likely continuing to the present (Watchman and Twidale, 2002; Burrough et al., 2009b).

A recent suite of publications have applied a LD chronology to constrain formation of landforms in

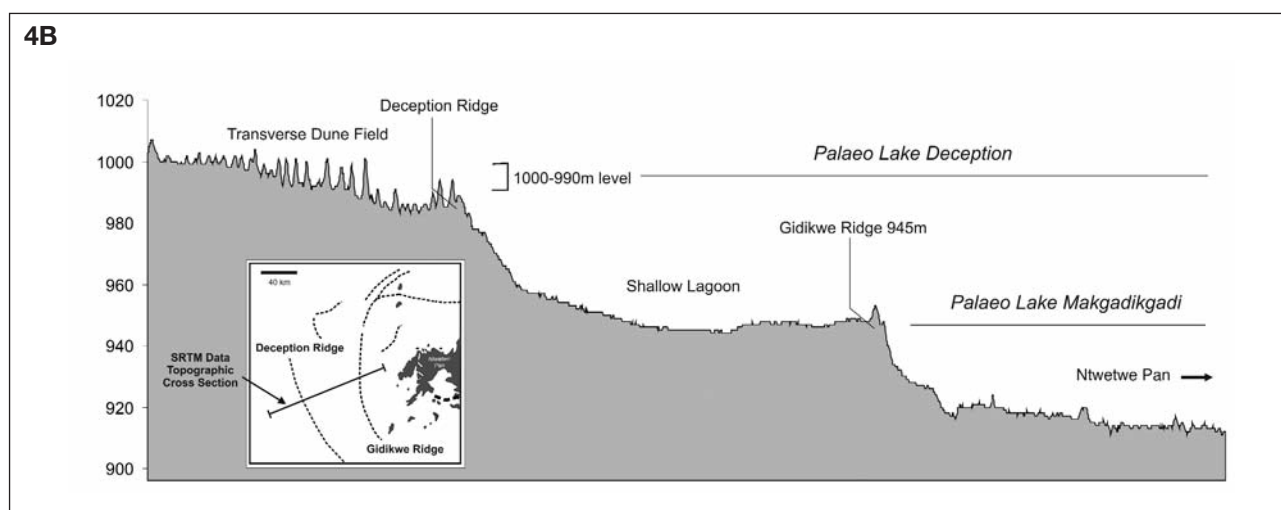
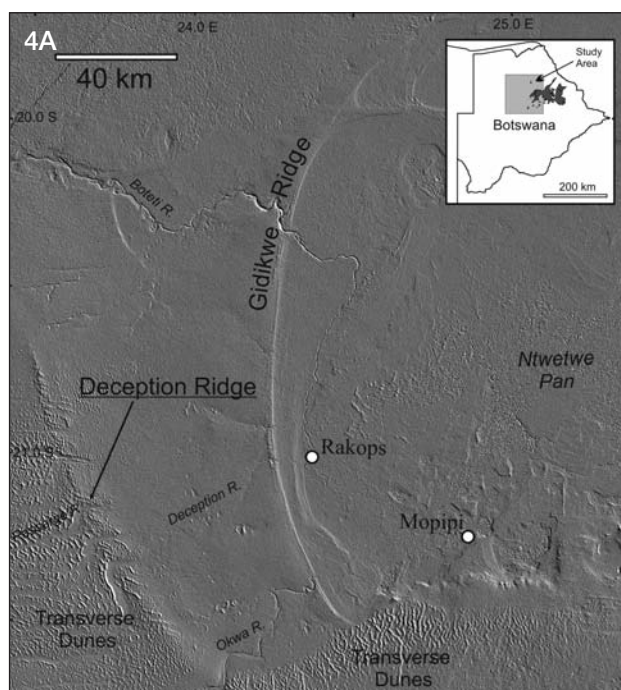


Figure 4. (A) Digital Elevation Model covering the west of the Makgadikgadi Basin, produced from SRTM-4 data. Note that the transverse dune field covers the Deception Ridge, and extends to the east of this feature, suggesting that these dunes were actively forming during the tenure of the 945 m shoreline. (B) Elevation profile across the Gidikwe and Deception Ridges.

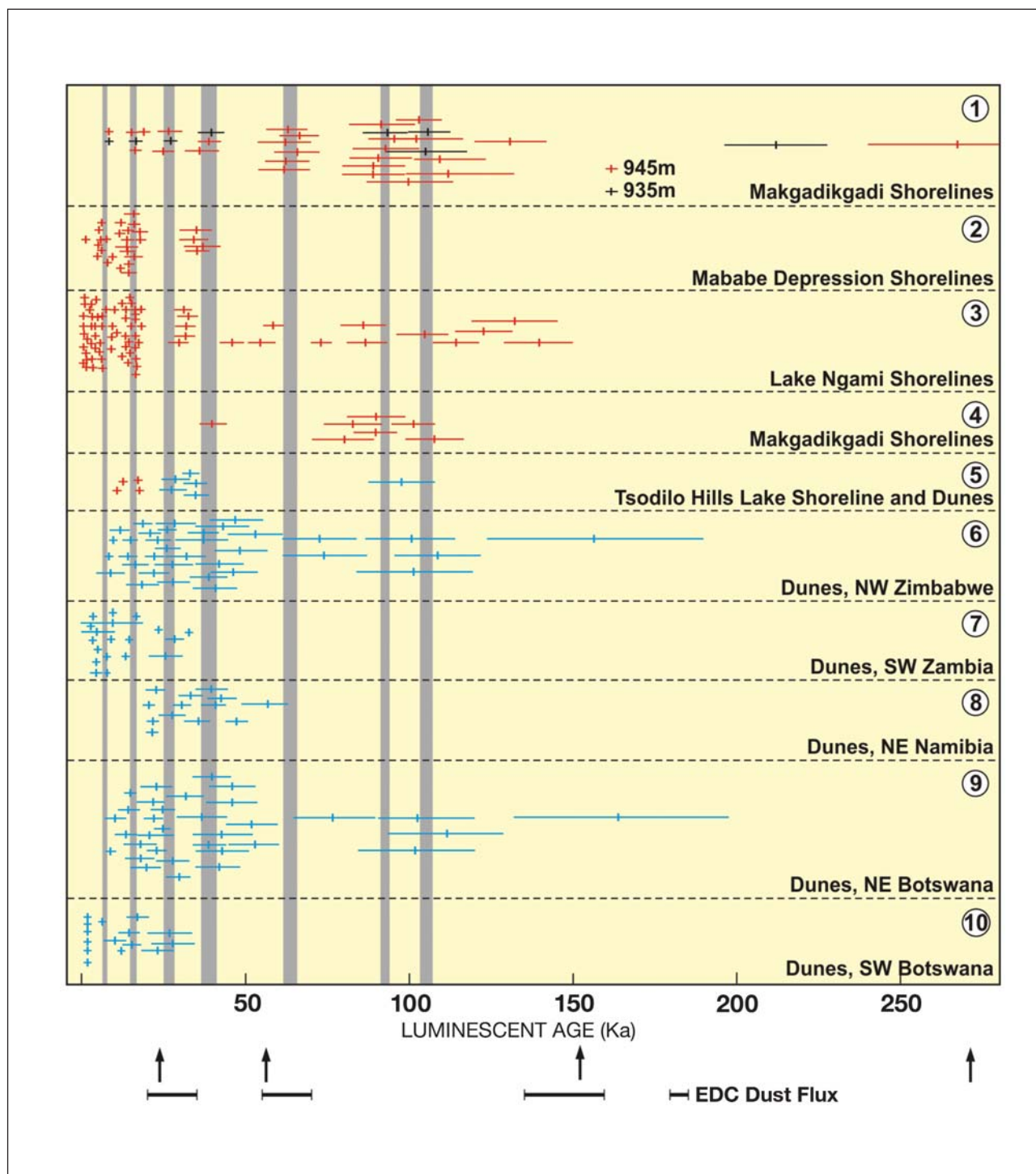


Figure 5. Summary of published quartz luminescence ages (mean with 1σ analytical error) for the high elevation shorelines of the Makgadikgadi Basin, and the degraded linear dunes in Botswana and surrounding countries. Sources of data: **1.** Burrough et al. (2009a); **2.** Burrough and Thomas (2008); **3.** Burrough et al. (2007); **4.** Ringrose et al. (2005); **5.** Thomas et al. (2003); **6.** Stokes et al. (1998); **7.** O'Connor and Thomas (1999); **8.** Thomas et al. (2000); **9.** and **10.** Stokes et al. (1997). Vertical grey bars denote palaeo-megalake stages inferred by Burrough et al. (2009a). EDC dust flux peaks from Petit et al. (1999).

northern Botswana and the surrounding region, and further to reconstruct the latter's palaeoclimatic history over the late Quaternary (e.g. Stokes, 1997; Stokes et al., 1997, 1998; Ringrose et al., 2005; 2009; Thomas et al., 2005; Burrough et al., 2007; 2009a; b; Burrough and Thomas, 2008; 2009; Thomas, 2012). Ringrose et al.,

(2005) concluded that the LD chronology for the Makgadikgadi shorelines correlated fairly well with reconstructions of the southern hemisphere palaeoclimatic record (Vostok core, Petit et al., 1999). This LD derived climatic proxy, proposed for south-central Africa, comprises luminescence shoreline ages

(generally <150 ka) from different localities across the Makgadikgadi Basin. Critically, however, the LD chronology defines a continuum rather than discrete episodes – if one acknowledges the analytical error (Figure 5). Further, the overlapping LD ages of palaeo-lake shorelines and the fossil dunes contradict the relative age succession demonstrated for these fossil landforms (previous section).

Fossil and archaeological evidence

Fossil evidence from the Etosha Pan brackets the ages of linear dunes in northeast Namibia at between 4 to 2 Ma (Miller et al., 2010). This contrasts against inferred aeolian activity estimates of 20 to 50 ka based on Luminescence dating (Figure 5). In southern Namibia, Miller (2008) reported un-abraded late ESA (Acheulian) artefacts from gravels along fossil rivers incised across linear dunes. At a *minimum*, this ESA (Mode 2) industry constrains fluvial activity of these drainages to before the Early to Middle Stone Age (ESA/MSA) transition (Miller et al., 2010). Reappraised ages of the oldest MSA industries are revised downward to a minimum of ~500 ka (McBrearty and Brooks, 2000; Herries, 2011; Balter, 2012; Wilkins and Chazan, 2012), which set an Early Pleistocene Age on these ESA artefacts (Beaumont and Vogel, 2006; Porat et al., 2010; Beaumont, 2011). Thus, this revised archaeological chronology sets an even older age on the river incision postdating these linear dunes, consistent with the fossil evidence.

Several lines of archaeological evidence conflict with the young shoreline ages indicated by both ¹⁴C and luminescence dating techniques. In northeast Botswana, McFarlane and Segadika (2001) reported an ESA factory site, located ~6 km to the north of Gweta, and situated below the 936 m palaeo-lake shoreline (Figure 3B). Its lithic artefacts include Mode 2 (Acheulian) handaxes, scrapers and associated debris knapped from the silcrete floor of the pan. McFarlane and Segadika (2001) argued accordingly for lake desiccation to below the 936 m level before the end of the ESA. The revised archaeological chronology on the earliest MSA and youngest ESA sets a minimum of 500 ka, and likely Early Pleistocene Age, for contraction of the lake below 936 m.

A possible counter-argument is that lake levels oscillated in the Makgadikgadi Basin, and that the Gweta ESA factory site reflects a temporary low lake stand. While this possibility cannot be ruled out entirely, it begs the remarkable coincidence that sequential wet climatic episodes were of such closely similar magnitude that the same shoreline was established during each mesic event. Further, an oscillating lake level does not receive strong support from the regional archaeological evidence (Figure 3B). The majority of Acheulian (Late ESA or Mode 2) sites are concentrated close to the 945 m shoreline, and their overall distribution is restricted to elevations above 920 m. Middle Stone Age artefacts (MSA Modes 3 and 4) show a wide distribution at elevations below the 945 m shoreline, with some sites recorded below the 920 m shoreline (Figure 3B).

A marked concentration of Mode 5 Late Stone Age (LSA) sites along the banks of the Boteti River points to occupation along an active flowing river (Walker, 1998; Figure 3B). Over much of its length, the Boteti is markedly incised, with the channel 5 to 10 m lower (Figure 6A) than the river banks at 920 m (Cooke and Verstappen, 1984). This association indicates the Gidikwe Ridge has been incised by the Boteti River, which then fed a smaller lake (shoreline < 920 m) during the LSA (Figures 3 and 4A).

Collectively, the archaeological evidence exhibits a trend with successively older Stone Age artefacts concentrated at progressively higher levels. According to published knowledge, these artefacts have not been reworked (reknapping is obviously of no concern for the ESA tools). It is also unlikely that fluvial processes reworked (rolled) these artefacts in a low energy lacustrine sedimentary environment. The first, recently discovered, Oldowan artefacts (Earliest ESA, Mode 1) south of the Makgadikgadi Basin underline this trend. Overlying the BK-9 kimberlite (Orapa cluster), this site coincides with the 995 m shoreline (Nick Walker, 2011, personal communications, Figure 3B). This relationship between distinct shorelines and archaeological industries is more readily interpreted in terms of sequentially contracting lakes, and not a single oscillating lake.

Evolution of Aquatic Biota: Phylogeographical evidence

Phylogeographic records in a Zambeziian species flock of *Synodontis* catfishes point to their radiation in a lacustrine environment that no longer exists on the Kalahari Plateau. This event is postulated to have occurred in a palaeo-lake in northern Botswana (Day et al., 2009), and is constrained by molecular dating at 1.5 to 0.8 to 0.5 Ma (mean age bounded by upper and lower 95% CI – format applies for all reported molecular dates). Genetic affinities among extant populations of Nile crocodiles (*Crocodylus niloticus*) in south-central African rivers (Kafue, Okavango and Zambezi) reveal that an ancestral, panmictic population underwent a significant demographic expansion, attributed to increased contiguous habitat in a palaeo-lake. The *Crocodylus* molecular clock constrains a minimum age on this event at 1.72 to 0.45 to 0.12 Ma (Bishop et al., 2007), broadly coeval with the *Synodontis* radiation. So we attribute the *Synodontis* and *Crocodylus* phylogeographic signatures as ecological responses to widespread, persistent lacustrine habitats of a major lake in northern Botswana in the Early to Mid-Pleistocene.

Geomorphic evolution of the Kalahari Plateau

Modern drainage on the Kalahari Plateau: Evidence for topology reorganizations

The modern drainage network of south-central Africa preserves striking evidence of several major reorganizations (Moore and Larkin, 2001; Goudie, 2005; Moore et al., 2007, Figure 2).



Figure 6. (A) View of incised channel of the Boteti. This river ceased flowing during the drought from the mid-1990's until 2008. Photo: A.E. Moore. (B) View upstream in the channel of the Zambezi River from the Batoka Discordance across the Chimamba Rapids, which delimits the eastern and western Batoka Gorges. Photo: F. Cotterill. (C) Overview of the abandoned terrace that extends downstream of the Batoka Discordance capping the basalt trench of the eastern Batoka Gorge, whose older, abandoned channel has been inherited and incised by the underfit Zambezi River. Photo: F. Cotterill. (D) Detail of the abandoned channel immediately downstream of Chimamba Rapids (Cotterill et al., unpublished data). Photo: F. Cotterill.

Dixey (1943, 1944) suggested the sharp change in flow direction of the upper Chambeshi River from southwest to northwest (where this drainage becomes the Luapula River) is typical of a capture elbow (Figure 2). He postulated that the Chambeshi originally flowed southwest as a headwater tributary of the Kafue River. The abrupt change in the Kafue's course from south to east, where it debouches across the Kafue Flats, also suggests a capture elbow. Fluvial gravels buried beneath alluvium on the southwest margin of the Kafue Flats, and under the Machili Flats (Dixey, 1944; 1950), reveal that the Proto-Kafue's course originally continued to the south. Here, it linked with the Upper Zambezi above the Victoria Falls, where a wind-gap preserves the fossil river channel linking the Kafue Flats and the Machili Flats (Figure 1).

Collectively, these observations indicate that the Upper Chambeshi and Upper Kafue Rivers are former segments of a major drainage net termed the Palaeo-Chambeshi (Cotterill, 2003, 2006), originally linked with the Upper Zambezi via the fault-bound Machili Flats (Cotterill, 2003; 2004; 2006; Cotterill and de Wit, 2011; Figures 1, 7A and 7B). The latter is interpreted as an extinct megafan, where the Palaeo-Chambeshi debouched into the Makgadikgadi Basin (Figures 7C and 7D). The entire catchment was originally larger, as the Upper Zambezi's headwaters (including part of the Kasai) extended further north of the modern Congo – Zambezi watershed (Veatch, 1935; Key et al., 2001, Figure 2). It appears these extensive headwaters also comprised the Trans-Katanga drainage system, which contributed significant inflow to the Palaeo-Chambeshi River. The formerly southerly flowing Palaeo-Lufira and Proto-Luongo Rivers were two of its tributaries (Cotterill, 2004, 2005; 2006; Figures 2 and 7B). (Hereafter, Chambeshi River refers to the river's catchment north of the Congo-Zambezi watershed, while Palaeo-Chambeshi denotes the former regional drainage net, inclusive of its former Proto-Kafue channel.) Similarly, the modern topology of the Zambezi is geologically young, formed by the diversion of the Upper Zambezi into the Mid-Zambezi (cf Derricourt, 1976; Moore and Larkin, 2001; Moore et al., 2007; Moore and Cotterill, 2010) and loosely constrained as Late Pliocene to Early Pleistocene.

The broad Matabele-Mulonga Plain (Figure 1) is a subtly depressed channel underlain by gravels bearing diamonds, and kimberlitic ilmenites and garnets (Motapa Diamonds Ltd., 2006). This evidence suggests the Matabele-Mulonga plain is the relic of a major drainage line (the Palaeo-Cuando) formerly linked with the Upper Zambezi River. The source of the kimberlitic minerals in these basal gravels has not been satisfactorily identified. However, as kimberlites are known in northeast Angola but not western Zambia, the diamondiferous gravels underlying the Matabele-Mulonga plain could be explained by a former link between the Upper Cuando and Zambezi Rivers.

Ferricretes are preserved along the Upper Zambezi's channel from the vicinity of Victoria Falls upstream to

the lip of N'gonye Falls (Clark, 1950, Figures 1 and 7D). This ferricretization appears to have been pedogenic. It constitutes evidence for an episode of protracted sub-aerial exposure, and points to a prolonged cessation of river flow. This was attributed to rifting, reflected in the very linear margins of the modern Bulozzi floodplain (Figure 1), which impounded the Upper Zambezi and its tributaries to form a lake, designated Palaeo-Lake Bulozzi (PLB), occupying the modern Bulozzi floodplain. Its extent is not known precisely, but its tentative estimated area of ~20 000 km² would have extended north of 13°S (Cotterill, 2006, unpublished data, Figures 1, 2 and 7D). Sangoan artefacts (early MSA, Mode 3), entombed in the ferricrete on the river floor at N'gonye Falls (Figures 1 and 7D), set a *minimum* age on initiation of this lake at ~500 ka (the estimated lower bound on the Sangoan industry representing the early ESA/MSA transition, Cotterill, 2006; Moore and Cotterill, 2010; Cotterill and Moore, unpublished). Moreover, phylogeographic evidence for geographical isolation of tigerfish (*Hydrocynus vittatus*) at 0.6 to 0.31 to 0.05 Ma (Goodier, 2010; Goodier et al., 2011) and cichlid fishes at ~0.4 Ma (Koblmüller et al., 2008; Cotterill and de Wit, 2011) is interpreted to represent the approximate tenure of PLB, which ended when the Upper Zambezi and Middle Zambezi Rivers were reunited. These phylogeographic constraints are thus broadly consistent with the archaeological evidence.

Drainage evolution and palaeo-lake tenures on the Kalahari Plateau

The sequence and timeframe of the drainage reorganizations can now be discussed in greater detail with reference to evolution of the Makgadikgadi palaeo-lakes (Figures 7A-D). Ultimate control over river evolution is attributed to tectonism linked to the southwest propagation of the EARS across the low-relief Kalahari Plateau.

The Palaeo-Chambeshi/Upper Zambezi system formerly emptied into the Indian Ocean, via the Proto-Limpopo River (Moore and Larkin, 2001). This link was disrupted by uplift along the Ovambo-Kalahari-Zimbabwe (OKZ) Axis (Figure 7A), concomitant with subsidence of the Kalahari Basin (du Toit, 1933; Moore, 1999). This tectonism, dated as late Palaeogene (Moore et al., 2009), initiated an endoreic fluvio-lacustrine system within the Kalahari Basin (Figure 7A). The Cubango-Cuito drainages, (the Okavango below their confluence) and Cuando were tributaries of the Proto-Limpopo River, until similarly impounded in the Kalahari Basin by this Palaeogene epeirogeny.

A dramatic decrease in the sediment supply to the Kalahari Basin followed the diversion of the Palaeo-Chambeshi/Upper Zambezi drainage network into the Mid-Zambezi (Figure 7B). The timing of this episode was poorly constrained in previous drainage models as Pliocene to Early Pleistocene (Moore and Larkin, 2001; Moore and Cotterill, 2010). Exoreic outflow of this Palaeo-Chambeshi/Zambezi system was subsequently

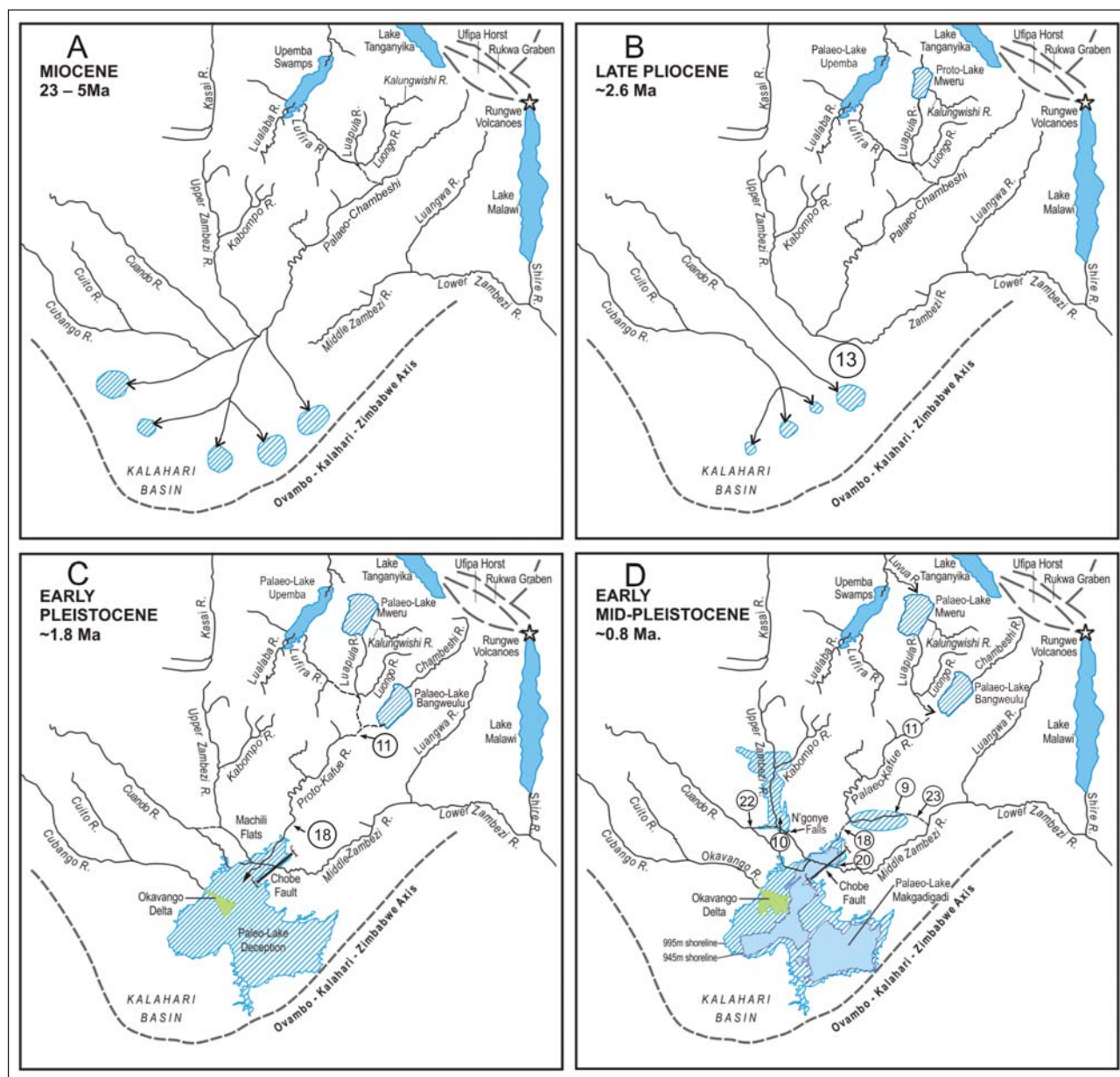


Figure 7. Summary of principal episodes in drainage evolution across the Kalahari Plateau. The geomorphological evidence and interpretations of focal landforms (numbered and summarized in Tables 1 and 2) are discussed in the main text. **(A)** Late Miocene. Late Palaeogene uplift along the OKZ Axis severs the link between the Palaeo-Chambesbi/Upper Zambezi drainage system and the Limpopo River to initiate fluvio-lacustrine deposition within the resultant Kalahari Basin, with sedimentation showing a progressive onlap to the north. **(B)** Late Pliocene. Mid-Zambezi captures Palaeo-Chambesbi/Proto-Kafue/Upper Zambezi, cutting off the major source of sediment supply to the Kalahari Basin, leaving the Cuito-Cubango Rivers as relics of the earlier endoreic drainage system. The redirected Palaeo-Chambesbi River initiates incision of the Eastern Batoka Gorge (13). **(C)** Early Pleistocene. Uplift across the course of the Upper Zambezi along the Chobe Fault associated with the south-westerly propagation of the EARS diverts the Palaeo-Chambesbi/Upper Zambezi drainage system into northern Botswana to initiate Palaeo-Lake Deception with a shore line elevation of 990 to 1000 m. The former links between the Upper Chambesbi and the Proto-Kafue (11), and the latter drainage system and PLD were all extant at this time, significantly before formation of the Kafue-Machili watershed (18). **(D)** Early to Mid-Pleistocene drainage disruptions (dashed lines) followed the chronological sequence (Tables 1 and 2) in reshaping a wetland archipelago: Link between the Upper Chambesbi and Kafue severed by uplift of Congo-Zambezi watershed (11). Palaeo-Lake Deception (PLD) (995 m shoreline) contracts to 945 m shoreline (Palaeo-Lake Makgadikgadi (PLM)). Severance of the link between the Kafue and Upper Zambezi (18) initiated Palaeo-Lake Patrick in the Kafue graben (9), with contraction of the Makgadikgadi Basin lake to the 936 m PLT. Palaeo-Lake Bulozhi (10) impounded in the vicinity of N'gonye Falls; 936 m PLT contracts to 920 m shoreline. Link between Upper Cuando and Zambezi severed to isolate Matabele-Mulonga Plain (22). Upper and Mid-Zambezi reconnected (20). 920 m lake shrinks to 912 m shoreline. Palaeo-Lake Patrick (9) drained by a tributary of the Mid-Zambezi to establish the modern course of the Lower Kafue River (23).

disrupted by major northeast to southwest faults, straddling the Machili graben and traversing the bed of the Zambezi for over 160 km upstream of Victoria Falls (Dixey, 1950; Nugent, 1990; 1992, Figure 1). Downstream of the Machili graben, the broad channel of the Upper Zambezi has incised tilted segments of the fault-bound Chobe horst, expressed in rapids (notably Mambova, Katombora and Chamsuzu, Figure 1): testifying to uplift of the eastern rift shoulder along the Chobe Fault (Moore and Cotterill, 2010).

Subsidence of the Machili graben (Figure 1) diverted the entire regional drainage net southwest to initiate the major Makgadikgadi Palaeo-Lake system (Figures 1 and 7). An Early Pleistocene age (Cotterill, 2006; Moore and Cotterill, 2010) inferred for uplift along the Chobe Fault (Figure 7C) was not tightly constrained. Phylogeographic records in *Synodontis* catfishes and *Crocodylus* (mean range = 0.8 to 0.45 Ma, overall 95% CI = 1.72 to 0.12, see above) sets a minimum age on initiation of this rifting in northeast Botswana - revising earlier suggestions of ~41 Ka (Kinabo et al., 2007, 2008).

A line of boreholes (the Tsoe Transect) in the west of the Makgadikgadi Basin (see Figure 3B for location) intersected a sedimentary sequence (Figure 8) consistent with the tectonic events discussed above. Jurassic Karoo basalts are unconformably overlain by a fluvio-lacustrine sedimentary sequence, dated as Miocene and likely late-Miocene on the basis of fossil pollens (du Plessis, 1998, Figure 8). We suggest that this unit reflects onlapping sedimentation in the Kalahari Basin, linked to the endoreic fluvial system that was initiated by late Palaeogene uplift along the OKZ Axis (Moore et al., 2009). The Miocene sediments are unconformably overlain by an undated sequence of anaerobic, inferred deep-water lacustrine sediments (du Plessis, 1998). We ascribe the unconformity to the marked decrease in sediment supply to the Kalahari Basin, following capture of the Upper Zambezi by the Mid-Zambezi. Deposition of the younger deep-water lacustrine sequence is inferred to have commenced following diversion of the Palaeo-Chambeshi-Zambezi system into northern Botswana to initiate the Makgadikgadi mega-lake sequence following uplift

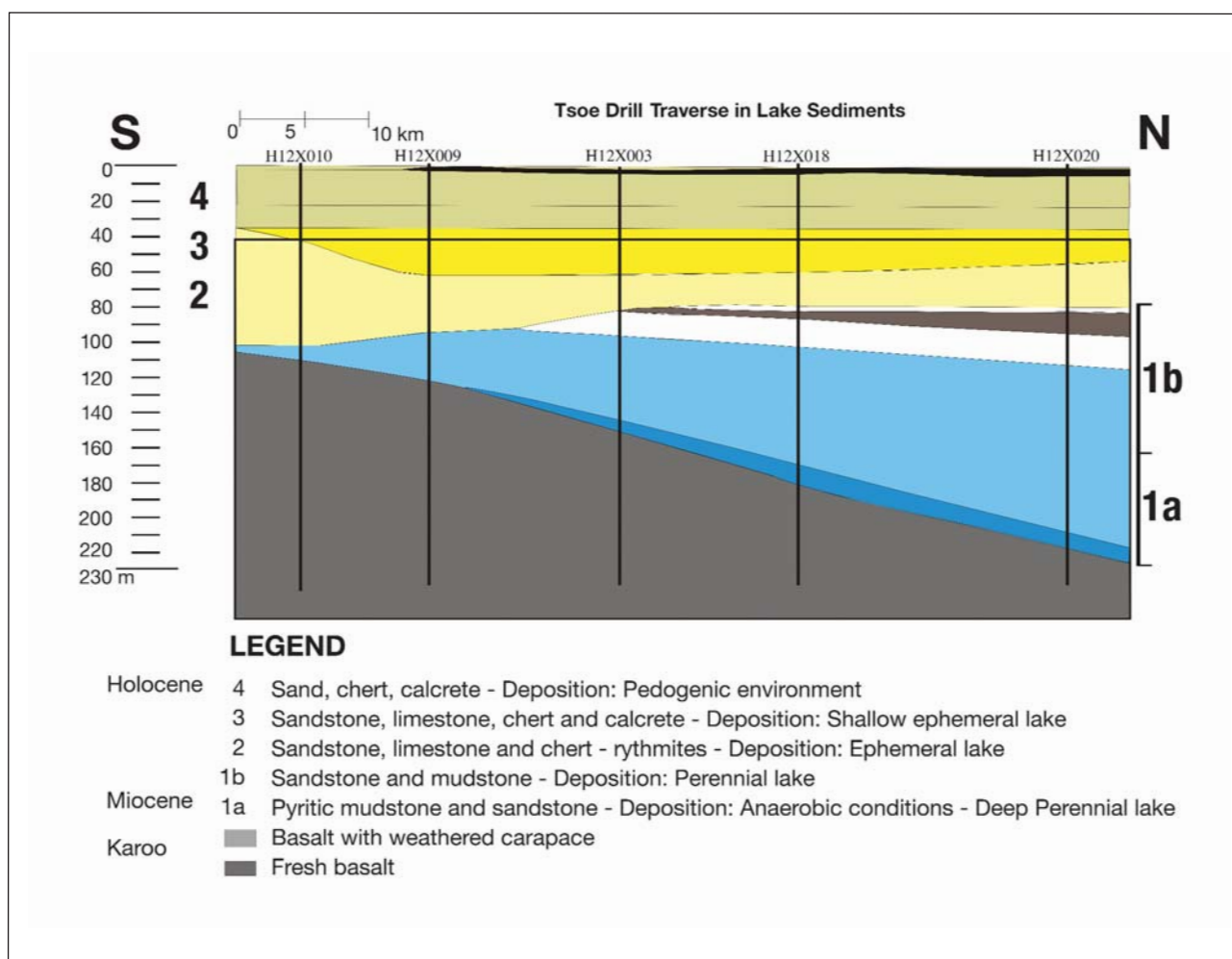


Figure 8. Schematic profile of the Makgadikgadi Depocentre depicts the infilled lacustrine sediments overlying the basalt basement (with a weathered carapace). This profile, modified from du Plessis (1998) is referred to as the Tsoe Drill Transect. Its approximate location is mapped in Figure 3A.

along the Chobe Fault (Figure 1). It should nevertheless be stressed that while this sedimentary sequence (Figure 8) is, at very least, consistent with the inferred tectonic controls on sediment supply to the Kalahari Basin, it does not provide unequivocal proof for this model.

Loss of the Chambeshi headwaters reduced the extent of the Kalahari drainage net significantly. Following an intricate interplay between river impoundment and piracy, the Chambeshi ultimately became a Congo tributary feeding the Luapula River (Figure 7D). Initial disruption severed the former link with the Proto-Kafue to isolate the Palaeo-Chambeshi headwaters in the Bangweulu Depression. This event established a protracted endoreic lake in northeast Zambia, termed Palaeo-Lake Bangweulu, prior to the ultimate capture of the Upper Chambeshi by the Luapula River (Cotterill, 2006, Figure 7D). Until recently, severance of the Chambeshi-Kafue link was loosely constrained as Early Pleistocene (Moore and Larkin, 2001). However, uplift of the Congo-Zambezi watershed is now dated at 2.2 to 1.4 Ma (overall 95% CI = 3.4 to 0.6) - the molecular dates for when four different species complexes of fishes were isolated in the Bangweulu-Chambeshi versus Kafue-Upper Zambezi drainage basins (collated from independent phylogeographic studies - Cotterill and de Wit, 2011; Cotterill and de Wit, unpublished data). This includes the 1.4 Ma (95% CI = 2.4 to 0.4) event that isolated Tigerfishes, *Hydrocynus spp.*, across the Congo-Zambezi watershed (Goodier, 2010; Goodier et al., 2011). We interpret this Early Pleistocene constraint (2.2 to 1.4 Ma) as the most recent time that Palaeo-Chambeshi inflow could have maintained any lakes in northeast Botswana. By extension, this sets a minimum age on initial disruption of the Makgadikgadi Lake system. This caused contraction of PLD to PLM (Table 1).

Following the loss of the Chambeshi headwaters, the reduced drainage line remained linked to the Zambezi via the Machili Flats as the Proto-Kafue River (Figures 1, 2, 7C and 7D). Gravels overlain by alluvium in the Machili Flats (Figures 7C and 7D) testify to the former link between the Upper Zambezi and Proto-Kafue Rivers, before disruption by tectonism. Mode 2 lithics recovered from buried gravels in both the Kafue and Machili Flats (Dixey, 1944; 1950) places this event within the ESA (i.e. earlier than 500 ka and likely Early Pleistocene, Figures 7C and 7D). A major endoreic lake formed after severance of the Proto-Kafue/Upper Zambezi link. Designated Lake Patrick by Simms (2000), and maintained by the Palaeo-Kafue River, it flooded the spatial extent of the modern Kafue Flats (Figure 7D). Lake Patrick had drained entirely in the Mid-Pleistocene (minimum U-series age = 200 ka possibly ~500 ka at Twin Rivers, Simms, 2000, Figure 2), when its eastern rim was breached by a Mid-Zambezi tributary. Following this event the Kafue River has remained a north-bank tributary of the Middle Zambezi (Cotterill, 2006).

It appears the tectonism that impounded the Upper Zambezi to form Palaeo-Lake Bulozzi (Figure 7D, minimum age 500 ka) also culminated in piracy of the Palaeo-Cuando by the lower Cuando River. Loss of this Upper Zambezi tributary likely followed on inundation of the Bulozzi graben. This raised the local base level along the Matabele-Mulonga Plain (Figures 1 and 7D), leading to senility of the Palaeo-Cuando. More recently, uplift along the Linyanti Fault (Figure 1) diverted the Cuando River from south-east (Moore and Larkin, 2001) to northeast, linking it with the Zambezi via the Chobe River (Figures 1 and 7D).

Evolution of Victoria Falls and Batoka Gorges

Batoka landforms and the Victoria Falls Formation (VFF)

The foregoing synopsis of drainage topology changes is reinforced by key evidence for the evolution of the Batoka Gorges (Figure 9A). Here, the knickpoint of the Victoria Falls demarcates two sections of the Zambezi River with marked differences in geomorphic character, designated the Upper- and Mid-Zambezi, respectively (Wellington, 1955). Above the Victoria Falls, the river flows in a broad, low gradient channel (its width can exceed 2 km), while downstream it is constrained in a series of narrow gorges (~101 km total length) collectively forming the Batoka Gorges. The latter's markedly steeper gradient testifies to abandonment of the broad Zambezi channel, incised by knickpoint migration upstream. The banks of this original broad channel are demarcated by low scarps cut into the surrounding basalt plain (Moore and Cotterill, 2010, Figure 9). Sediments of the Victoria Falls Formation (VFF) are preserved as a series of terraces above the Zambezi's channel (Moore and Cotterill, 2010). These sediments entomb stone artefacts ascribed to a sequence of hominin cultures, documented meticulously by archaeologist Clarke (1950; 1975) and geologist Dixey (1950). They preserve independent evidence for episodes in the evolution of the Zambezi River (Figures 9A to 9C).

A 6 m drop in the river profile at the Chimamba Rapids, 40.7 km downstream of the Victoria Falls, marks the distinct break in geomorphic character of the Batoka Gorges. The narrow western Batoka Gorge is deeply incised upstream of the Chimamba Rapids (= Choomoomba, the onomatopoeic name for the ground hornbill, *Bucorvus leadbeateri*, in the local Leya language). Upstream in the western Batoka, the surrounding basalt plain is incised by short, deeply entrenched tributary streams (Figures 6B to 6D and 9). Below the Chimamba Rapids, the eastern Batoka Gorge broadens; there is a marked decrease in gradient, and the surrounding topography, with broader entrenched tributaries, reflects a relatively prolonged period of dissection. Clark (1950) appreciated that the Chimamba Rapids represented a marked dichotomy in the erosion history of the Batoka Gorges. The sections of the Zambezi River above and below Chimamba Rapids are

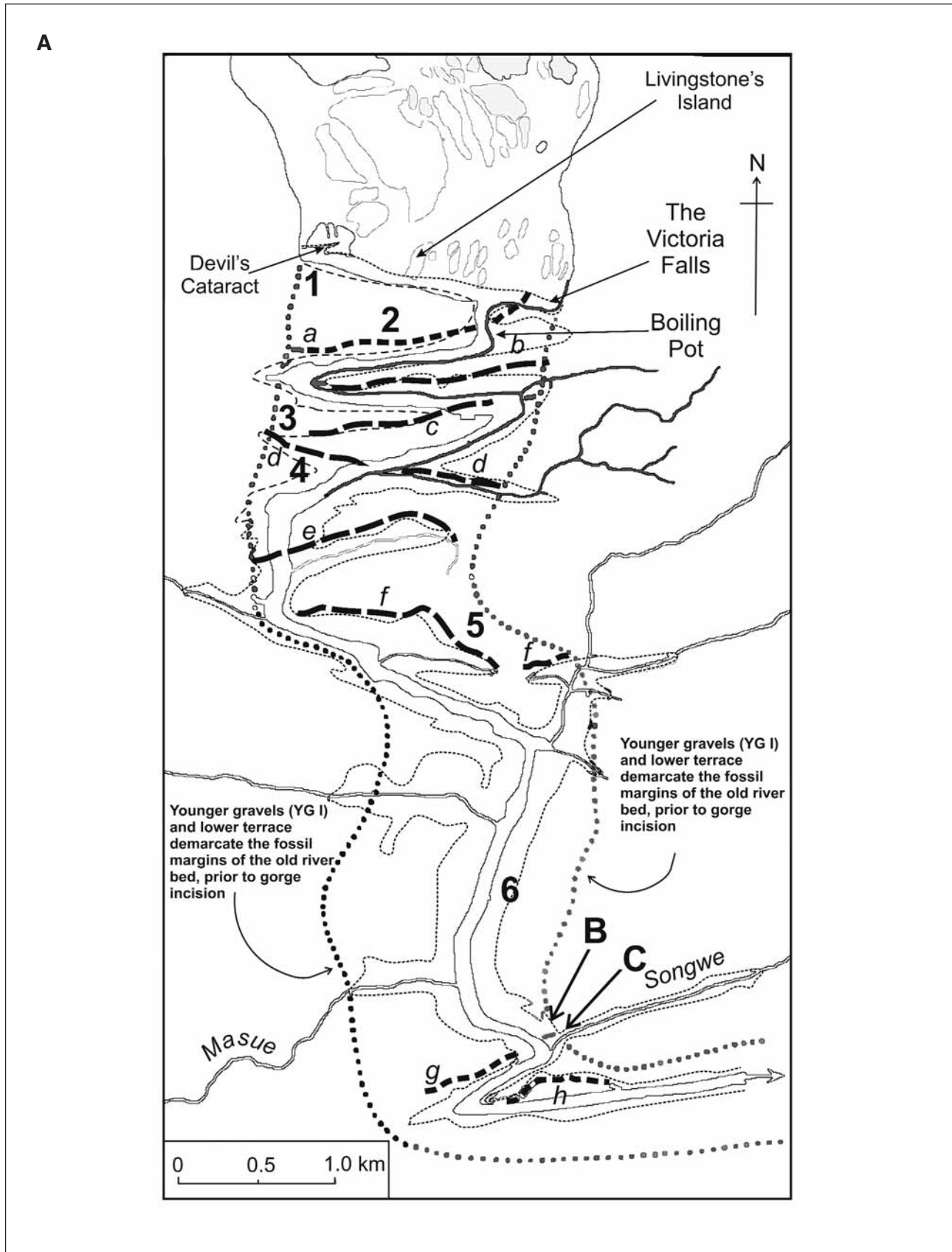


Figure 9. (A) Geomorphology of the Zambezi River in the vicinity of Victoria Falls illustrates the relationship between Younger Gravel beds of the Victoria Falls Formation (VFF) and the narrow incision of the western Batoka Gorge (dotted lines), and its principal gorges (numbered 1 to 6) downstream of the extant knickpoint. Distances in main text refer to length along the incised river channel (central solid lines). Photographic sites 'B' and 'C' depict Figures 9B and 9C respectively. Modified from Moore and Cotterill (2010).



Figure 9. continued (B) View downstream along the Zambezi River at its confluence with the Songwe River depicting the deep, vertically incised channel of the western Batoka Gorge. Photo: F. Cotterill. (C) Detail of the deflated surface of abandoned Younger Gravels I near the Songwe-Zambezi confluence. Larger gravel fragments include Middle Stone Age (Mode 3) lithic artefacts, described by Clark (1950, 1975). Photo: F. Cotterill.

profitably interpreted as two composite landforms, such that the western Batoka is much younger than the eastern Batoka downstream. This dichotomy, termed the Batoka Discordance (Cotterill, 2006; Moore and Cotterill, 2010), was interpreted by Clark to reflect a break, or marked change in erosion rates, following incision of the eastern Gorge (Figures 6B to 6D). It was ascribed to diversion of the Zambezi into the Makgadikgadi Basin by uplift of the Chobe Horst across the river course (Moore and Cotterill, 2010).

The geomorphic character of the eastern Batoka Gorge is more readily explained by a river with a far greater flow and concomitant erosive power than the modern Zambezi. Moore and Cotterill (2010) proposed that this reflected more extensive headwaters at this time, and that the Upper Chambeshi and Proto-Kafue (the Palaeo-Chambeshi, Cotterill, 2003; 2006) were linked with the Upper Zambezi River via the Machili Flats, above the Victoria Falls (Figure 7B). An aerial reconnaissance by Clark (1950) identified prominent terraces bracketing the gorge floor, preserved as remnant benches above the modern course of the Zambezi, *only* downstream of the Chimamba Rapids. Recent field observations support this interpretation. Investigation of one of these benches, on the north bank revealed a veneer of rounded pebbles preserved on an abandoned terrace, consistent with Clark's prescient interpretation. These remnant landforms are interpreted as the abandoned surface on the older gorge floor (~10 m above the high-water stand of the modern Zambezi's channel). In summary, downstream of Chimamba Rapids, an underfit Zambezi River inherited

the Palaeo-Chambeshi's channel within the antecedent eastern Batoka Gorge (Cotterill et al., unpublished data; Figures 6B to 6D).

Previously, two mechanisms were invoked to explain the Batoka Discordance (Figures 6B to 6D) at Chimamba Rapids: (1) a significant break in river flow, and/or (2) a period of reduced river flow (sustained mainly by local run off) after drainage diversion into the Makgadikgadi Basin (Moore and Larkin, 2001; Moore and Cotterill, 2010, Figures 7C and 7D). Moreover, initiation of incision of the western Batoka was attributed to a key event – when the Mid Zambezi re-established its link with headwaters draining the Kalahari Plateau, and ceased to sustain any mega-lake stand in the Okavango graben (Moore and Cotterill, 2010). However, if the Makgadikgadi Basin lakes overtopped the Chobe horst at Mambova Rapids (see below), erosion likely persisted in the Batoka Gorge during the tenures of the three highest lake stands. Erosion rates would have been linked to the volume of outflow, controlled by the lake overtopping at the Chobe horst barrier. The timing of such overtopping can only be constrained within the overall erosion episode of the western Batoka (next section).

Erosion rates and formation of the Batoka Gorges

Updating estimates by Clark (1950), Derricourt (1976) applied estimated ages of the stone artefacts in VFF sediments to calculate rates of regression of the gorges of 0.09 to 0.15 m/yr, and concluded that it had taken approximately 460 to 315 ka to erode the 40.7 km of the western Batoka Gorge upstream of

Chimamba Rapids. Nevertheless, Derricourt (1976) noted that an accurate painting of the Western Falls (Devil's Cataract) by Thomas Baines, who visited Victoria Falls in 1862, suggests that there had been no more than a few metres of knickpoint retreat in over a century. This evidence conflicts with the predicted back-cutting of 14 to 23 m over ~150 years implicit in Derricourt's estimates, which were calculated on two interrelated constraints:

1. The downstream limit on the Younger Gravels (YG I) indicated by the Mode 3 MSA artefacts. This limit of YG I approximates where the former river channel was abandoned to gorge incision, which Derricourt set at the Songwe Gorge (total channel length = ~9.7 km downstream of Victoria Falls, Figure 9). However Clark (1950) established a minimum downstream limit for YG1 of 20 km below the Victoria Falls.
2. A ~130 to 100 ka age for the ESA/MSA transition to date the Mode 3 industry in the VFF (Derricourt 1976). This is far younger than the revised minimum date of ~300 to 250 ka for inception of established Mode 3 MSA cultures (McBrearty and Brooks, 2000), notably represented in the oldest U-series dating (median age 260 ka) of the Lupemban culture, at Twin Rivers, northeast margin of the Kafue

Flats, Zambia (Barham, 2000, 2001; Figure 2). The earliest Mode 3 (early MSA) has recently been revised downward to ~500 ka at two sites in the northern Cape, South Africa (Porat et al., 2010; Beaumont, 2011; Balter, 2012; Wilkins and Chazan, 2012) and in western Kenya (Roure Johnson and McBrearty, 2010).

These recent, downward revisions of African MSA industries establish a conservative age estimate of 300 to 250 Ka on the older VFF Mode 3 culture described by Clark (1950). It in turn sets rates of 0.067 to 0.080 m/yr on erosion of the upper 20 km of the western Batoka Gorge. A revised age bracket of 71 to 57 ka constrains the Mode 4 culture (younger MSA) previously named Magosian (Clark, 1950) and Tshangulan (Cotterill, 2006; Moore and Cotterill, 2010), and here assigned to Mode 4 following Haynes and Klimowicz (2009). As mapped by Clark (1950), these Mode 4 artefacts set erosion rates of 0.042 to 0.052 m/yr over the 2.96 km channel section (from Victoria Falls to the end of the Third Gorge, Table 4).

The reason for the discrepancy between these estimated erosion rates is not clear. The lowest rate (0.042 m/yr) implies erosion of ~6 m over 150 years, which accords best with the evidence for minimal erosion in the western (or Devil's) Cataract based on the

Table 4. Estimated erosion rates of the Batoka Gorges for respective gorge sections. This updates estimates of Moore and Cotterill (2010). Sources and details of the two archaeological constraints – Mode 3 and Mode 4 of the Middle Stone Age (MSA) – are discussed in the main text with reference to respective gorge sections (2.96 and 20 km) of the western Batoka Gorge, incised downstream of the Victoria Falls. The estimate for the eastern Batoka is presented as an absolute minimum – in the absence of direct constraints to calibrate erosion rates for the lower gorges, which appear to have been incised by the much larger Palaeo-Chambeshi River.

Estimates of erosion rates of lower gorges				
Section of gorge used for erosion rate estimate	Distance eroded (km)	Stone Age culture constraining erosion rate	Age bracket of culture	Estimated erosion rate (m/yr)
Modern Falls to end of Third Gorge	2.96	Mode 4	71 to 57 ka	0.042 to 0.052
20 km downstream of modern Falls	20	Mode 3	300 to 250 ka	0.067 to 0.080
Estimated time taken to erode the gorges				
Section of gorge	Distance (km)	Stone Age culture constraining erosion rate	Estimated erosion rate (m/yr)	Time required for erosion
Victoria Falls to Chimamba Rapids	40.71	Mode 4	0.042 to 0.052	970 to 783 ka
		Mode 3	0.067 to 0.080	608 to 509 ka
Age limits for erosion of western gorges assuming VVF Unconformity = 140 ka			0.042 to 0.080	1100 to 649 ka (*)
(*) (970+140) to (509+140) ka				
Age limits for erosion of eastern Batoka Gorge (below Chimamba Rapids)	60	Mode 4	0.042 to 0.052	1.43 to 1.15 Ma
		Mode 3	0.067 to 0.080	0.90 to 0.75 Ma
Time for erosion of entire Batoka Gorge excluding time gap represented by the Batoka Discordance	100.71	Mode 4	0.042 to 0.052	2.54 to 2.07 Ma
		Mode 3	0.067 to 0.080	1.65 to 1.40 Ma
Time bracket for erosion of entire Batoka Gorge excluding time gap represented by the Batoka Discordance	100.71		0.042 to 0.080	2.54 to 1.40 Ma (**)
(**) (0.970+1.429+0.14) Ma to (0.529+0.750+0.14) Ma				

painting by Baines. Nevertheless, the Batoka Gorge is clearly structurally controlled, exploiting faults and shatter zones in the basalts (Bond, 1975, Figure 9A), so erosion rates likely varied along different sections of the gorge. In light of available evidence, the average rate of gorge regression is bracketed between 0.042 to 0.080 m/yr.

These revised estimates of gorge incision also include an episode (estimated minimum = 140 ka) for the break in river flow represented by the VFF unconformity, and coeval with the tenure of Palaeo-Lake Bulozzi (Cotterill, 2006; Moore and Cotterill, 2010, Table 4). This constrains the total erosion time for the entire 40.7 km western Batoka Gorge to within 1100 to 649 ka. It in turn sets a minimum age on initiation of the Makgadikgadi mega-lakes. However, we emphasize that this estimate assumes that erosion rates calculated using MSA (Mode 3) lithic artefacts for the upper 20 km of the western Batoka Gorge are also applicable to the lower half (~20.7 km) of the western Batoka. This lower section was undoubtedly incised after re-establishment of the link between the Upper- and Mid-Zambezi. Earlier, however, it is possible that overtopping at the Chobe Horst barrier, at Mambova, maintained reduced erosion along the Batoka Gorges. If our reconstruction of this two-stage erosion history is credible, then it not only extends the age of the entire western Batoka Gorge, but endorses a downward revision for lake initiation in the Makgadikgadi Basin. Available evidence reveals that erosion of the upper 20 km of the western Batoka Gorge took 616 to 390 ka [476 + 140 to 250 + 140 ka, respectively]. This estimate sets a minimum age for when the Upper- and Mid-Zambezi River were reunited. Erosion of the full length (40.7 km) of the western Batoka Gorge would have taken far longer. It likely began in the late Neogene (Table 4, Figure 11).

These estimates will undoubtedly be refined where and when future researchers can date key Batoka landforms and VFF sediments (possibly using cosmogenic isotopes) and independently refine landform tenures, and thus affinities and tenures of preserved artefacts. Nevertheless, constraining incision of the western Batoka in the Early Pleistocene fits well with the palaeo-lake contraction constrained by ESA (Mode 2) artefacts (minimum age = 500 ka), knapped from the silcretes formed on the desiccated floor of the Makgadikgadi depression below the 936 m contour (McFarlane and Segadika, 2001).

Evolution of Palaeo-Lakes in northern Botswana

Early Pleistocene

The evidence compiled above positions us to evaluate key hydrological controls over the Makgadikgadi lake stands – specifically links between climate, tectonism and drainage evolution. The shoreline sequence (Figures 3 and 4) and sedimentary deposits (Figure 8) in the Makgadikgadi Basin raises interesting questions as to what mechanisms maintained the lake stands.

Critically, how did discrete lakes persist in their respective episodes?

This question highlights how the prescient observation of Grove (1969) has been generally ignored. He noted that no realistic rainfall increase could have maintained the 945 m PLM, because it could not ameliorate a hydrological regime of 400 to 500 mm annual precipitation and high evaporation rates ~1800 mm (Botswana Meteorological Services Climate Data for Sua Town) over a lake approximating the size of PLM (surface area then estimated as 34 000 km², Grove, 1969). These hydrological constraints emphasize that the dynamics of the northern Botswana mega-lake complex cannot be understood unless we account for river inflows, and thus drainage evolution across south-central Africa. This broadened hydrological context has profound implications for understanding the evolution of these Makgadikgadi Lakes, if changes in the regional drainage network concomitantly controlled inflows into the depocentre. It highlights an interesting mechanism, which potentially caused sympathetic contraction of lakes – not only to successively lower shorelines but in discrete episodes.

To evaluate this possibility, it is instructive to compare the estimated water budgets required to balance the evaporative water loss for each lake stand (the hydrological model is summarized in Table 3 and Figure 10, and detailed in Supplementary File 1) (*see Supplementary File 1 – pg 000). We note that although Makgadikgadi lake volumes were likely deeper prior to sediment infilling, lack of data prevents including this variable in the present model. The hydrological model reveals an interesting asymmetry in respective evaporative losses against annual and cumulative inflows from discrete drainage nets (the Upper Zambezi system, the now extinct Proto-Kafue and Palaeo-Chambeshi systems, and the Okavango and Cuando Rivers). Their respective inflows are approximated by 33 km³/yr and twofold and threefold multiples of the total inflow (Table 3; Figure 10A). In the absence of sufficient river inflow, the Net Annual Inflow Deficit required to balance evaporation loss, from a vast lake surface, could only be compensated by rainfall increase and/or reduced evaporation (Table 3). A first order observation invokes prior evidence for regional drainage evolution; this assumes the highest lake level (~995 m PLD) was sustained by inflow contributed by the entire former Palaeo-Chambeshi/Zambezi headwaters (minimum volume – 80 km³/yr). Contraction to the 945 m PLM followed the loss of the Chambeshi headwaters, because the cumulative inflow decreased from 80 to 66 km³/yr. Contraction to the 936 m shoreline followed loss of the Proto-Kafue inflow (Figure 7D) where after the total inflow decreased to 53 km³/yr (Table 3).

Nevertheless, it is clear from Table 3 that persistence of both the PLD (995 m) and PLM (945 m) lake stages cannot be explained by inflow from the regional drainage network alone. Assuming present-day flow and

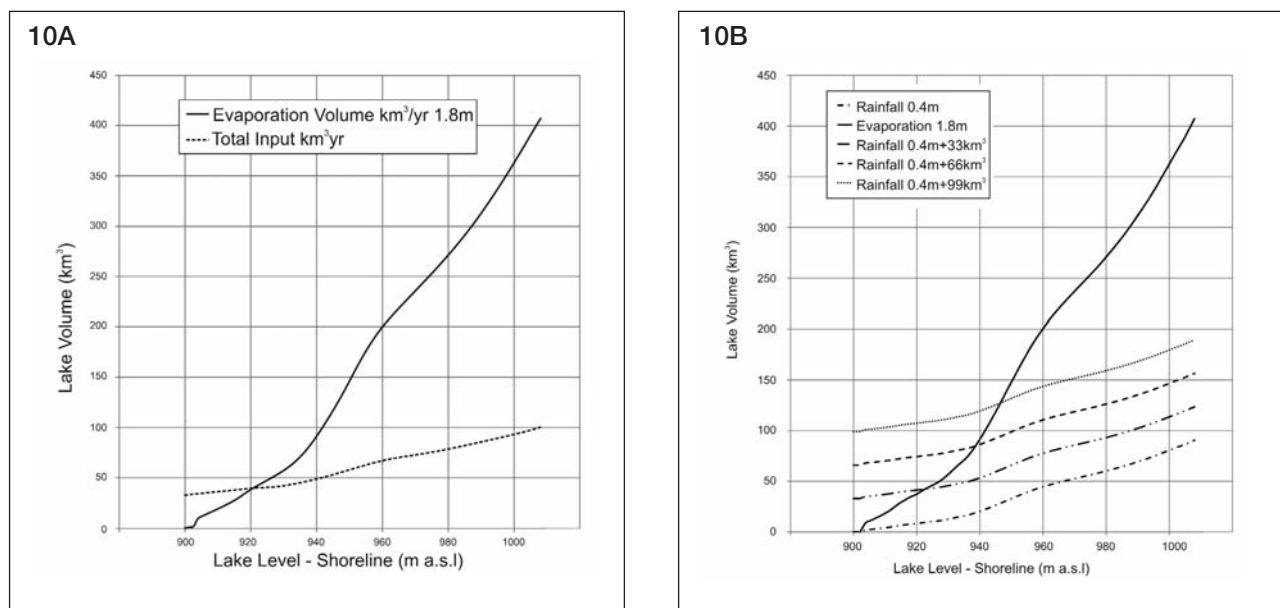


Figure 10. Hydrological model of Makgadikgadi Palaeo-Lakes summarizes relationships between different regional drainage inflows and contrasting extremes of annual rainfall for principal lake stands. See Table 3 and Supplementary File 1 for additional details. (A) Relationship between estimated annual evaporation and precipitation (mm) in relation to minimum estimated lake volumes (920, 936, 945, 995 m shorelines) in the absence of any additional drainage run off into the Makgadikgadi Basin. (B) Hydrological budgets (Table 3) of the respective lakes (920, 936, 945, 995 m shorelines) in the Makgadikgadi Basin (Figure 3) under the contemporary modern climate for estimated differences in three different drainage nets (total annual inflow, km^3/yr). The latter represent single, double and threefold inputs of entire annual average inflow of the Upper Zambezi River. The simulation reveals the positive feedback on local climate between prevailing rainfall and the rainfall/evaporation thresholds over estimated lake volumes in northern Botswana (analogous to modern rainfall induced over $68\,800\text{ km}^2$ Lake Victoria). Positive feedback on hydrological input was highest over the 945 m and 995 m lake stands, and would have maintained overtopping into the Zambezi's channel at the fault-controlled Mambova Barrage (Figures 1 and 7).

rainfall/evaporation rates, total inflow from the modern drainage system into the Makgadikgadi Basin falls far short of the budget for the two highest lake levels. Increased rainfall during wetter interglacials could possibly explain this budget deficit. Nonetheless, persistence of the PLM stage would still have required inflow from the entire Palaeo-Chambeshi/Zambezi catchments. Not only had this drainage already been disrupted by the Mid-Pleistocene (minimum age on this event), but invoking such inflow alone as an explanation raises severe problems to account for the major budget deficit for the highest lake (PLD).

The feedback mechanism we invoke to explain these deficits identified in the hydrological budget model (Table 3), further identifies discrepancies in the proposal by Burrough et al. (2009b) that climate was the major driver of landform evolution in northern Botswana. These authors argued that a water body (approximating the area of PLM) might have increased rainfall by 10 to 15%. We highlight two weaknesses in this hypothesis.

One, it fails to explain what hydrological mechanisms maintained a large lake at not just one, but a sequence of at least four discrete shoreline altitudes. Second, the hydrology of Lake Victoria provides an instructive extant analogue to model this problem. It reveals that Burrough et al. (2009b) significantly

under-estimated the magnitude of climatic feedback over a lake the size of PLM ($65\,700\text{ km}^2$, Table 3). The enhanced rainfall within and across Lake Victoria (similar to PLM in area – $68\,000\text{ km}^2$ and maximum depth $\sim 70\text{ m}$, Song et al., 2002) is explained by a positive feedback mechanism. It elevates mean annual rainfall (~ 850 to $1800\text{ mm}/\text{yr}$) over Lake Victoria, and its immediate vicinity, but decreases rapidly to significantly lower levels ($\sim 800\text{ mm}$) over the drainage basin away from the shoreline (Shahin, 2002; Yin and Nicholson, 1998). Moreover, the annual precipitation of 3000 mm over an island in the centre of Lake Victoria drops to 2200 mm near the northwest shore. Night time offshore winds generate this markedly higher rainfall over the lake's centre, but the paucity of meteorological stations prohibits accurate modelling of rainfall patterns across the entire lake (Nicholson and Yin, 2001).

Whilst rainfall forcing is evident overall, this marked gradient in rainfall from the shore to the middle of such a large lake complicates precise estimates of finer-scaled spatial variation in rainfall. Nevertheless, it is reasonable to invoke an additional significant change to the water budget of the Makgadikgadi Basin, if increased humidity off the palaeo-lake lowered evaporation losses overall. Thus a 200 mm decrease in the evaporation rate (from 1800 to 1600 mm , equivalent to $\sim 11\%$ decrease in the evaporation rate) could account for the $\sim 13.3\text{ km}^3$

shortfall required to sustain the 945 m lake level (supplementing river inflows, Table 3). A lowered evaporation rate over these palaeo-lakes was likely analogous to the mean evaporation rate over Lake Victoria, estimated at between ~1280 mm/yr (Shahin, 2002) and 1550 mm/yr (Yin and Nicholson, 1998). This estimated range is well below the documented evaporation rates for northern Botswana. Positive feedback forcing under a mesic, local climate could have compensated for insufficient river inflow, after uplift of the Congo-Zambezi watershed excluded inflows of the Chambeshi catchment (and the Trans-Katanga drainage if still extant). In summary, we attribute persistence of PLM to this mesic feedback mechanism of enhanced local rainfall. Moreover, the hydrological model identifies an input surplus for the largest lakes, which points to their overtopping at Mambova. This possibility of lake overtopping explains how erosion persisted in the Batoka Gorges (discussed above, Tables 3 and 4).

Despite input from a vast drainage network (including the Upper Zambezi and Palaeo-Chambeshi), the highest lake (PLD) reveals an input deficit of ~166 km³/yr for its maintenance. One explanation is that the drainage net was even larger, and/or a mesic climatic feedback mechanism compensated for this budget deficit. The hydrological model estimates that at least 946 mm (annual precipitation) would have been required to maintain PLM. While such an increase is significantly higher than in the case of PLM (395 mm), it is feasible given the greater area of PLD (over ~2.7x the area of PLM, Table 3). To summarize, in light of the steep rainfall gradient generated over Lake Victoria, the vast area of PLD would have considerably enhanced climatic feedback. Unfortunately, there are no extant tropical lakes of comparable size to PLD to provide even a qualitative analogue to evaluate whether this postulated feedback mechanism is of the correct order of magnitude.

It should be emphasised that insufficient data for water input and evaporation rates (let alone precise dates on the VFF stratigraphy) fail to reveal if these largest Makgadikgadi lake stages overtopped. Nevertheless, it is plausible that during the Early Pleistocene, the hydrology of the Makgadikgadi Basin was analogous to modern Lake Victoria, with sustained inflow into the Victoria Nile.

Compared against the 936 m PLT, maintenance of the 920 m lake (less than half the area of PLT) required a far greater water budget (Table 3), above that increased by diversion of the Palaeo-Cuando River into the Okavango graben (postulated as following on formation of PLB). This apparent anomaly suggests that a climatic feedback mechanism maintained this 920 m lake. A possible explanation is that the tenure of Palaeo-Lake Bulozzi, impounding the Upper Zambezi, overlapped the tenures of both Makgadikgadi Lakes. So Zambezi inflow into PLT was substantially lower than today (modern Upper Zambezi flow = 40 km³ yr, Tables 1 and 3). Conversely, this reduced Zambezi inflow during the

920 m lake's tenure would have supplemented inflows from the Okavango and Cuando. These results suggest a climatic feedback mechanism helped maintain the 936 m PLT, but was not operant over the 920 m lake. The latter would have contracted below the 920 m shoreline once the Upper and Lower Zambezi were reconnected, thereafter terminating significant inflow into the Makgadikgadi Basin.

Historical fluctuations in water levels of Lake Victoria are ascribed primarily to rainfall variability, and reflect minor shrinkage, as the lake overtops into the Victoria Nile at the Rippon Falls (Nicholson and Yin, 2001; Kizza et al., 2009). This raises the question as to whether long-term seasonal changes explain these different Makgadikgadi shorelines. We consider this most unlikely, as Lake Victoria's shoreline has only varied between approximately +/-2 m of the present day level since 1800 (Nicholson and Yin, 2001) – far less than the 50 m drop from the 995 m PLD to the 945 m PLM.

Although this Regional Model invokes step-wise decreases in drainage nets to explain punctuated contractions of discrete palaeo-lakes, it is unlikely that these entailed instantaneous lacustrine responses. Severance of a feeder river's inflow was likely gradual (10³ to 10⁴ yr). Moreover, if drainage disruptions occurred during mesic periods increased precipitation and decreased evaporation likely compensated hydrological budgets. So this mechanism explains time lags in lake contraction, until the reduced river inflow contributed proportionately more to the hydrological budget in a drier period.

In summary, this hydrological model clarifies critical aspects of the Regional Model. Stepwise disruption of inflow from the regional drainage net, modulated by a local decrease in mesic climatic feedback over a progressively shrinking lake body, accounts for the sequential reductions in the lake shorelines (990 > 945 > 936 > and 920 m). Importantly, the model excludes expansions to any former, higher shoreline following a major lake contraction. Moreover, the mechanisms invoked as primary controls over lake evolution provide a consistent explanation. It causally links progressive contraction of the regional drainage network to the graben depocentre (Figures 7 and 10).

Middle to Late Pleistocene

A complete narrative of the history of the northern Botswana palaeo-lakes must also account for their final desiccation. This is ascribed to a progressive decrease in water supply, linked to severance of the Cuando, and modulation of Okavango inflow into the Makgadikgadi Basin. Postdating the tenure of the youngest palaeo-lake (Figure 11) the present-day Okavango delta formed by partial impoundment within the graben, bounded between the Gumare and Thamalakane Faults (Figures 1 and 3A). Uplift along the latter fault redirected the Okavango River to establish the fault-controlled Thamalakane River, which in turn breached the fault into the Boteti River (Figures 1 and 3A). Thus, evolution

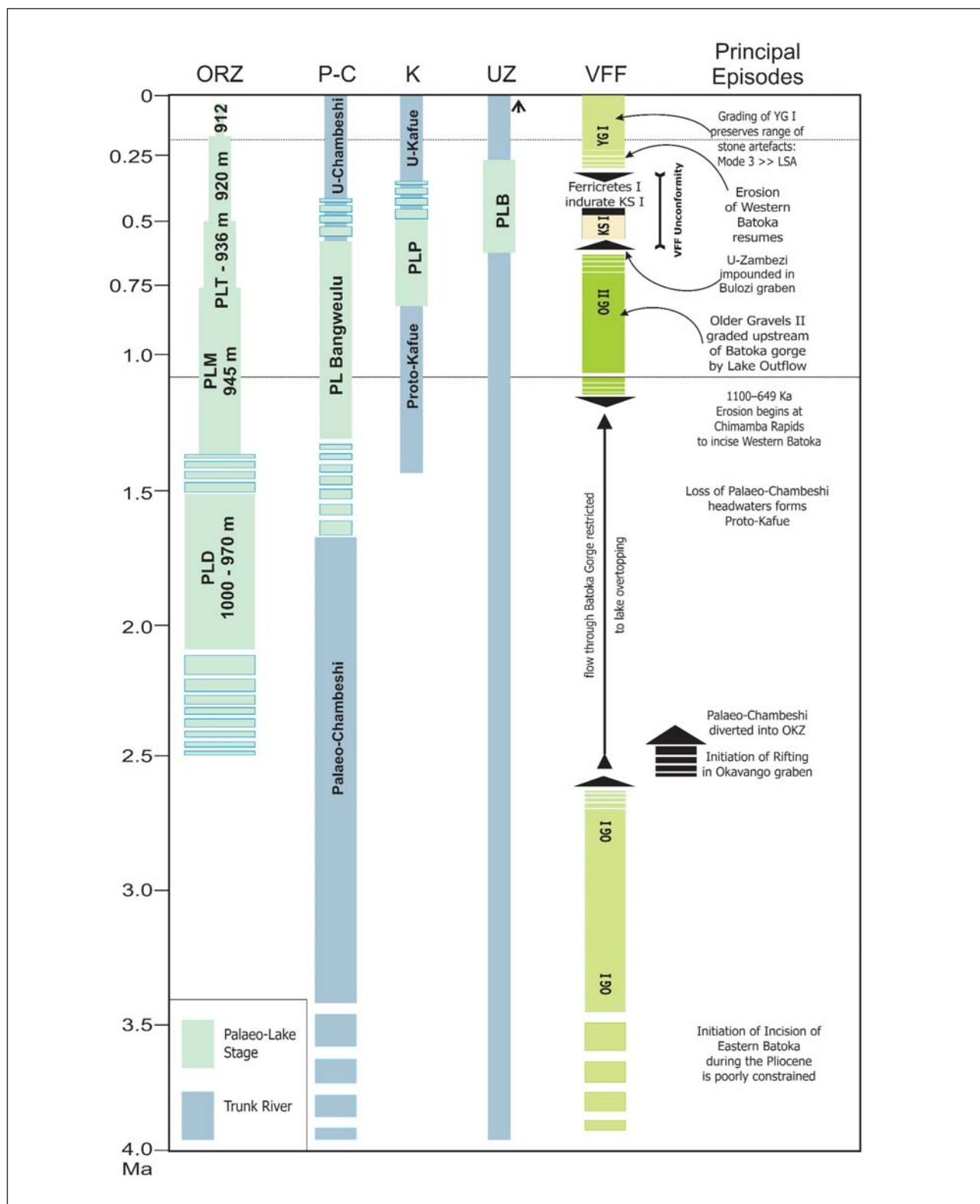


Figure 11. Schematic chronology of the principal episodes compiled in the Regional Drainage Evolution Model over the Late Cenozoic across the Kalahari Plateau. It depicts interlinked formative events and lake stands in the Bulozzi and Kafue graben, and Okavango Rift Zone (ORZ), and the Kafue (K), (Palaeo-Chambeshi (PC) and Upper Zambezi (UZ) Rivers. The evolution of the Batoka Gorges represented in the Victoria Falls Formation (VFF) are summarized from Clark (1950), Cotterill (2006), Moore and Cotterill (2010) and Cotterill and Moore (unpublished data). Abbreviations additional to Table 1: KSI = Kalahari Sands I; OG I = Older Gravels I; OG II = Older Gravels II; YG I = Younger Gravels. Modified from Cotterill (2006) with additions. See main text for discussion of discrepancies between the Early and Mid-Pleistocene lake tenures, delimited in this study, and Late Pleistocene lakes (Figure 5) proposed by Burroughs et al. (2009a). The VFF Unconformity represents the tenure of Palaeo-Lake Bulozzi maintained by the impounded Upper Zambezi River (Figures 2 and 7).

of the Boteti River followed on deepening of the Okavango graben.

Today, high evapo-transpiration across the vegetated shallow expanses of the Okavango Delta explains why only ~3% of the flow into the upper panhandle reaches the Thamalakane River, ultimately linking Okavango distributary channels via the Boteti into the Makgadikgadi Basin (McCarthy and Ellery, 1998). Arguably, higher volumes of water probably reached the Thamalakane during the early stages of delta formation. Consistent with this hypothesis, the deeply incised Boteti River is markedly underfit in its upper channel (discussed above, Figure 6A). Moreover, a series of abandoned deltas testifies to where the Proto-Boteti emptied into the 920 m and 912 m lakes (Cooke and Verstappen, 1984). These deltas reflect progressive contraction from the 920 m shoreline to the 912 m lake. So the lower reaches of the Boteti River (below the 912 m level) postdate abandonment of this shoreline.

Moore and Larkin (2001) identified a major delta in the northwest of Sowa Pan, attributed to inflow from the Cuando River into the lake within the modern Sowa Pan (i.e. below ~912 m). This inflow persisted until uplift beheaded the Cuando, deflecting it along the Linyanti Fault to its extant confluence with the Upper Zambezi River (Figure 2).

The timing of the 920 m lake's contraction is not well constrained. Preservation of rare earlier Mode 3 and more abundant late Mode 3 artefacts below the 920 m shoreline (Figure 3B) suggest the 920 m lake was abandoned between 300 to 100 ka. Rare late Mode 3 and abundant Mode 5 (LSA) sites on the lower reaches of the Boteti (below 912 m, Figure 3B) suggest the 912 m lake desiccated within the last 100 ka (dates on the MSA and LSA from Barham, 2000; 2001; Deacon and Deacon, 1999; Jacobs and Roberts, 2008). This requires a major downward revision of the estimate (based on ^{14}C dating of a fossil gastropod, *Potadoma* sp.) that a permanent riparian environment was established on the Boteti River by 46 ka (Riedel et al., 2009).

Conflicting age evidence

Consilience of the phylogeographic records of aquatic vertebrates with archaeological evidence from northern Botswana (Table 1, Figure 11) sets broad but robust constraints on initiation of the lake system in the Makgadikgadi Basin as Early Pleistocene, with its desiccation to below the 936 m PLT before the end of the Early Stone Age (Mid-Pleistocene). Episodes in evolution of the Batoka Gorges, below Victoria Falls on the Zambezi River, exhibit further consilience with this scenario. Archaeological and fossil evidence constrains formation of the linear dunes to significantly before the ESA/MSA transition (i.e. >500 Ka), revealing that major aeolian activity pre-dates the Acheulian industry. These lines of evidence conflict with ^{14}C ages for calcretes and gastropod shells, and apparently high precision quartz luminescence dates, which invoke

Upper Pleistocene - Holocene Ages (an order of magnitude younger) for linear dunes and fossil shore lines in northern Botswana and the surrounding region (Figure 5).

As discussed earlier, ^{14}C ages probably integrate multiple phases of calcrete formation, continuing to the present. So the geological significance of these ages is questionable. The LD chronology (Figure 5) raises interesting questions as to why it is nested within tenures of older landforms. It is argued that the discrepancy between these respective bodies of evidence represents a fundamental divergence in spatio-temporal scale. Such disparities exemplify how process and form shape geomorphic systems (cf Huggett, 2011); structured across hierarchical levels, and these spatio-temporal divergences are characterized by time lags and partial linkages. This is exemplified by the nesting of local earth surface processes within landform dynamics operant at regional to subcontinental scales. Critically, the rate and mode of landscape dynamics is skewed, because formative events at larger scales dominate landform evolution (Brunsden, 1993; 1996). A consensus acknowledges how this scale-dependency in process and form both challenges and structures entire research disciplines in geomorphology (e.g. Simpson, 1963; Brunsden, 1993; 1996; Phillips, 1995, 1999; 2006; 2012; Summerfield 2005; Bishop, 2007; Beck, 2009; National Research Council, 2009; Slaymaker, 2009; Walker, 2010; Gregory and Goudie, 2011). In the context of spatio-temporal structuring of process and form, the LD dates represent local sediment turnovers only – encompassed within tenures of landforms shaped by larger scale processes.

This scale-dependent dichotomy is underscored by questions raised by McFarlane et al. (2005) about the validity of luminescence dating techniques in the Kalahari environment. They highlighted several lines of evidence for significant bioturbation of the Kalahari sediments, which “cannot be disregarded as a complication which overprints the luminescence signals.” Bateman et al., (2007) similarly flagged the likely effects of bioturbation to account for discordant luminescence dates on linear dunes near the Tsodilo Hills, northwest Botswana. These observations highlight the potentially critical role of bioturbation in modifying Kalahari sediment profiles. Testing this explanation for scale-dependent discrepancy requires independent dates on Kalahari landforms (almost entirely lacking). This highlights the potential for cosmogenic burial dating of suitable sediments (as demonstrated for Neogene sediments in the Chad Basin, Lebatard et al., 2008).

Conclusions

As a contribution to the quest to reconstruct the tempo and mode of landscape evolution across High Africa, this paper demonstrates the importance of evidence preserved in the Kalahari Basin and the Batoka Gorges. Consilient synthesis of this evidence from across the

subcontinent reveals how evolutionary events were causally linked across the Makgadikgadi Basin and neighbouring depocentres. Late Cenozoic propagation of the EARS into south-central Africa has played a pivotal role in shaping the geomorphology of the Kalahari Plateau. Formative events in the evolving landscape modified a wetland archipelago: dynamics of its lakes were linked with reconfigurations of the drainage topology. We identify consecutive disruptions of the regional drainage network as the primary control over a progressive step-wise contraction of palaeo-lakes in the Makgadikgadi Basin. This underlying control was reinforced by a coupled second order modulation of climate over the largest lakes. The significance of this climatic forcing has interesting implications for palaeo-climatic modelling. Further, elevated precipitation over the higher lake stands was possibly important in elevating runoff in the local drainage network (represented today in the fossil Kalahari Rivers).

This Regional Drainage Evolution Model answers long-standing questions about the origins of Kalahari landforms. The order of magnitude mismatch identified between luminescence dates of quartz grains versus ages placed on key Kalahari landforms highlights questions about the role and extent of bioturbation in modifying Kalahari sediments. It opens the arena to tackle outstanding questions, to quantify key events in Kalahari geochronology and landscape evolution. The model can be tested in Kalahari depocentres by direct dating of alluvial and lacustrine facies (combining dating of cosmogenic isotopes and zircons). These opportunities underscore the need for stratigraphical records across the wetland archipelago, represented today in the Congo and Zambezi drainage systems.

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Supplementary File 1. Excel spreadsheet detailing the data and calculations of the hydrological model (Table 3 and Figure 10). Areas of principal mega-lake stages, bounded by shorelines at different elevations, were calculated using the Shuttle Radar Telemetry Dataset-4 (SRTM). Each lake stage is related to the inflows of respective drainage nets, and associated estimates of evaporation. Two different regimes of annual rainfall (400 mm and 1 800 mm) contrast the extremes of meteoric input over the lake surface. The highest estimate is derived from prevailing climate over Lake Victoria. See main text and Figure 10 for details.