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Sedimentary facies and geomorphic evolution of a blocked-valley lake: Lake Futululu, northern Kwazulu-Natal, South Africa

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ABSTRACT

Blocked-valley lakes are formed when tributaries are impounded by the relatively rapid aggradation of a large river and its floodplain. These features are common in the landscape, and have been identified in the floodplains of the Solimões-Amazon (Brazil) and Fly-Strickland Rivers (Papua New Guinea), for example, but their inaccessibility has resulted in studies being limited to remotely sensed image analysis. This paper documents the sedimentology and geomorphic evolution of a blocked-valley lake, Lake Futululu on the Mfolozi River floodplain margin, in South Africa, while also offering a context for the formation of lakes and wetlands at tributary junctions. The study combines aerial photography, elevation data from orthophotographs and field survey, and longitudinal sedimentology determined from a series of cores, which were sub-sampled for organic content and particle size analysis. Radiocarbon dating was used to gauge the rate and timing of peat accumulation. Results indicate that following the last glacial maximum, rising sea-levels caused aggradation of the Mfolozi River floodplain. By 3980 years BP, aggradation on the floodplain had impounded the Futululu drainage line, creating conditions suitable for peat formation, which has since occurred at a constant average rate of 0·13 cm year^{-1}. Continued aggradation on the Mfolozi River floodplain has raised the base level of the Futululu drainage line, resulting in a series of back-stepping sedimentary facies with fluvially derived sand and silt episodically prograding over lacustrine peat deposits. Blocked-valley lakes form where the trunk river has a much larger sediment load and catchment than the tributary stream. Similarly, when the relative difference in sediment loads is less, palustrine wetlands, rather than lakes, may be the result. In contrast, where tributaries drain a steep, well-connected catchment, they may impound much larger trunk rivers, creating lakes or wetlands upstream.

Keywords Blocked-valley lake, floodplain, sedimentary facies, wetland.

INTRODUCTION

Occasionally, aggradation on the floodplain of a large river with a large sediment supply may exceed the rate of sedimentation in smaller tributary valleys, leading to the formation of blocked-valley lakes or wetlands. While considerable attention has been paid to ox-bow and serpentine lakes on floodplains, very little is known of the sedimentology and geomorphic history of blocked-valley lakes. Descriptions of blocked-valley lakes have been based predominantly on remotely sensed imagery, rather than on field studies of sedimentology and geomorphology (e.g. Blake & Ollier, 1971; Neller *et al.*, 1992; Hess *et al.*, 2003), although some work has been done on the chemistry and biology of blocked-valley lakes in Australia (Timms, 1986; Humphrey *et al.*, 1990). The aim of the present paper was to characterize the sedimentology of a blocked-valley lake, Lake Futululu, a flooded tributary valley abutting the Mfolozi River floodplain, in KwaZulu-Natal, South Africa. In addition, a conceptual model of the geomorphic evolution of Lake Futululu is presented. Finally, the paper aims to contextualize the formation of lakes and wetlands at tributary junctions with respect to the relative sediment supply of the tributary and trunk (main) river channels.

Blake & Ollier (1971) provided the first relatively detailed description of blocked-valley lakes with reference to the alluvial plains of the Fly River in Papua New Guinea. Since this study, confusion has surrounded the term 'blocked-valley lake', with numerous alternative names being suggested and then abandoned (see Neller *et al.*, 1992), the most popular of which include 'ria lakes', 'lateral lakes', 'backstow lakes', 'tributary mouthbays' and also 'Rückstauseen' (Wilhelmy, 1958), used to describe blocked-valley lakes along the Yangtze River in China. The original term, 'blocked-valley lake', has been used here as it avoids confusion with coastal and estuary terminology, and provides useful insight into lake origin.

In the original study, Blake & Ollier (1971) described how blocked-valley lakes on the Strickland River formed due to differences in catchment size and sediment load. Smaller tributaries of the large Strickland River had restricted, gently sloped catchment areas, that carried insufficient sediment to keep pace with alluviation in the main valley. As such the tributary valleys eventually became dammed by the alluvial deposits of the larger Strickland River to form lakes, the biggest of which is Lake Murray. The resultant lakes had the characteristic shape of drowned valleys, with remarkably level floors, and were frequently connected to the main river channel by 'tie channels' that conveyed bi-directional flow and created small deltas at the point at which they entered the lake. Where flow was only in one direction, the connecting channel was termed an 'overflow channel'.

The blocked-valley lakes of the Fly and Strickland Rivers in Papua New Guinea were revisited by Parker *et al.* (2008), who described lake formation as a response to Pleistocene–Holocene sea-level rise that had caused aggradation on the main river channel. It was also noted that not all blocked-valleys were lakes, but that some were wetlands. Indeed, Grenfell *et al.* (2008) provide an account of the formation of a wetland in the Drakensberg Foothills of South Africa, where flow from a tributary valley is impeded by floodplain aggradation of the trunk river. In another study, tin mining in the Australian Ringarooma River catchment accelerated erosion and enhanced sedimentation on the trunk channel leading to the formation of blocked-valley lakes (Knighton, 1989).

In addition to these accounts, Neller *et al.* (1992) identified and described blocked-valley lakes in the Amazon River Basin using radar and satellite imagery. Similar to those of Papua New Guinea, the lakes of the Amazon are believed to have formed as sea-levels rose following the last glacial maximum (Mertes *et al.*, 1996). Tributaries with small catchments and low sediment yields were blocked by more rapid alluviation on the Amazon trunk channel and floodplain, resulting in open water bodies surrounded by flooded woodland, shrubland and forest (Hess *et al.*, 2003). Neller *et al.* (1992) argue that the formation of blocked-valley lakes continues, as river avulsions create new floodplains and small tributaries are subsequently blocked.

Apart from a few detailed sedimentological studies of Quaternary blocked-valley lakes, these features have not been described extensively in the geological record. Meandering river deposits represent only a minor proportion of the fluvial-channel record, possibly because of their relative size (which is small compared to those of braided rivers) and their low preservation potential (Gibling, 2006). As such, the preservation of blocked-valley lakes in the geological record should be rare. Nevertheless, in the Permian Rangal Coal Measures of Australia, lake sediments abutting vertically stacked channel sandstones were described by Michaelsen *et al.* (2000). The channel type could not be discerned in outcrop, as bar deposits could be interpreted as both meandering river point bar deposits and braided river lateral bar deposits, a problem also highlighted by Gibling (2006). Nevertheless, the lake sediments could represent either backwater or blocked-valley lakes, and were characterized by well-sorted carbonaceous siltstone with rhythmical, varve-like laminations and rare plant fossils. Lenticular bodies of sandstone amidst carbonaceous siltstone were interpreted as representing occasional crevassing of the trunk channel into the lake. Roberts (2007) described similar finely laminated calcareous siltstone deposits in the Cretaceous Kaiparowits Formation of Utah, USA. These deposits were associated with both meandering and anastomosing channels with stable banks, but were interpreted as backwater lakes rather than blocked-valley lakes. Sedimentation patterns of present-day backwater lakes have been studied extensively, particularly in the floodplain of the Mississippi River (e.g. Eckbald *et al.*, 1977; Theis & Knox, 2003). Sedimentation in these lakes is characterized by sediment fining and a decrease in sedimentation rate with distance from the trunk channel, as would be expected (Pizzuto, 1987). However, they are hydrologically distinct from blocked-valley lakes, as their only source of water and sediment is overtopping of the trunk channel.

Biological investigations have found that the water quality of blocked-valley lakes is variable. The bottom water of blocked-valley lakes in Australia is frequently acidic and anaerobic, becoming polymictic during the wet season (Hart & McGregor, 1980). Similarly, Nabout & Nogueira (2007) described Lake Tigris on the Amazon River as being unproductive, although it was oxygen rich, as it was nutrient poor. Furthermore, as blocked-valley lakes generally are shallow, they are prone to desiccation during dry years (Swales *et al.*, 1999).

Study area

Lake Futululu is located on the northern edge of the Mfolozi River Floodplain on the eastern seaboard of South Africa, *ca* 200 km north of Durban on the coast of KwaZulu-Natal (Fig. 1). Precipitation is seasonal, with *ca* 80% falling during the months of November to April (Tyson, 1986). Mean annual precipitation is 1288 mm at the coastal town of St. Lucia, located 12 km east of Lake Futululu. Annual potential evapotranspiration is frequently more than double that of precipitation, but averages 1800 mm (Schulze, 1997).

The Futululu valley drains a small catchment (1600 ha) of *Eucalyptus* plantations and indigenous sand forest. The base of the valley is level and has no definable thalweg, suggesting that water movement occurs primarily as groundwater

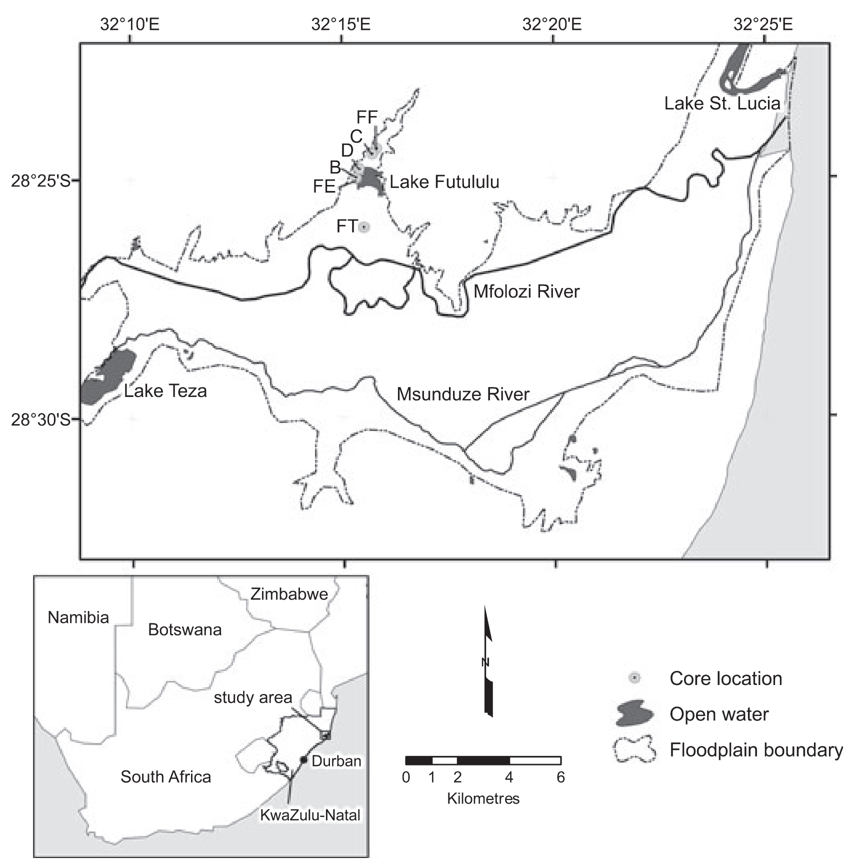

Fig. 1. Location and surface water extent of Lake Futululu, from the earliest available photography (1937), on the northern boundary of the Mfolozi River Floodplain in northern KwaZulu-Natal, South Africa. The location of cores FF, C, D, B, FE and FT is also shown.

flow or diffuse overland flow. In the upper portions, the wetland is dominated by *Phragmites mauritianus* reeds. Towards the open water of the lake, floating reed beds of *Cyperus papyrus* and isolated *Ficus trichopoda* trees occur. The actual extent of Lake Futululu, while variable from year to year, is on average *ca* 100 ha.

The catchment of Lake Futululu is underlain by Zululand Group siltstones and sandstones, which were deposited between 145 and 65 Ma in the newly formed Indian Ocean. Following an erosional hiatus, a second marine transgression allowed the formation of the Maputaland Group *ca* 50 Ma, which is comprised of several fossiliferous beds and palaeodune deposits. This lithological sequence is capped by a deep, unconsolidated veneer of aeolian deposits that were deposited during several phases of dune formation and remobilization (Porat & Botha, 2008) and which are now primarily responsible for surface topography in the region.

The southern margin of the Futululu valley comprises the floodplain of the Mfolozi River, which drains a catchment some $1{\cdot}1 \times 10^6$ ha in size. Other than Lake Futululu, two additional lakes occur on the floodplain periphery. Lake Teza, on the south-western margin, is fed by the Msunduze River, which eventually flows into the Mfolozi River at the coast (Fig. 1). The much larger Lake St. Lucia is located just north of the Mfolozi River estuary mouth, and stretches *ca* 60 km northwards behind the coastal dune barrier complex, with an estimated area of between 300 and 350 km^2, depending on water levels (Begg, 1978). The lake is fed by five rivers, namely the Mkuze, Mzinene, Hluhluwe, Nyalazi and Mpati, which have a combined catchment area of *ca* 665 000 ha.

On its southern and northern sides, the floodplain is bordered by relatively steep outcrops of Zululand and Maputaland Group rocks, while the Maphelane dune cordon, which generally reaches a height of over 100 m, marks its eastern boundary. The Mfolozi River is a meandering alluvial river dominated by suspended load, and the floodplain is dominated by sediment, which fines progressively towards the coast (Grenfell *et al.*, 2009). Aggradation on the alluvial ridge of the river is substantial, and results in it being elevated above the surrounding floodplain by >2·5 m (Grenfell *et al.*, 2009). Groundwater tables slope down from the Mfolozi River, recharging the floodplain during periods of low flow (Grenfell *et al.*, 2009). Peat accumulation on the floodplain is limited, partially because of the seasonality of discharges that cause overbank flooding, and partially because of the large clastic sediment input.

METHODS

Six sediment cores were extracted along the western margin of Lake Futululu using a combination of a Russian peat corer and a clay auger (Fig. 1). Where possible, cores were retrieved to the depth of the sand bed of the previous valley surface. For Cores B, C and D, the complete core was retained in a PVC pipe and sub-sampled in the laboratory. The remaining cores were sub-sampled on site by placing contiguous 0·10 m sections in plastic bags. The location of each core was recorded using a GPS with differential correction using a remote base station (sub-metre accuracy in the *x*, *y* and *z* fields). Loss-on-ignition involved burning dried samples in a muffle furnace for 4 hours at 450°C in order to determine the organic content of the samples, which were classified as peat when the organic content was >30%. A Malvern Mastersizer 2000 (Malvern Instruments Limited, Malvern, Worcestershire, UK), which employs laser diffraction techniques on a wet, dispersed sediment sample, was used to determine particle-size distribution after organic matter had been removed from samples with hydrogen peroxide. Particle size was described according to median particle size and classified according to the Wentworth-Udden particle size scale. Sedimentary facies were described using a combination of the Miall (1996) facies codes and the lacustrine sediment description methods of Schnurrenberger *et al.* (2003). Radiocarbon dates were determined for 10 samples, eight from Core FF and two from Core FE, by the CSIR Quaternary Dating Research Unit in Pretoria, South Africa.

A longitudinal profile of the Lake Futululu drainage line and the Mfolozi River floodplain was compiled from an assortment of data collected using GPS instrumentation with differential correction capabilities (sub-metre accuracy for a remote base station, sub-centimetre accuracy for a local base station). Corrections from spheroidal to geoidal surfaces were not made, as the variation between these surfaces was considered small due to the localized nature of the data being collected. Valley cross-sections were drawn from 1 : 10 000 orthophotographs, georeferenced aerial photography obtained from the Surveyor General of South Africa, with 5 m contour intervals (2·5 m accuracy). The depth of peat and fine sediment infill in Lake Futululu was determined by probing the sediment with steel poles until refusal. This method had been verified at core sites where the sediment could be examined at depth. Probing sediment infill was completed systematically along valley cross-sections at measured intervals of 25 m.

Five generations of aerial photographs from 1937 to 1996 were studied in order to determine temporal variation in the extent and distribution of lake surface water. Unfortunately, there is no available information on seasonal fluctuations of the lake surface water level. Aerial photographs were rectified using control points from georeferenced orthophotography, and the geomorphology of each was mapped using ArcView GIS.

RESULTS

Historical geomorphology

In 1937, Lake Futululu was extensive with a surface area of more than 300 ha (Fig. 2). The longitudinal axis of the lake was from the north-west to the south-east, onto the floodplain periphery, while the Mfolozi River was characterized locally by a large loop towards the south

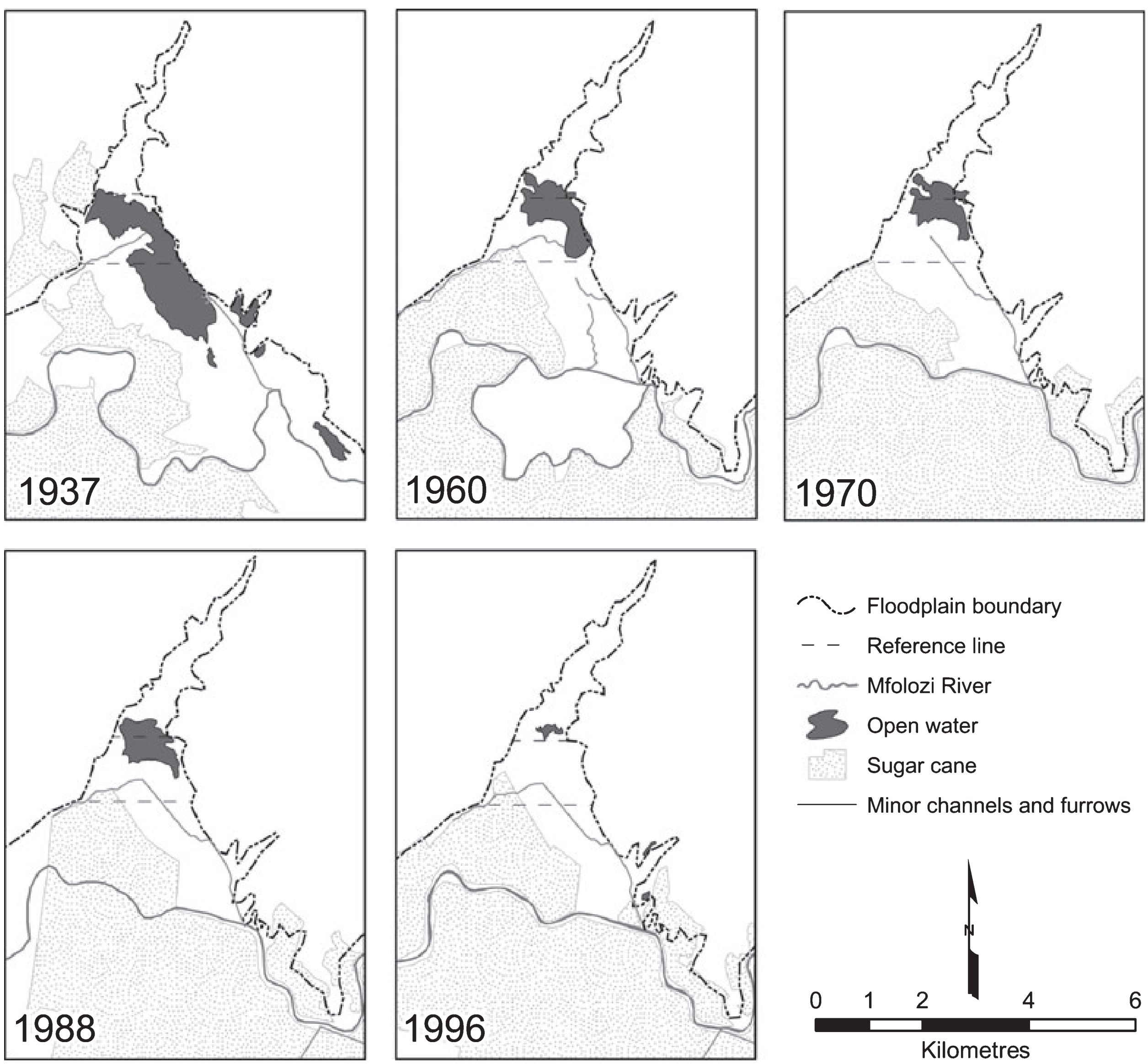

Fig. 2. Changes in geomorphology and land-use over the period of historical aerial photography (1937 to 1996). Two east-west reference lines have been drawn to allow the location of the lake to be compared between years.

away from the Futululu drainage line, before turning north further eastwards. A floodplain channel, called Crocodile Creek, drained into the lake from the south-west, resulting in the formation of a large arcuate delta in the lake. In addition, a tie channel connected Lake Futululu with the Mfolozi River on its south-eastern downstream end, also resulting in the formation of a delta much smaller than that associated with Crocodile Creek. Between 1937 and 1960, sugar cane farmers on the Mfolozi Floodplain began to shorten the course of the river by circumventing the large meander loop and, by 1960, water flowed down both courses. The newly created course of the Mfolozi River flowed directly over previously flooded areas that comprised part of Lake Futululu in 1937, halving the area of open water in the lake to 150 ha. In addition, Crocodile Creek was extended upstream towards the west by sugar cane farmers to enhance the drainage of cultivated fields.

By 1970, the Mfolozi River flowed only on the straightened course, and the old loop had been completely abandoned. The region of open water in Lake Futululu decreased to *ca* 100 ha. In 1988, the area of open water once again measured *ca* 100 ha and the two channels had been completely formalized as drainage furrows. By 1996, the river course remained unchanged and surface water was substantially reduced to <10 ha. In addition, the southern margin of open water had moved north by 0·4 km, while the northern margin had remained in the same position.

Overall, there is a general trend over the period of record of a gradual shift of the southern lake margin towards the north. Using the common reference lines in Fig. 2, a comparison between years was made. Overall, the southern shoreline of the lake has moved northwards by over 3 km since 1937, with the largest change occurring between 1937 and 1960, when the southern margin moved north by 2·3 km. Thereafter change occurred more gradually. Contrastingly, the northern margin has remained relatively static during historical times, with the largest change occurring between 1937 and 1960, when the northern margin moved northwards by 0·37 km.

Valley geomorphology

The current Futululu valley surface is level in cross-section and the wetland is situated between relatively steep valley walls (Fig. 3). Towards the head, the valley is narrow (<1 km, Fig. 3A), widening progressively downstream to 5·5 km at cross-section ‘D’ (Fig. 3D), to more than

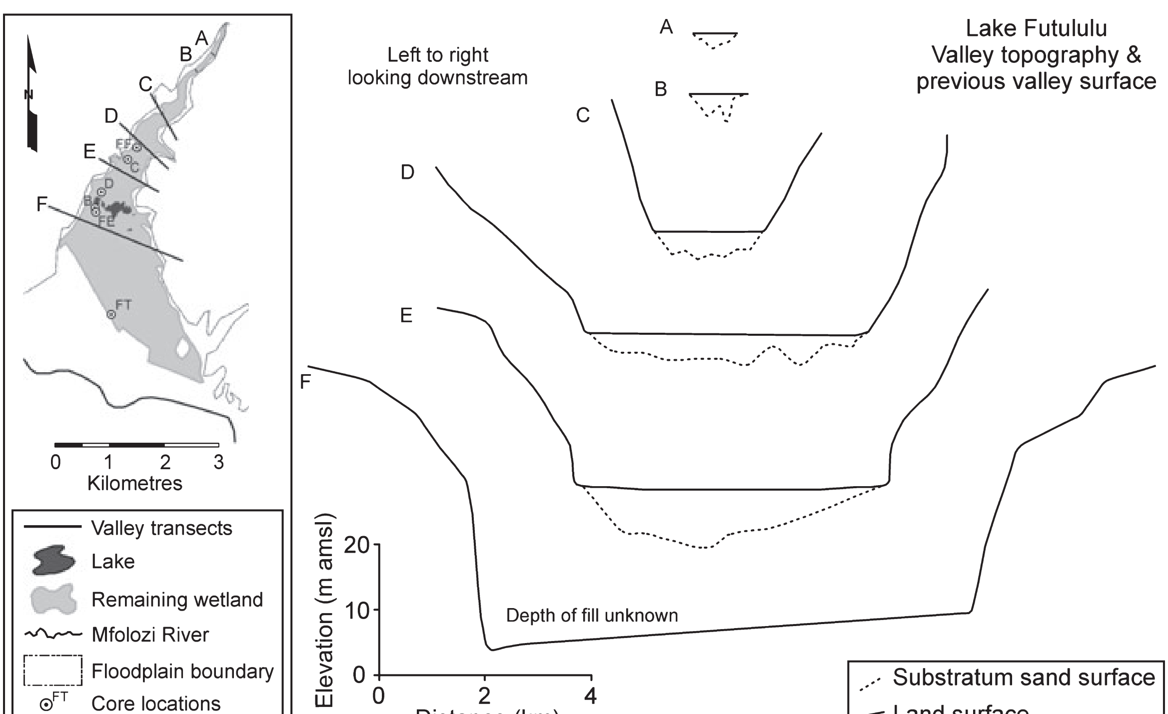

Fig. 3. ‘A’ to ‘F’: topography of the current and palaeo-valley surface. Elevation data for the valley sides were unavailable for cross-sections ‘A’ and ‘B’. Cross-section locations, relative to the surface water extent of Lake Futululu in 1996, are shown in the inset.

11 km south of the current-day lake (Fig. 3F). At cross-section 'F', the valley is gently sloped downwards towards the south-east (Fig. 3F).

The palaeo-valley surface prior to peat formation was reconstructed for cross-sections 'A' to 'E' (Fig. 3A to E). Unlike the current valley surface, the palaeo-valley was U-shaped with a clearly defined thalweg. In the uppermost cross-section, one thalweg position is evident as a depression on the pre-existing valley floor (Fig. 3A). Downstream, two thalweg positions are evident (Fig. 3B to D), eventually converging to form one palaeochannel (Fig. 3E). The Futululu valley terminus is marked by the alluvial ridge of the Mfolozi River, which is currently aligned at right angles to the Futululu drainage line (inset, Fig. 4). The levées of the Mfolozi River are 6·4 m above the lowest point of the valley (Core B in the inset of Fig. 4).

Open water usually occurs between Cores FE and D (the planform location of cores is indicated in Fig. 1); this is associated with a depression in the lake bed (at Core B). In addition to this depression, there is substantial variation in elevation along the longitudinal gradient of the valley that cannot be attributed to GPS error. However, the variation could conceivably be attributed to the proximity of the measurements to the valley side. Nevertheless, the average current valley gradient upstream of the lake is 0·02%, half the gradient of the palaeo-valley surface determined by probing, which was 0·04%.

Sedimentology

Core FT was located south of the present-day Lake Futululu shoreline and north of the current Mfolozi River course. This 7 m deep core was dominated by clastic sediments, ranging in size from fine silt to very fine sand (Fig. 4), while organic contents never exceeded 10% (Fig. 5). Core FE was taken immediately south of the present-day open water body of Lake Futululu, and comprised fine to medium silt layers with varve-like laminations less than 0·5 cm thick. A peak in organic content occurred between 7 and 8 m above mean sea-level (a.m.s.l.), where organic content reached 58% (Fig. 5). Below this depth, organic content decreased suddenly to <10%. Unfortunately the core was abandoned at 5·7 m a.m.s.l. as no more material could be retrieved from the core hole.

Core B was characterized by an alternating series of fine sediment (clay, very fine silt and silt) and peat. At 4·4 m a.m.s.l., the core coarsened to medium silt, below which another sequence of alternating clayey peat and fine silt layers occurred. An upwardly fining sand layer with

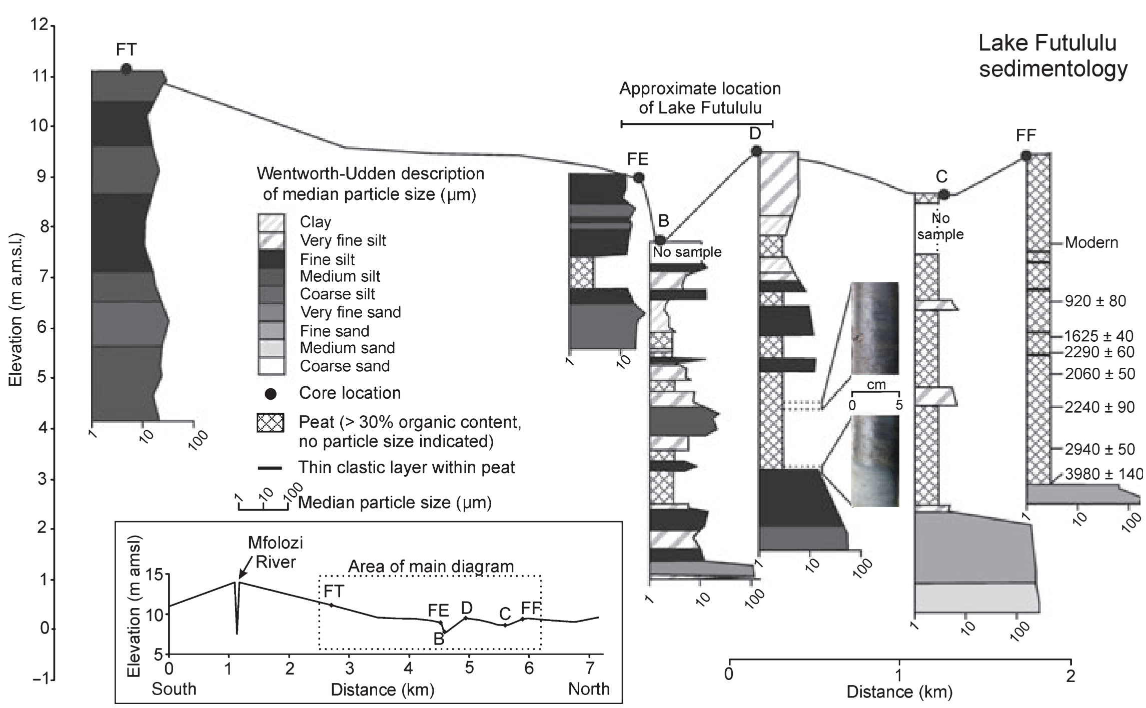

Fig. 4. Sedimentology of the Lake Futululu drainage line. Radiocarbon ages and thin clastic layers within peat are only indicated for Core FF. The longitudinal profile of the drainage line, and the locations of cores on the longitudinal profile, are indicated in the inset.

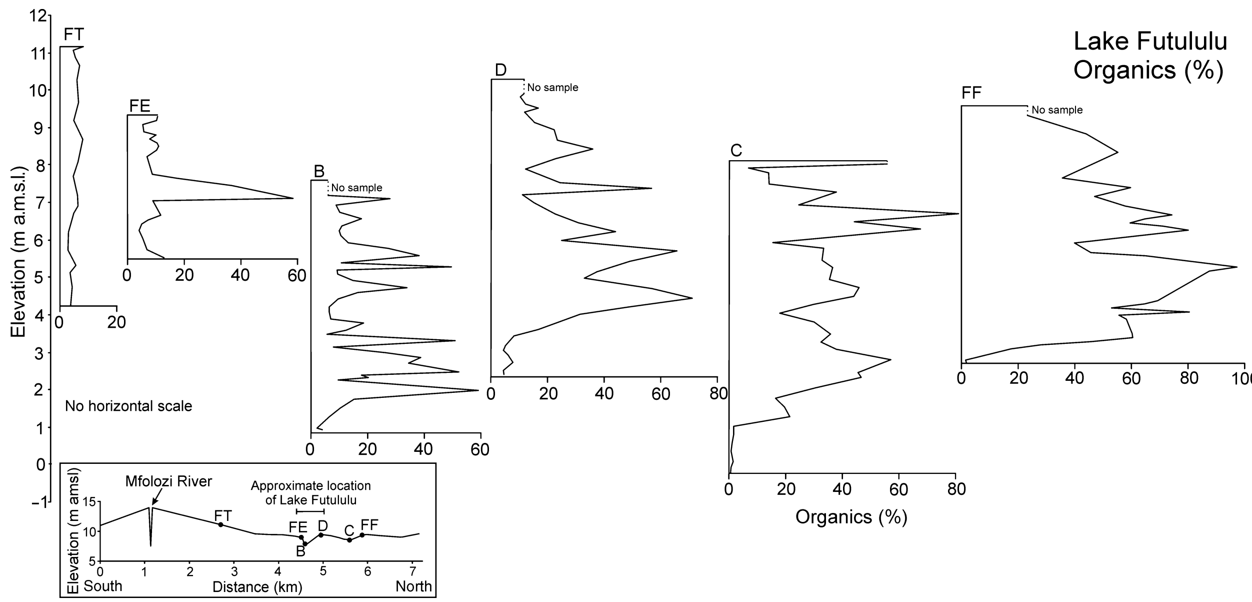

Fig. 5. Organic contents with depth along the Lake Futululu drainage line. The locations of the cores are indicated in the inset.

an organic content <6% marked the base, above which organic contents rapidly increased to 59% at 3 m a.m.s.l. Thereafter, organic content decreased progressively up the length of the core, with a second subsidiary peak encountered at 6·1 m a.m.s.l. (Fig. 5). In general, the thickness of organic sediments increased with depth.

The palaeo-valley floor in Core D was again marked by an upwardly fining sand and silt layer with a low organic content (<8%). Above the basal sand layer, organic content increased sharply, reaching a peak of 66% at 5 m a.m.s.l. Thereafter, the organic content decreased systematically towards the surface as the thickness of peat layers decreased, while the thickness of clay to fine silt layers increased. The peat was rhythmically varved in appearance.

Core C, located north of the present-day Lake Futululu, was 8·26 m in length, with the basal sand reached at an elevation of 2·5 m a.m.s.l. The basal unit fined upwards from medium sand to fine sand, with a very low organic content of <2%. Above the basal sand, the core was predominantly peat with thin layers of very fine silt at 6·6 and 4·8 m a.m.s.l. (Fig. 4). A floating peat mat was encountered at the top of the core from which a sample could not be retrieved. Organic content of the material above the basal sand increased to 57% at 2·8 m a.m.s.l. (Fig. 5), above which the organic content gradually decreased until 6·5 m a.m.s.l. (organic content 11%), after which the organic content again rose to a peak of 81% at 7 m a.m.s.l.

The upwardly fining basal sand unit in Core FF was situated at an elevation of 3·2 m a.m.s.l. (organic content <2%, Fig. 5). Above the sand, the organic content of the peat followed a fairly systematic trend with depth, increasing from the base of the core until 5·5 m a.m.s.l., where a compressed charcoal layer *ca* 0·3 m thick was encountered (organic content 98%). Above the charcoal layer, organic content gradually decreased towards the surface.

There were a number of similarities in the sedimentology of the cores. Most noticeably, several cores were characterized by an upwardly fining sand to silt base with a low organic content (typically <2%). The change in organic content from a minimum in the basal sand unit, to a peak generally occurred 2 to 3 m above the sandy base. Furthermore, the peak in organic content was usually followed by an upward systematic decrease in organic content. The occurrence of peat increased upstream along the valley. Core FT had no peat, and relatively low organic contents throughout. Cores FE, B and D exhibited interfingering of peat and sediment, while Core C had only thin layers of very fine silt, and Core FF was entirely peat. The particle size of sediments decreased from the Mfolozi River towards the lake. Varve-like laminations, suggesting processes of cyclic clastic sedimentation, were characteristic of almost all the cores.

In addition to the systematic trend of decreasing organics up valley, Cores FF, C, D and B all displayed organic content minima at a similar elevation. At Core FF, this minimum occurred just above the charcoal layer, at *ca* 6 m a.m.s.l. Cores B, D and C had minima at elevations of 5·5, 7 and 6 m a.m.s.l., respectively. Considering the GPS error, these minima are within a depth range of <1 m.

Radiocarbon ages

In Core FF, all but one of the dates was stratigraphically consistent (sample FF 3·8-3·9). In Core FE, radiocarbon ages for the two samples processed were reversed stratigraphically. Processing difficulties, and the rather unlikely age outcome, suggest that these samples may have been contaminated and they have thus been disregarded. All dated samples had an organic content >30% and were thus classified as peat, although the degree of humification and compaction varied (Table 1). Generally, compaction increased with depth. Many of the samples were characterized by *C. papyrus* plant fossils, particularly rhizomes. In contrast, sample FF 4·2-4·3 consisted of highly compacted charcoal 0·3 m thick. ^{14}C dating of Core FF suggests that peat accumulation began in the Futululu drainage line 3980 ± 140 years BP.

DISCUSSION

Geomorphic evolution of Lake Futululu

Coastal incision during the last glacial maximum (ca 18 000 years BP)

During the last glacial maximum (*ca* 18 000 years BP), sea-level along the coast of southern Africa was *ca* 125 m below the present level (Fleming *et al.*, 1998). The lowered base level caused rejuvenation of rivers and thus vertical incision along coastal areas of KwaZulu-Natal. Upstream of the present-day coastal floodplain, the Mfolozi River incised a series of entrenched meanders into resistant Lebombo Group basalts, while downstream, the river encountered more erodible sedimentary rocks of the Zululand and Maputaland Groups. These rocks were eroded to form a wide, deep valley in which the present-day Mfolozi Floodplain is now situated. Tributaries were similarly rejuvenated, and the Msunduze River and a stream from the Futululu drainage line flowed directly into the Mfolozi River.

The onset of coastal valley infilling and the Holocene highstand (ca 18 000 to 4480 years BP)

Sea-level rose steadily from the low attained during the last glacial maximum, until *ca* 8000 years BP when sea-level reached −1 m a.m.s.l. (Ramsay, 1995; Fig. 6). Thereafter, the rate of sea-level rise slowed, reaching current levels *ca* 6500 years BP, culminating in the Holocene highstand that persisted for *ca* 2500 years. During the highstand, sea-level reached a maximum height of +3·5 m a.m.s.l. along the northern KwaZulu-Natal coast 4480 years BP (Ramsay, 1995).

The ocean transgression had wide-scale geomorphic impacts, particularly for coastal areas. The Maphelane dune cordon began forming as early as 11 100 years BP, stabilizing at *ca* 2700 years BP (Porat & Botha, 2008). In addition, parts of the Mfolozi River floodplain were flooded, with salt water intrusion detected as far upstream as Lake Teza (Scott & Steenkamp, 1996). More importantly, however, the rise in base level induced by the raised sea-level brought an end to a period of widespread river incision and, instead, rivers lost sediment transport capacity and a period of deposition ensued.

Table 1. Radiocarbon ages and sample description for samples from Cores FE and FF.

Core	Analysis number	Sample name	Description	^{14}C result (years BP)	Depth (cm)
FE	Pta 9693	FE 1·375-1·5	Compressed peat	880 ± 150	140
	Pta 9696	FE 2·37-2·5	Fibric peat	155 ± 40	240
FF	Pta 9699	FF 1·5-1·9	Compressed fibric peat	Modern (i.e. >1950)	170
	Pta 9687	FF 2·8-2·9	Peat with *Cyperus papyrus* rhizomes present	920 ± 80	285
	Pta 9698	FF 3·5-3·65	Peat with *C. papyrus* rhizomes present	1605 ± 40	355
	Pta 9690	FF 3·8-3·9	Peat	2290 ± 60	385
	Pta 9688	FF 4·2-4·3	Charcoal (40 cm thick layer)	2060 ± 50	425
	Pta 9697	FF 5·0-5·1	Peat with *C. papyrus* rhizomes present	2240 ± 90	505
	Pta 9692	FF 5·8-5·9	Peat with *C. papyrus* rhizomes present	2940 ± 50	585
	Pta 9694	FF 6·7-6·8	Peat with *C. papyrus* rhizomes present	3980 ± 140	675

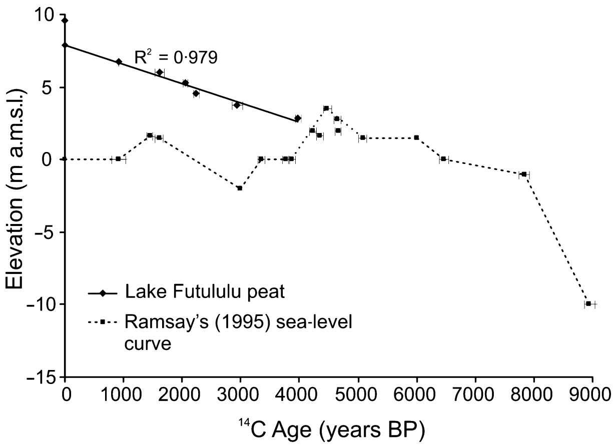

Fig. 6. The rate of peat accumulation in Lake Futululu (excluding sample FF 3·8-3·9) compared to the Ramsay (1995) sea-level curve for the southern African coast.

In the sedimentological record, this early period of aggradation is reflected in the Futululu drainage line by the fluvial reworking and deposition of aeolian sands, the thalwegs of which are visible in Fig. 3. Elevation data indicate that during the highstand, portions of the Futululu drainage line were below sea-level but, at this time, the valley was not filled with marine or estuarine sediment; this suggests that from 4480 years BP, the upper Futululu drainage line was disconnected from the fluvial network by aggradation on the Mfolozi River floodplain.

Aggradation on the Mfolozi River floodplain and blocked-valley lake formation (4480 to 3780 years BP)

Sea-level began receding 4480 years BP, reaching current levels 3780 years BP (Ramsay, 1995). This change in sea-level is not reflected by sedimentation processes in Lake Futululu. The small, low gradient catchment of the Futululu valley did not supply sufficient sediment to keep pace with aggradation on the floodplain of the much larger Mfolozi River. Instead, aggradation on the floodplain of the Mfolozi River had completely disconnected the Futululu valley from the drainage network, resulting in the formation of a depression and lake. By 3980 years BP, sediment supply from the head of the Futululu valley was negligible as the longitudinal slope of the tributary valley had been reduced by aggradation at the toe. These environmental conditions were suitable for the growth of *C. papyrus*, a prolific peat former (Ellery *et al.*, 1995, 2003).

Peat accumulation in Lake Futululu (3980 years BP *to present)*

Since 3980 years BP, peat accumulation has continued at an almost constant rate of 0·13 cm year^{-1}, despite variations in sea-level and climate (Fig. 6); this indicates that, throughout this time period, the Mfolozi River floodplain has acted as a base level for the Futululu drainage line. However, it appears that the influence of the river in supplying sediment to the lake has increased in modern times. Large floods on the Mfolozi River are preserved in the Lake Futululu sedimentary record as thin sediment bands bounded by peat, the age of which can be interpolated using the constant age-depth relationship established from radiocarbon dating. The first layer of sediment in the predominantly organic core occurred *ca* 1700 years BP, followed by floods again at 1470, 700, 550 and 180 years BP. Unfortunately, it cannot be determined whether the increasing frequency of intruding floods is indicative of changing climate conditions or the changing proximity of the river to Lake Futululu.

While changing climate has had no effect on the rate of peat accumulation in Lake Futululu, changes may still be reflected in the sedimentary record. Sea-level fell between 3360 and 1610 years BP, reaching −2 m a.m.s.l. *ca* 3000 years BP (Ramsay, 1995). Lee-Thorp *et al.* (2001) attributed vegetation changes in the interior of southern Africa to a cooler environment between 3200 and 2500 years BP, a change reflected in the temperature index of the Cango stalagmite (Talma & Vogel, 1992). This neoglacial period, causing a cooler and drier climate in southern Africa, has been recorded across the globe (Ramsay, 2005). In Lake Futululu, a large peat fire, indicated by a charcoal layer in core FF, occurred 2060 ± 50 years BP, indicating a period of decreased rainfall which caused lowering of the water table, and desiccation of the surface peat deposits. This peat fire, although lagging slightly behind the neoglacial period, may be locally indicative of a period of below average rainfall.

Depositional processes and sedimentary facies of blocked-valley lakes

The geomorphology and sedimentology of Lake Futululu is controlled by the development and dynamics of the Mfolozi River floodplain. Overbank sedimentation on floodplains characteristically results in sediment fining away from the

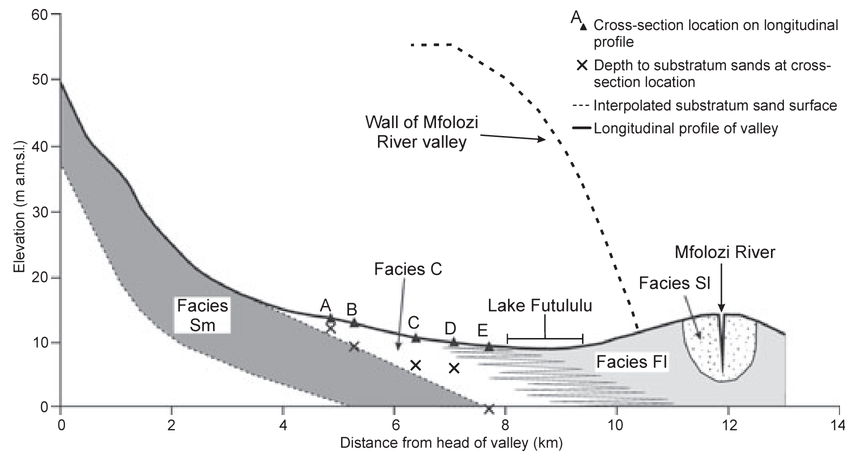

Fig. 7. The shape and depth of sedimentary facies on the Lake Futululu drainage line. The locations of valley cross-sections are shown in Fig. 3.

main river course (Pizzuto, 1987; Asselman & Middelkoop, 1995; Makaske *et al.*, 2002). During flood events, the Mfolozi River overtops its banks as sediment-laden water flows into Lake Futululu. Sediment is deposited such that coarse sediment settles first, creating levée deposits, while finer sediments are transported furthest from the trunk stream. The finest particles, suspended clay and very fine silt, are transported further up the valley, where eventually they are deposited on the peat valley floor. Between floods, clastic sedimentation ceases, and peat formation predominates wherever standing water is permanent. The combined process of sedimentation during flood events, and peat formation between flood events, results in inter-fingering of organic and clastic sediments at the interface of the floodplain and blocked-valley lake.

At a larger scale, overbank sedimentation and alluvial ridge formation causes aggradation of the floodplain as the Mfolozi River infills a valley incised during the last glacial maximum, ultimately raising the elevation of the floodplain. As the Mfolozi River floodplain provides a local base level for the Futululu drainage line, the gradual infilling of the floodplain basin continually raises this local base level, causing a movement of the lake northwards with time, which is visible during historic times despite the recent impact of human activities. Sedimentologically, the rising base level of Lake Futululu causes the central locus of peat formation to move north, creating an organic sediment wedge as peat accumulates progressively further up the tributary valley (Fig. 7). In turn, floodplain aggradation propagates further northwards, creating a series of back-stepping sedimentary facies associations (Fig. 8).

Carboniferous facies – C

Partly humic, *C. papyrus* peat with very fine silt to fine silt laminations. This facies is formed by the accumulation of organic plant matter on the lake floor, and is best illustrated by the Cores C and FF (Fig. 4). Thin laminations (<2 mm) of very fine to fine silt, characterized by a sharp peat-silt contact, are formed by gravity settling of suspended sediment, which is injected into the lake by the Mfolozi River overtopping its banks during floods. The peat generally is partly humic at the base of the deposit, to non-humic at the top where deposits are essentially modern. The facies

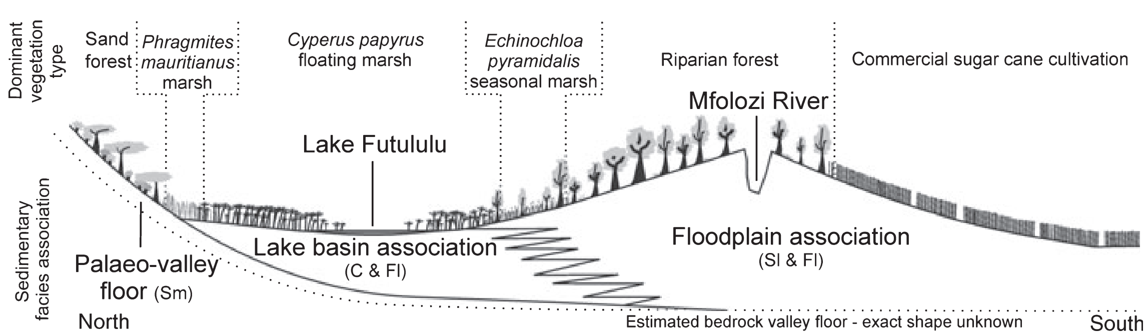

Fig. 8. Sedimentological facies associations and longitudinal variations in vegetation type in Lake Futululu.

reaches a maximum depth of between 6 and 7 m, while the length of active organic accumulation is *ca* 1·5 km.

Fine sediment facies – Fl

Gleyed, very fine silt to medium silt with few laminations. Deposits vary in width, representing deposits thicker than the laminations described in facies C, but with individual beds usually less than 1·5 m. The contact between this facies and others is usually sharp, while the contact between beds of the same facies is often gradational. The beds of very fine silt and fine silt in Cores FT, FE, B, C and D (Fig. 4) are illustrative of this facies. This facies represents overbank and waning flood deposits of the Mfolozi River, an interpretation which is consistent with that of Miall (1996).

Sand facies – Sm and Sl

Facies Sm. This facies includes massive, very fine to fine sand with a frosting of quartz grains. The cores revealed facies Sm as upwardly fining with organic contents always less than 2%. This facies represents the veneer of unconsolidated dune deposits that overlie bedrock in this region of the coastal plain, and have been described in detail most recently by Porat & Botha (2008), among others. These sediments are relatively old, having accumulated since the beginning of the Cenozoic.

Facies Sl. This facies includes cross-bedded fine to medium sand. This facies was not encountered during the present study, but was described for abandoned channel courses in the Mfolozi floodplain by Grenfell *et al.* (2009). The facies is characterized by cross-bedded upwardly fining sands, with the total sequence up to 4 m in depth. This facies represents in-channel and overbank levée sedimentation on a meandering river.

Facies associations and environment of deposition

Palaeo-valley floor

The palaeo-valley floor comprises facies Sm, which represents an old unconsolidated dune deposit that is regionally pervasive as a surface veneer over bedrock. The depth of facies Sm has not been determined locally. The surface contact of the palaeo-valley floor facies is distinct, suggesting an erosional hiatus; this is indeed the case, as aeolian sands were fluvially reworked during the last glacial maximum by two small streams flowing down the Futululu valley towards the Mfolozi River (Fig. 3).

Lake basin association

The lake basin facies association comprises facies C and Fl, and lies unconformably over facies Sm. The organic contents of *C. papyrus* peat deposits, of facies C, generally decrease towards the valley surface as clastic sediment inputs (facies Fl) increase. Similarly, organic contents increase upstream in the Futululu valley, indicating a decrease in sediment inputs in the upstream direction. The downstream end of the lake, towards the Mfolozi River, is characterized by the increasing occurrence of facies Fl. Interfingering of facies C and Fl towards the south indicates that river-derived sediment increasingly impinges on organic sediment accumulation in the lake.

At present, the basin is dominated by *C. papyrus* floating marsh, a vegetation type restricted to permanently saturated settings where there is little or no active clastic sedimentation. The northern margin of the basin, at the transition zone of peat to dune sand, is characterized by a stand of *Phragmites mauritianus* marsh (Fig. 8); this suggests that the head of the basin is only semi-permanently to seasonally flooded and that clastic sedimentation may be marginally higher here than elsewhere. However, as floodplain sedimentation continues and slopes decrease upstream, this margin will be increasingly flooded, and thus move northwards.

Floodplain association

The sedimentology of the Mfolozi Floodplain is described in detail by Grenfell *et al.* (2009). In the region of the blocked valley lake, the floodplain association comprises facies Sl and Fl. The association is indicative of sedimentary and geomorphic processes in an aggrading meandering river floodplain. Cross-bedded, upwardly fining sands are characteristic of channel and levée deposits, and occasionally overbank deposits proximal to the channel deposited during very large floods. During floods, sediment is deposited on the floodplain, resulting in facies Fl. Although overbank sedimentation does result in a general trend of decreasing particle size away from the Mfolozi River, the mosaic of inter-ridge depressions leads to some variability in sediment particle size in the main floodplain region (Grenfell *et al.*, 2009). Floodplain sediment is predominantly medium to fine silt, while the lack of clay in overbank deposits probably reflects a lack of supply due to sediment provenance (Magilligan, 1992; Grenfell *et al.*, 2009). Indigenous vegetation of the main floodplain has been replaced with cultivated sugar cane (Fig. 8).

Overbank sedimentation on the river levées and in-channel sedimentation has created an alluvial ridge elevated above the surrounding floodplain and Lake Futululu. Aggradation on the alluvial ridge and floodplain raises the base level of Lake Futululu, a process that continually decreases valley slopes upstream. The levées of the Mfolozi River presently are vegetated with riparian forest, while on the lower-lying area towards Lake Futululu, *Echinochloa pyramidalis* marsh occurs on minerogenic soils, indicating seasonal inundation in a region of active clastic sedimentation.

Trunk–tributary relationships and the formation of blocked-valley lakes and wetlands

Further consideration of the geomorphic relationship between Lake Futululu and the Mfolozi River floodplain in the context of additional literature suggests that trunk–tributary relationships can operate between two extremes (Fig. 9). One extreme occurs when tributary sediment supply is high, usually due to a steep catchment. As such, the rate of sedimentation at the tributary junction is relatively high. When the sediment supplied by the tributary channel exceeds the sediment transport capacity of the trunk channel, it accumulates at the stream confluence and begins to impound flow in the trunk channel. In this case, the confluence can be said to be ‘tributary-dominated’ (Fig. 9).

In contrast, some tributaries have relatively gentle gradients, and the amount of sediment that they supply to a trunk channel is negligible compared to the amount of sediment transported by the trunk channel. In these cases, trunk channels have the ability to drown the confluence with sediment, and prevent the tributary stream from joining the flow. As such, the trunk channel controls the geomorphic outcome, and the relationship may be considered to be ‘trunk-dominated’. These two extremes should not be considered as isolated responses to different tributary sediment regimes, but rather as two opposite ends on a continuum of trunk–tributary relationships.

The evolution of Lake Futululu represents the trunk-dominated end member of trunk–tributary relationships (Fig. 9). Since sediment inputs from the Futululu stream are negligible compared to sediment deposited by the Mfolozi River, aggradation on the trunk channel has overwhelmed the Futululu drainage line, isolating it from the drainage network and creating a lacustrine environment.

In some cases, the trunk channel may carry only slightly more sediment than the tributary channel and, as a result, the rate of alluvial sedimentation is lower. However, sedimentation still overwhelms inflowing tributaries and results in the tributary streams losing competence even though a basin may not have formed behind the alluvial ridge of the trunk channel. In such a system, the greater aggradational potential of the trunk channel results in the formation of a valley-bottom wetland (as defined by Kotze *et al.*, 2009) or tributary channel discontinuity (Grenfell *et al.*, 2008). An example of the development of a palustrine wetland environment at a trunk-dominated tributary confluence is the formation of the Stillerust valley-bottom wetland abutting the

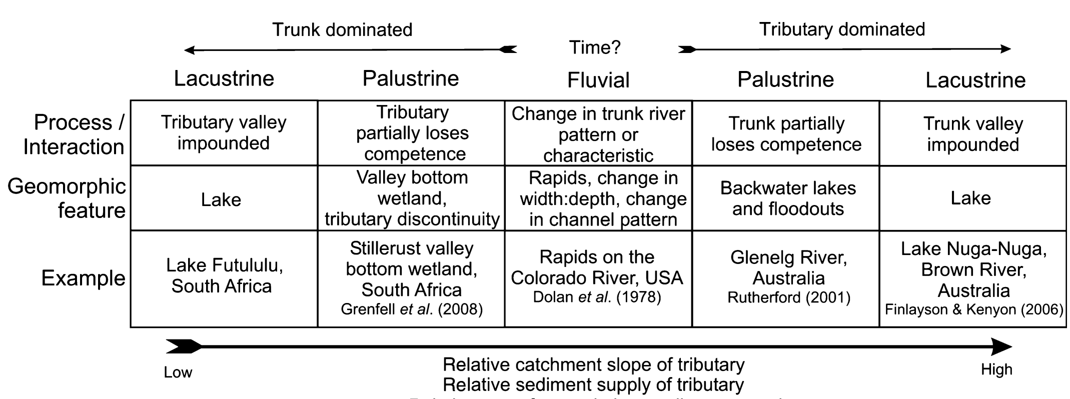

Fig. 9. Conceptual continuum of trunk–tributary relationships and the geomorphic implications of varying catchment slope and sediment supply between tributary and trunk rivers.

trunk Mooi River floodplain (Grenfell *et al.*, 2008).

In contrast, where tributary sediment inputs are much greater than the sediment transport capacity of the trunk river, palustrine or lacustrine drowning may occur. In the tributary-dominated end member, extremely large sediment discharges, from a steep or well-connected tributary, may completely or partially block the drainage line of a trunk channel, causing the trunk to lose competence. For example, Lake Pepin, on the upper Mississippi River, was formed as glacially derived sediments transported by the Chippewa River partially blocked flow in the Mississippi River (Schumm, 2005). Similarly, Finlayson & Kenyon (2007) describe the impoundment of the Brown River behind the levées of a smaller tributary called Moolayember Creek, resulting in the formation of Lake Nuga-Nuga in Australia. In this case, the tributary is much steeper and has a better-connected catchment than the trunk river. Sometimes sediment discharge from tributary streams is less severe, and may serve to intermittently block trunk channel flow resulting in the formation of a palustrine, rather than a lacustrine, environment. Sand supplied by the tributaries of the Glenelg River in Australia accumulates in the trunk channel at the stream confluence, creating backwater lakes and wetlands (Rutherford, 2001).

Between these two end members, tributary sediment inputs are not so great as to overwhelm the trunk channel, and trunk river aggradation is not so rapid that it overwhelms the tributary channel. As a result, normal fluvial processes dominate and tributary sediment inputs may be assimilated by adjustments to the trunk channel. For example, most major rapids on the Colorado River, USA, have been attributed to sediment discharge from steep tributaries (Dolan *et al.*, 1978), while Schumm (2005) describes how tributary sediment may cause the channel pattern or width to depth ratio of the trunk channel to change to accommodate increased sediment supply. Nevertheless, despite increased sediment inputs from tributaries, or the high sediment load of the trunk channel, both systems are able to compensate and accommodate the change to the sediment transport regime, without palustrine-type or lacustrine-type drowning occurring. Nevertheless, sediment inputs from tributaries may still impact upon bedload texture (Rice, 1998), or cause rivers to shift position on the floodplain floor (Schumm, 2005).

In some cases, sediment deposits from tributaries and trunk rivers can overlap, without a major geomorphic impact on either. Florsheim (2004) documented the sedimentology of side-valley tributary fans and attributed the inter-layering of coarse and relatively fine sedimentary facies to different sources. It was found that transport and depositional processes occurred in three settings: (i) when tributary flows deposited sediment on the fan; (ii) when the trunk channel overtopped its banks and fine sediment was deposited over the fan; and (iii) when both systems were in flood, and sediment became mixed.

CONCLUSION

This study combines the use of aerial photographs, elevation data, field surveying, physical analyses of sediment cores and radiocarbon dating to determine the geomorphic evolution of Lake Futululu, a blocked-valley lake in South Africa. The geomorphology and sedimentology of Lake Futululu is controlled by the development and dynamics of the Mfolozi River floodplain, and the evolution of Lake Futululu is a clear example of a trunk-dominated trunk–tributary relationship. Results indicate that the Futululu drainage line was impounded by aggradation on the Mfolozi floodplain by 3980 BP, forming a lacustrine environment suitable for the growth of *C. papyrus*, a prolific peat former. During intermittent flood events, the Mfolozi River overtopped (and continues to overtop) its banks and sediment-laden water flowed into Lake Futululu. Peat formation, punctuated by periodic flood deposits, results in inter-fingering of organic and clastic sediments at the interface of the floodplain and blocked-valley lake. At a larger scale, this overbank sedimentation causes aggradation of the Mfolozi floodplain downstream of the lake, raising the base level of the tributary drainage line and shifting the lake upstream over time, thus creating the characteristic series of back-stepping sedimentary facies.

Blocked-valley lakes are potentially useful palaeo-archives of environmental change and may help to disentangle the evolution of the large floodplain systems that they abut. This study has provided a context in which the sedimentary record of these systems can be interpreted. However, substantial investigation is still required in order to fully understand the role which blocked-valley lakes have in the evolution of large floodplains, particularly with respect to avulsion occurrence and fluvial style. In addition, blocked-valley lakes currently are not portrayed accurately by software designed to interpolate and model drainage networks (for example, the ArcView version 9 *Topo to Raster* facility), partly because depressions are unusual on drainage lines, and partly because their formation is linked to elevational differences of <10 m. Considering their potential as carbon sinks, or as palaeo-archives of environmental data, further clarification of the relative rates of aggradation, catchment slope and catchment size that leads to variation in confluence geomorphology, from a fluvial junction to a wetland or lake, is vital.

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