Geomorphology and dynamics of the Mfolozi River floodplain, KwaZulu-Natal, South Africa

S.E. Grenfell\textsuperscript{a}, W.N. Ellery\textsuperscript{b} and M.C. Grenfell\textsuperscript{c}

\textsuperscript{a}Geography Department, Rhodes University, P.O. Box 94, Grahamstown, 6140, South Africa

\textsuperscript{b}Department of Environmental Science, Rhodes University, P.O. Box 94, Grahamstown, 6140, South Africa

\textsuperscript{c}River Basin Science, Department of Geography, University of Exeter, Exeter, EX4-4RJ, UK

Abstract

The geomorphology and dynamics of the Mfolozi River floodplain and estuary, located in the subtropical region of northern KwaZulu-Natal, South Africa, were considered with respect to existing models of avulsion and alluvial stratigraphy. The Mfolozi River floodplain may be divided into regions based on longitudinal slope and dominant geomorphic processes. Confinement of the Mfolozi River above the floodplain has led to the development of an alluvial fan at the floodplain head, characterized by a relatively high sedimentation rate and avulsion frequency, at a gradient of 0.10%. The lower floodplain is controlled by sea level, with an average gradient of 0.05%. Between the two lies an extremely flat region with an average gradient of 0.02%, which may be controlled by faulting of the underlying bedrock.

Avulsion occurrences on the Mfolozi floodplain are linked to the two main zones of aggradation, the alluvial fan at the floodplain head, and toward the river mouth in the lower floodplain. On the alluvial fan, normal flow conditions result in scour from local steepening. During infrequent, large flood events, the channel becomes overwhelmed with sediment and stream flow, and avulses. The resulting avulsion is regional, and affects the location of the channel from the floodplain head to the river mouth. Deposits resulting from such avulsions contribute significantly to the total volume of sediment stored in the floodplain, and tend to persist for long periods after the avulsion. Contrastingly, on the lower floodplain, reaching of the avulsion threshold is not necessarily linked to large flood events, but rather to long-term aggradation on the channel that decreases the existing channels gradient while
increasing its elevation above the surrounding floodplain. Resultant avulsions tend to be local and do not contribute significantly to the overall volume of floodplain alluvium.

1. Introduction

Fluvial geomorphologists have tended to overlook floodplain geomorphology and sedimentology (Dollar, 2000), and thus substantial gaps exist in our understanding of these systems, especially with respect to subtropical floodplains. To date, research conducted on the subject has tended to focus on major anastomosing or meandering river systems situated in the northern hemisphere, such as the Saskatchewan River ([Cazanacli and Smith, 1998], [Morozova and Smith, 2000] and [Morozova and Smith, 2003]), Columbia River (e.g. Makaske et al., 2002) and Mississippi River (e.g. [Gomez et al., 1997], [Hudson and Kesel, 2000] and [Kesel, 2003]). In addition, Törnqvist (1994) and Törnqvist and Bridge (2002) have compared sedimentation on the Rhine-Meuse and Mississippi alluvial floodplains. These studies have tended to focus on the evolution of fluvial style, as well as developing an understanding of basin infilling.

Bridge and Leeder (1979) introduced one of the first process based simulation models of alluvial stratigraphy, which was later modified by Mackey and Bridge (1995), who developed a three-dimensional model to simulate the spatial distribution, proportion, and connectedness of coarse-grained channel belt deposits relative to overbank floodplain deposits. In general, superelevation of the channel above the surrounding floodplain and rate of alluvial ridge aggradation are considered two of the most important parameters in determining likelihood of avulsion (e.g., [Bryant et al., 1995], [Heller and Paola, 1996] and [Törnqvist and Bridge, 2002]). However, how sediment is partitioned between the parent and avulsed channels, and the relative ability of the two channels to adjust their morphology to sediment and flow transport capacity, may also play a role ([Slingerland and Smith, 1998] and [Slingerland and Smith, 2004]). While avulsions always occur in regions that are aggrading, superelevation of the channel-belt is not always a pre-requisite for avulsion when sedimentation rates are very low (Slingerland and Smith, 2004).

As avulsions are generally linked to floodplain sedimentation rates, they may be caused by autogenic or allogenic controls, or sometimes a combination of the two (Stouthamer and Berendsen, 2007). An allogenic control, sea level rise following the Last Glacial Maximum, was found to lead to a series of landward backstepping, progradational avulsions in the Brazos River floodplain, which continued after
sea level reached a still stand (Taha and Anderson, 2008). In contrast, Aslan et al. (2005) found evidence for an autogenic control in the Mississippi Floodplain, as avulsions mostly occurred over old channel belts since coarse channel deposits were more easily scoured than overbank fines. As a result, channels were more likely to be reoccupied than newly formed. Indeed, a model developed by Jerolmack and Paola (2007) found that channel reoccupation was far more common than large nodal avulsions, and that new channel lengths tended to be generated in short segments.

The aim of this paper is to investigate the geomorphology and dynamics of the Mfolozi River floodplain in South Africa, with respect to existing models of avulsion and alluvial stratigraphy. In particular, the research considers how climate, geology and sea level interact, producing a particular style of fluvial dynamics and sedimentology. The Mfolozi floodplain, unlike other floodplains discussed in avulsion literature, is located in a region of distinctly seasonal rainfall, which is also highly variable. As a result, clastic sediments dominate the Mfolozi River floodplain, and backswamp areas are seldom suitable for peat formation. Additionally, it is likely that flow variability influences process rates in the floodplain, such as the rate of aggradation, floodplain cycling, the persistence of flood features, and also the frequency at which avulsions and meander cut-offs may occur.

2. Regional setting

The catchment of the Mfolozi River is characterized by a steep hinterland, with the headwaters in the Drakensberg Mountains at an altitude of 3000 m. Rainfall in the region of the coastal Mfolozi floodplain averages 1090 mm/a, declining to 645 mm/a toward the upper catchment boundary. Potential evapotranspiration on the floodplain is 1805 mm/a (Schulze, 1997). Inter-annual flow variation on the Mfolozi River is high with a coefficient of variation of 79%, suggesting flashy hydrology with infrequent large floods and frequent below average flows (Garden, 2008).

The southern African subcontinent experienced two periods of uplift ~ 20 and 5 Ma. Uplift in the eastern region of southern Africa was 250 and 900 m respectively, creating an anomalously high continental region (Partridge and Maud, 1987). Widespread rejuvenation of river networks and the concomitant incision of the subcontinent have since occurred, and as a result almost all rivers and wetlands in the region are predestined to erosion. However, despite continental scale incision, variations in sea level may locally affect the evolution of coastal drainage lines. In general, coastal
wetlands degrade during periods of low sea level, but they may also undergo renewed formation and growth as sea level rises, provided vertical accretion keeps pace with coastal submergence.

The Mfolozi floodplain owes its origin to a rise in sea level, from 120 m below present sea level during the last glacial maximum, following which, sea level rose relatively steadily at 8 mm y\(^{-1}\), until 8000 YBP (Ramsay, 1995). Sea level reached a highstand of + 3.5 m ~4480 YBP, but then regressed to its present level 3880 YBP, remaining stable for 500 years. A neoglacial event occurred between 3200 and 2500 YBP, resulting in global sea level lowering, and cooler and dryer conditions in the Maputaland region ([Talma and Vogel, 1992] and [Ramsay, 2005]). This cooling event caused extensive peat fires in Lake Futululu, a blocked valley lake north of the Mfolozi floodplain (Garden, 2008). Following a second short-lived highstand, sea level reached its present elevation 900 YBP and has since remained stable.

The floodplain is one of South Africa's largest, ~ 30 km long from its head at the foothills of the Lebombo Mountains to its entry into the sea just south of Lake St. Lucia (Fig. 1). The floodplain is bordered on its southern and northern sides by relatively steep outcrops of Zululand and Maputaland formation rocks, while the Maphelane dune cordon, which is over 90 m in height, blocks its eastern boundary. Three large lakes occur on the floodplain periphery: Lake Teza toward the southwest, Lake Futululu in the north, and Lake St. Lucia in the northeast. In addition to the Mfolozi River, which flows eastward along the northern part of the floodplain, a second river (the Msunduze River) drains a localized catchment, and flows along the southern margin before turning northward at the Maphelane dune cordon, and joining the Mfolozi River near its mouth. Occasionally, long shore drift forces the Mfolozi-Msunduze estuary to combine with the Lake St. Lucia estuary to the north, such that they share a common mouth.
The upper two-thirds of the floodplain have been transformed to cultivate sugar cane. The remainder falls within the iSimangaliso Wetland Park but has nevertheless been extensively cultivated by small-scale subsistence farmers. Historically, the floodplain was a mosaic of permanent and seasonal herbaceous wetland, with *Cyperus papyrus* and *Phragmites australis* as the dominant plant species. Where vegetation has not been cleared, *Ficus trichopoda* trees occur on the banks of abandoned and active channel courses.
3. Methods

3.1. Floodplain morphology

The most recent set of 1:10,000 orthophotos, georeferenced aerial photography with 5 m contour intervals (2.5 m accuracy) developed by the Surveyor General of South Africa in 1979, were used in conjunction with aerial photographs from the years 1937, 1960, 1970, 1988, and 1996 to map geomorphic features. The orthophotos were used to georeference and mosaic all the aerial photographs for each year in Arcview 9 in order to develop an historical time sequence in terms of land use, river course and behaviour, and other geomorphic elements.

A longitudinal valley profile and a series of north–south cross-sectional profiles were constructed from the orthophotos. In addition, a longitudinal profile of river water and levee elevation, accurate to 0.01 m in the z-field, was surveyed using real time differential GPS surveying, with a base station and a GPS receiver. Core locations were also surveyed using this technology. The floodplain surface was mapped using a Trimble GPS with differential correction capabilities using a remote base station in Durban, with accuracy in the z-field of ~ 1 m or less. Data collected using the Trimble GPS and the base station survey were integrated into a digital elevation model using the topo to raster facility in Arcview 9. The digital elevation model was constructed to indicate general surface elevation trends, although insufficient data were collected in some inaccessible areas of the floodplain. The surface topography of an abandoned channel was surveyed using an automatic level.

3.2. Floodplain sedimentology

3.2.1. Sediment sample collection

Fourteen cores were augered using standard auger equipment along a series of three systematic north–south transects across the floodplain (B — upper floodplain, A — central floodplain, and C — lower floodplain; Fig. 1) until sediment could no longer be retrieved because of limitations imposed by equipment. Core lengths varied from 3.5 to 6.9 m. Three additional holes were augered to obtain some sense of variation in sediment longitudinally on the floodplain (core names UC, MC and LC). At the site of core UC, six additional holes were augered in a transect line across an old alluvial ridge. At each auger site, the core was logged. Sediment samples were taken every half metre, or whenever a
change in sediment characteristics was observed. In addition, 74 surface samples were collected across the upper two-thirds of the floodplain and a GPS point taken at each sample site. These were augmented with surface samples taken at each auger site.

### 3.2.2. Sample treatment

Loss-on-ignition was used to determine the organic content of samples, and involved oven-drying samples at 105 °C, followed by incineration in a muffle furnace at 450 °C for 4 h. The difference in mass, prior to and after incineration, was considered the organic content of the sample.

For the purpose of particle-size determination, coarse organic fragments were removed by sieving the remaining sample through a 2-mm sieve, and then lightly crushing soil peds with a pestle and mortar. If the sediment had a high organic content (> 10%), organics were digested using hydrogen peroxide. A Malvern Mastersizer 2000, that employs laser diffraction techniques on a wet, dispersed sediment sample, was used to determine particle-size distribution.

### 4. Results

#### 4.1. Floodplain morphology

##### 4.1.1. Changes in floodplain characteristics over time

Although aerial photograph coverage was not complete, the available 1937 photographs provided useful information on the likely original appearance of the floodplain (Fig. 2). In the upper floodplain, the Mfolozi River course was relatively straight, and the floodplain surface was marked by numerous southeastward-trending lineations oriented away from the Mfolozi River. Abandoned channel courses were not visible in the upper part of the floodplain. South of Lake Futululu, the Mfolozi River became sinuous with a series of large bends with active scroll bars, that ended immediately to the east of the peninsula of land extending into the floodplain from the north. This series of bends is known as the Uloa loop. Downstream, the channel straightened with a degree of sinuosity developing before the Mfolozi River joined the Msunduze River. Seaward of the Mfolozi/Msunduze River confluence, the channel once again developed large meanders. Some abandoned channel courses were visible toward the lower floodplain.
Although the coverage of the lower floodplain was incomplete, it is likely that much of the area had indigenous wetland vegetation, as sugar cane cultivation was generally restricted to the upper floodplain and to an abandoned alluvial ridge orientated toward the southeast. In 1937, the network of artificial drains and furrows, designed to reduce water logging of soils, was limited in extent. Lake Futululu, on the northern floodplain boundary, was the largest floodplain lake, partially occupying a drainage line entering the floodplain from the north. Lake Teza, on the southern side of the floodplain, occupied the Msunduze drainage line entering the floodplain from the southwest, and further open water appeared in the region where the Msunduze River turned north, adjacent to the Maphelane coastal dune.

By 1960, more than 50% of the floodplain had been converted to sugar cane cultivation (Fig. 2). In addition, the Uloa loop had been straightened to shorten the Mfolozi River course, presumably to increase the efficiency of water flow down the floodplain, and as a result, the extent of Lake Futululu
was substantially reduced in comparison to its extent in 1937. The furrow network in the region of
cultivation had also been extended to lower the water table, and limit flooding of sugar cane during
floods. The full coverage of the floodplain in the 1960 photographs indicated numerous abandoned
channels on the lower floodplain that were not visible in the incomplete imagery of 1937.

By 1970, sugar cane cultivation had been associated with increasing land reclamation toward the east
and around Lake Futululu through the development of a drain network (Fig. 2). In addition, there was
evidence of attempts to straighten channels in the lower floodplain toward the Mfolozi River mouth.

Between 1970 and 1988, KwaZulu-Natal experienced the two largest floods on record. The first
occurred in January 1984, as the consequence of a tropical cyclone, Cyclone Domoina, which moved
southward in the Mozambique Channel reaching as far south as Durban. Discharge on the Mfolozi
River peaked at 16,000 m$^3.s^{-1}$, approximately three times the 100-year return flood, while flood
current velocities of 2.6 m s$^{-1}$ were measured (Travers, 2006). In September 1987, flooding once
again occurred, this time as a result of a cutoff low pressure system in the interior of KwaZulu-Natal.
The limited coverage of the 1988 aerial photography is thus very unfortunate (Fig. 3). Nevertheless,
the lower portion of a large depositional feature is visible on the western edge of the area covered by
aerial photography. During the Cyclone Domoina flood, the Mfolozi River avulsed from its northern
course into the southern Msunduze River near the floodplain head (van Heerden, 1984). Following the
flood, agriculturalists returned the river to its original northern course, and as such, no major river
adjustments were visible in the 1988 imagery. However, two crevasse splay complexes, still preserved
in 1996, formed on the Msunduze River upstream of its confluence with the Mfolozi River, while a
third crevasse splay formed on the conjoined rivers, presumably during flood conditions of either 1984
or 1987. Other notable observations included several open water features visible on the floodplain,
three of which occurred between abandoned river courses of the Mfolozi River, and the excavation of
the ‘Link Canal,’ an unsuccessful attempt by KwaZulu-Natal Wildlife officials to introduce fresh
water from the Mfolozi River to Lake St. Lucia.
The full extents of flood deposits from Cyclone Domoina, 1984, are shown in imagery from 1996 (Fig. 3). A large lobe of sediment, ~ 10 km long and averaging 3 km wide was deposited in a southeastward-trending swathe by a visible net of distributaries. Once again, regions of open water were located on the lower floodplain between abandoned channel belts, while excessive wetness in the lower floodplain had caused local abandonment of sugar cane fields by 2007.

4.1.2. Valley morphology

In the uppermost region of the floodplain, the Mfolozi River is confined to a deep (> 60 m), narrow valley of ~ 1.0 km in width, which narrows further (to 0.6 km) at the floodplain head (Fig. 4A, B). Downstream of this confined reach, the floodplain widens rapidly to a width of ~ 6.5 km over a downstream distance of just 1.15 km (Fig. 4C). At this point, the floodplain is bounded by steep features > 60 m in height in the north and 17 m in the south.
Also visible in the upper floodplain, is the alluvial ridge of the Mfolozi River, which is elevated between 2 and 3 m above the floodplain, over a width of ~ 2.2 km (Fig. 4C). The depression to the south of the ridge contains Lake Teza, while a minor lake is situated in the depression north of the ridge. These two water bodies occur at different elevations: Lake Teza is at an elevation slightly < 14 m a.m.s.l., while the northern lake, which is much smaller in extent, is situated at an elevation of 17 m a.m.s.l.. The alluvial ridge of the Mfolozi River extends eastward on the floodplain, where it is set up against the high-lying ground adjacent to the floodplain (Fig. 4D). At this point the floodplain reaches a width of 5.8 km, and the alluvial ridge can be clearly seen by the change in elevation ~ 2.3 km south of the Mfolozi River. The Msunduze River occupies the lowest region of the floodplain.

The floodplain continues to widen downstream such that in the region of Lake Futululu it is 10.5 km wide (Fig. 4E). Lake Futululu occupies a depression < 2 m below the alluvial ridge. Apart from this, the floodplain is flat, at a fairly consistent elevation of ~ 10 m. Here the Mfolozi River is centrally located on the floodplain while the Msunduze River hugs the southern floodplain boundary. The
floodplain reaches its maximum width of 11.7 km to the east of the Uloa Peninsula (Fig. 4F), where it is characterized by a gentle north–south gradient. The southern edge of the floodplain contains a small lake, north of which is the Msunduze River. At this point, the floodplain is confined between two steep escarpments with maximum elevations of 32 and 23 m in the north and south, respectively. Toward the sea, the floodplain becomes progressively narrower and flatter such that at the lowermost cross-section, it is ~ 4 km wide (Fig. 4G, H). The Mfolozi and Msunduze Rivers are blocked from the sea on the eastern end by a large dune cordon, which reaches up to 90 m in height, a northward moving system that forces the river system northwards to a break in the dune cordon.

The river surface longitudinal profile, as measured using differential GPS, was completed (April 2005) when discharges were slightly above average from good rainfall in the catchment in the weeks prior to conducting the survey. The water surface profile is generally concave (Fig. 5). At the head of the floodplain, the slope on the water surface is remarkably uniform at ~ 0.06%. Downstream of this region of uniform slope, the stream steepens (0.09%) and then flattens (0.03%) relative to the slope in the upper part of the floodplain. Thereafter, slope steadily decreases downstream as far as the river mouth, where the profile is truncated, with an elevation of 0.6 m measured at the estuary mouth.

Fig. 5. River longitudinal profile of April 2005.

The longitudinal profile of the levee bank is somewhat irregular (Fig. 5), with a region of greater than expected elevation between 32 and 18 km upstream of the mouth. The height of the levees above the
water surface varied between 4 and 6 m high at the head of the floodplain (Fig. 5). From ~ 25 km upstream from the mouth, levee height decreases.

4.2. Floodplain surface characteristics

The floodplain surface dips in elevation toward the coast (Fig. 6). At the floodplain head, the northern region of the floodplain along the current river course is at a greater elevation than the south. As a result, in the mid and upper floodplain, the local gradient on the floodplain surface is downward toward the south and southeast. In addition, the alluvial ridge of the Mfolozi River is elevated above the surrounding floodplain in this region, with a superelevation of between 5 and 10 m. Lakes Futululu and Teza occupy depressions adjacent to the alluvial ridge of the present day Mfolozi River course.

Fig. 6. Digital elevation model created using differentially corrected Trimble GPS data.

Toward the central floodplain, two prominent rock pinnacles are visible as elevated features in the surrounding alluvium. Once again, the central floodplain has a downward slope toward the southeast.
However, there is substantial variation within this trend, with localized depressions and areas of high ground. Some portions of the lower floodplain appear to be below sea level, particularly along the lower Msunduze River.

The median particle size was interpolated, using the *Topo to Raster* 3D analyst developed for fluvial systems in Arcview 9, for the entire floodplain from surface samples (Fig. 7). Silt-sized sediments dominate the floodplain surface, with the majority of sample medians being characterized as medium silt. There is substantial variation in particle size toward the head of the floodplain and less toward the lower floodplain in the east.

**Fig. 7.** Interpolated median particle size on the floodplain surface, classified according to the Wentworth–Udden scale.
The upper floodplain is the coarsest in terms of particle size, with median particle size varying from coarse silt to medium sand. Surface grain size is not associated with the current day alluvial ridge at the floodplain head, but coarser sediments (very fine sand) are roughly orientated as a linear feature from the point where the Mfolozi River enters the floodplain toward the southeast. An additional linear feature of coarser sediments, this time predominantly of coarse silt size, is located in the central floodplain at a southward orientation.

4.3. Floodplain sedimentology

The uppermost transect of cores (transect B) consisted of four holes orientated roughly north–south, with B4 in the north and B1 in the south (Fig. 1). The corresponding water table of the transect slopes away from the highest point on the floodplain surface at B3 toward the Mfolozi River in the north and Lake Teza in the south (Fig. 8).

Fig. 8. Sedimentology and topography of transect B in the upper floodplain.
The northernmost core, B4, was augured on the southern levee of the Mfolozi River. Coarser sediments of coarse- and medium-grained sand mark the base of core B4. This lower unit is overlain by a varied sequence that is generally upward coarsening, and then upward fining from 16 m a.m.s.l. However, within these general trends, the sequence is interrupted by a number of thin layers that may be coarser (fine to very fine sand) or finer (coarse to medium silt). Ash contents were consistent with particle size, with the coarser layers having higher ash contents.

Core B3 was relatively coarse, comprising a sequence of medium and very fine sand, with a lower upward fining sequence, followed by an upward coarsening sequence, and a second upward fining unit. The upper part of the core comprised an upward fining sequence of medium sand. The percentage ash content was relatively constant throughout, reaching a minimum of 97.7% at 1 m depth.

Core B2 consisted of a lower unit that fined upward from very fine sand from a depth of 4 m, to medium and fine silt at 1.9 m depth. The upper part of the core coarsened upward from very fine sand, to fine sand and then medium sand. Ash contents were generally high, and mostly uniform.

The final core of this transect (B1) was augured on the boundary of Lake Teza in the south. B1 is dramatically finer throughout than any of the other cores on the transect. The predominant particle size class was fine silt. Ash contents were also lower and more variable than the cores to the north. A medium silt layer marked the base of the core. Thereafter, the sediment coarsened upward until a depth of 4.2 m, where a sudden change from medium silt to fine silt occurred. Within the middle fine silt layer, a sequence of upward coarsening and then upward fining sediment was found. This fine silt layer was separated from an overlying fine silt layer by a thin layer of very fine silt. The uppermost fine silt layer also tended to coarsen upward. An unusually coarse layer of medium silt was found at the top of B1. Organic content was highest in the top 10 cm of the core, with an organic content of > 10%.

Transect A was augured toward the central floodplain, with core A1 just south of the Uloa peninsula, and A6 next to the Msunduze River in the south (Fig. 1). The piezometric surface of transect A at the time of study sloped away from the Mfolozi River to the north and south (Fig. 9). Further floodplain groundwater recharge occurred from the Msunduze River that is located south of core A6. In general, samples from transect A were finer than those of transect B. Core A1, was augured north of the Mfolozi River, in a region that was once intermittently flooded by Lake Futululu before the Uloa loop
was circumvented by agriculturalists. The core comprises three main sequences, the first of which is a lower upward coarsening sequence that coarsens from very fine silt to medium silt. This is followed by two upward fining sequences — both of which fine upward from fine silt, culminating in clay and very fine silt, respectively. *Cyperus papyrus* plant fossils occur between 2.5 and 3.5 m below the surface, corresponding to an increase in organic content to > 8%.

Core A2 was taken on the current Mfolozi River levee, where ash content varied little. The core comprised two upward fining sequences, which both fined from very fine silt to fine silt. Core A3 was sampled just south of the current day Mfolozi River course in a depression between cores A2 and A4. The core comprised three units of different median particle size, a lowermost unit of fine silt ~ 1.5 m thick, overlain by a thick unit of very fine silt unit, topped by a 30 cm deep of sediment that coarsened upward to very fine sand.
Core A4 was sampled close to an abandoned alluvial ridge and is consequently elevated above surrounding auger holes on the same transect. Cores A4 and A5 were slightly coarser than others from the same transect, with no samples characterized as finer than fine silt in respect of median particle size. The base of A4 was an upward coarsening sequence of coarse silt overlain by fine sand. This was overlain by a general upward coarsening unit with a median particle size of fine silt and intervening layers of coarser sediment. In core A5, the base upwardly fined, the trend being disrupted by thick layers of fine sand and very fine sand. Organic contents of both A4 and A5 were generally below 5%. In contrast, the southernmost core, A6, was very similar in terms of sedimentary sequences to core A3. As in the case of core A3, A6 comprised a lower unit that fined upward from fine silt to very fine silt, and was overlain by a thin, upwardly coarsening sequence of fine silt.

The lowermost transect, transect C, was located on the easternmost accessible part of the floodplain and consisted of four core holes, with C1 just south of the Mfolozi River and C4 just north of the Msunduze River. The piezometric surface in this transect generally followed the topography as it sloped down from the highest elevation in the north (Fig. 10). The northernmost core, C1, consisted of two major sequences: a lower upward fining sequence that graded from fine silt to very fine silt, and an upper sequence that fined upward from very fine silt to medium silt. There are intermittent layers of coarse silt within the sequence. Organic contents were generally low throughout the core, with a maximum value of 9% at 3.5 m depth from numerous plant fossils and roots.
Fig. 10. Topography and sedimentology of transect C in the lower floodplain.

The base of core C2 was characterized by relatively coarse sediments of fine and very fine sand, which changed at 3 m depth to an upward coarsening sequence of medium silt to coarse silt. Above the upward coarsening sequence, an upward fining sequence of fine silt gave way upward to a layer of medium silt. Organic contents were relatively uniform throughout the core, except for a maximum value recorded 0.5 m below the surface where organic content reached 8.9%.

As in core C2, the base of core C3 was unusually coarse, consisting of coarse silt and very fine sand. Above this layer, particle size suddenly declined to fine silt, which was overlain by an upwardly fining sequence of medium silt to coarse silt. The organic content reached an unusual peak of 55% 2.5 m below the surface due to a layer of nondecomposed wood. In contrast, organic contents in the southernmost core, C4, were relatively low. C4 comprised two upward fining sequences, the lower of which fined upward from medium silt at 4.5 m to fine silt at 0.8 m, while the top 0.8 m were coarse and medium silt.
In order to establish differences in particle size and sediment sequences along the longitudinal axis of the floodplain, the central core from each of the transects were illustrated together with two additional cores, MC and LC (Fig. 11). The floodplain head (as represented by B3) is much coarser than the remainder of the floodplain, and there is a general fining trend toward the east when the uppermost portion of each core is compared. Core A3 is anomalously fine with regards to this trend. In terms of overall particle size variation with depth, there is no consistent trend in cores B3, A3 or C3. In cores MC and LC, there is an insignificant upward coarsening trend.

Fig. 11. Longitudinal variation in sedimentology.

4.4. Morphology of the alluvial belt

The abandoned alluvial ridge is elevated above the surrounding floodplain by at least 2 m, sloping more steeply from the abandoned channel toward the north (4.3%) than toward the south (0.6%, Fig. 12). The morphology of the pre-existing channel is not clearly discernable because of extensive ploughing and cultivation that has removed details of the channel.
Cores T1 and T2 consisted primarily of medium silt, with intervening layers of fine sand and coarse silt, while core T3, toward the centre of the abandoned channel, was much coarser and was dominated by medium to fine sand that consistently collapsed at a depth of 2.2 m. The top of core T3 was marked by a medium silt layer 0.4 m thick, a similar deposit of which occurred on top of all of the cores. In cores T4, T5 and T6, coarse sediments were encountered at greater depth. In T4, silt was encountered until a depth of 1.7 m, whereupon silt changed suddenly to very fine sand. The same unconformity was encountered at 1.2 and 1.56 m depths in cores T5 and T6, respectively. No similar sandy layers were encountered in cores T1, T2, or T7. Core T7 was markedly finer than the other cores and was dominated by medium silt sediments with two intervening layers of coarse silt, with the base of the core marked by fine silt.

5. Discussion
5.1. Floodplain origin and development

Upstream of the Mfolozi floodplain, the Mfolozi River occupies an incised valley characterized by entrenched meanders over 30 m high. This square-shaped valley is cut into olivine-poor tholeiitic basalts of the Sabie River Formation (Lebombo Group) that erupted during a failed rifting event 179 Ma (Watkeys et al., 1993). This early rifting event, occurring on the supercontinent of Gondwana, was the first episode to lead to the formation of a sedimentary basin in northern KwaZulu-Natal, in which the Mfolozi floodplain is now situated. The crust was further extended during rifting events that eventually separated the continents of Africa, Antarctica, South America, and Australia, leading to localized subsidence and the formation of a basin, in which the Zululand and Maputaland Group rocks were deposited.

More recently, sea level reached 120 m b.m.s.l ~ 18,000 YBP (Ramsay, 1995), initiating a new erosional phase as coastal rivers were locally rejuvenated. In regions where lithologies were resistant, deep square valleys were incised and in the case of the Mfolozi River, this resulted in the development of entrenched meanders upstream of the floodplain. However, as the Mfolozi River flowed over the Sabie River Formation basalts, it encountered less resistant rock of the Maputaland and Zululand Groups downstream. These were more conducive to erosion, and the wide, deep valley of the Mfolozi River was carved.

Following the Last Glacial Maximum, sea levels began to rise. Beach rock evidence suggests that sea level along the Maputaland coasts was 3.5 m above current levels until 4880 YBP, reaching current levels of 3780 YBP (Ramsay, 1995). Palynological evidence from Lake Teza suggests that higher than current sea levels drowned portions of the Mfolozi River valley (Scott and Steenkamp, 1996), in part because the rate of sea level rise exceeded valley aggradation. Eventually, ongoing sediment accumulation and the development of a sea level stasis prevented the intrusion of the sea. However, some portions of the floodplain are still located below sea level (Fig. 6).

The development of the Mfolozi River Floodplain is different from that of other wetlands studied in southern Africa that primarily owe their origin to portions of their drainage lines overlying resistant rocks (e.g. Tooth et al., 2004). Floodplains of this type are typically characterized by mixed bedrock-alluvial rivers that experience long-term erosion of the valley floor, and as such, the depth of sediment
accumulation is usually < 8 m. In contrast, the Mfolozi River is alluvial and the sediment depth is > 8 m.

5.2. Floodplain geomorphology and sedimentology

The Mfolozi River Floodplain may be subdivided into four geomorphic zones that reflect different controls and floodplain processes (Fig. 5). The sedimentology and geomorphology of each zone is described in the following section, with the upper two zones discussed in tandem because of their interconnected nature.

5.2.1. Upper floodplain and alluvial fan

Two distinct slopes mark the upper floodplain region. In the upper floodplain, the river gradient is 0.06%. Below this region, the river slope steepens to 0.9% over a 4 km long stretch. This gradient represents the prograding face of an alluvial fan that has because of a sudden loss of confinement at the floodplain head. Above the floodplain region, the Mfolozi River flows in a confined valley, which rapidly widens as the river encountered more erosive lithologies. During flood events, the Mfolozi River loses confinement as inundation of the floodplain takes place, and stream capacity thus declines, resulting in deposition that has created a southeastward sloping lobe of sediment at the floodplain head.

The alluvial fan is dominated by sand size sediments that vary from very fine to coarse. As a result of the permeability of the sediments, the fan is a groundwater recharge area as rainfall easily infiltrates the sandy sediment and drains freely to recharge the groundwater table. As such, the piezometric surface slopes away from the central region of the lobe of sandy sediment. The dominant manner in which relief is built on the alluvial fan must be accredited to overbank flood flows, rather than channel aggradation. While the maximum depth of the Domoina deposits is not represented in transect B (Domoina deposit depths vary from 0.7 m at B3 to 1.8 m at B2), they are still substantial for a single flood event lasting a few days. The channel pattern of the Mfolozi River in this region may also be used as an indication of the importance of flood flows. Often aggrading and steepened floodplain regions are characterized by high sinuosity (Schumm, 2005). Contrarily, the Mfolozi River is relatively straight in this reach, as during flood events, the steepest gradient is required to
accommodate flood flows. In this reach, the morphology of the Mfolozi River represents the most recent channel-changing event, rather than the most dominant flow.

Rapid aggradation on the alluvial fan has implications for tributaries flowing onto the floodplain from its boundaries. On the southern boundary, the Msunduze River flows into the floodplain and is impounded by the alluvial fan, resulting in the formation of Lake Teza. The Msunduze River flows out of the lake as a yazoo stream. While the lake may appear to be too close to the western boundary of the floodplain to receive sediment from flood flows of the Mfolozi, Domoina deposits are represented in the upper unit of core B1 as a 0.4 m deep layer of medium-grained silt. Domoina deposits in Lake Teza have also been described by Scott and Steenkamp (1996). Other layers of medium silt at 4.2 and 5.9 m depths must be indicative of previous large flood events on the Mfolozi River.

The depression at the head of the floodplain north of Lake Teza is anomalous and reflects the nature of sedimentation in the vicinity of an alluvial ridge, which results in steepened gradients perpendicular to the channel. Thus, as floodwaters move away from the alluvial ridge and levees, flow responds to local and then regional floodplain gradients. Depositional features close to the Mfolozi River should therefore be expected to be oriented north–south, but that farther away from the river, depositional features would be oriented toward the southeast, such as the depositional feature created by Cyclone Domoina.

5.2.2. Central floodplain

Below the alluvial fan, the stream gradient flattens to 0.03%, then follows a stepwise drop of just over 1 m in 1.3 km. Thereafter, gradient decreases again to 0.03%. A valley longitudinal profile showed a similar region of flattening, suggesting that gradient in this region is controlled structurally across the entire floodplain. In conjunction with the extremely low slope, the floodplain is anomalously wide (~ 10 km) just upstream of the central region. The combination of the width and change in gradient are frequently an indication of faulting in an alluvial setting (Schumm et al., 2000). Anomalies in river sinuosity may also be interpreted as an indicator of faulting, but the location of the alluvial fan upstream of the region complicates the use of sinuosity as an indicator.

The location of the probable fault is visible on satellite images of the St. Lucia area as a linear feature extending across the central floodplain and bordering False Bay of Lake St. Lucia. A second lineament
comprises the western boundary of the main water body of Lake St. Lucia and is roughly parallel to the coastline. The area is currently seismically active, with the most recent report indicating the existence of WNW–ESE striking fault lines (Umvoto Africa, 2004). However, in the study of Krige and Venter (1933) on the St. Lucia earthquake of 1932, isoseismal lines drawn using onshore observations suggested a fault line approximately parallel to the coast. Lineations observed in the Lake St. Lucia area are consistent with this strike. However, coastal features follow a similar strike to the potential fault. Nevertheless, the combination of data (from adjustments in gradient, floodplain width, and visible lineations in the area of interest), strongly suggest the existence of such a fault.

The sedimentology of the central and lower floodplain is dependent on various factors besides structural control, the most important of which is distance from the channel. Many studies have highlighted the importance of distance from the channel as a determinant of sediment particle size (e.g. [Pizzuto, 1987], [Asselman and Middelkoop, 1995] and [Makaske et al., 2002]). However, in this case, distance from abandoned channels and the concomitant mosaic of inter-ridge depressions plays an important role in resultant sediment particle size. As a result, the central floodplain is marked by large variability in particle size, as indicated by transect A (Fig. 9). Cores A4 and A5 were located on or near abandoned channel courses and were characterized by slightly coarser sediments than the other cores, with fine silt and fine sand layers well represented. Contrastingly, despite the proximity of core A3 to the channel, the majority of the core is extremely fine, with a thick sequence of very fine silt and capped by recent coarse deposits, presumably from recent flood deposits. The very fine sediments of core A3 are representative of those of small depressions created by basins that occur between alluvial ridges. Asselman and Middelkoop (1995) also found that ponding in closed depressions was an important factor in determining the nature of sediment accumulation.

5.2.3. Lower floodplain

The slope of the lower region (from the central floodplain to the coast) resembles a graded profile that is controlled by sea level, with slopes of between 0.03% and 0.02%. The lower floodplain has been a region of enhanced aggradation due to its proximity to sea level since the last transgression. In addition to controlling the occurrence of depositional or erosive periods through transgression and regression, sea level and tidal patterns also have an influence on channel pattern close to the river mouth as channel sinuosity in this region is influenced by the extent of the tidal prism (Dalrymple et al., 1992), resulting in frequent changes in sinuosity.
The sedimentology of the lower floodplain region is represented by cores MC and LC as well as, to some extent, by the lowermost transect, C. Unexpectedly, the median particle size of all the samples was never finer than very fine silt in the lower floodplain region, either at the surface or at depth; and the typical median particle sizes were fine and medium silt. This seems somewhat surprising considering that overbank areas generally consist of clay- to silt-sized sediments, and, in many cases, peat (e.g., [Magilligan, 1992], [Törnqvist, 1994] and [Makaske et al., 2002]). However, the study of Magilligan (1992) of the Galena River Basin in Wisconsin showed that local geology and sediment provenance could play a major role in determining the sedimentology of floodplain alluvium. Particle size determinations of suspended sediment loads showed that the average median particle size was 5.2 μm (very fine silt), while the minimum median size recorded was 4.0 μm, also very fine silt (Garden, 2008). The lack of clay in overbank deposits probably reflects a lack of supply.

5.3. Floodplain processes and dynamics

5.3.1. Fluvial style

The sedimentology of the abandoned alluvial ridge clearly indicates that prior to channel straightening, the Mfolozi River actively meandered in the central and lower floodplain regions. The river historically (and currently) occupied a position of elevation on the floodplain, flowing more than 2 m above the surrounding floodplain. The alluvial ridge was noticeably coarser than the surrounding floodplain (e.g., core T7), and showed coarsening with depth on the inner bend (right bank) that is consistent with the deposition of point bars. Cores T1 and T2, located on the outside meander bend, were finer and had thin intervening layers of fine and very fine sand. Finer sediments are indicative of normal overbank flooding and resultant deposition, while the coarser layers may be interpreted as larger flood events that were capable of carrying coarser sediments over the levee and onto the floodplain.

5.3.2. Floodplain dynamics

The avulsion sequence of the Mfolozi River was interpreted through geomorphic relationships in the aerial photography (Fig. 13). The sequence acknowledges two types of change to the channel's course: natural avulsions and human induced channel straightening events. Fig. 13A illustrates the earliest known course of the Mfolozi River still preserved on the floodplain surface. This course flowed
relatively straight down the alluvial fan, completing a heart shaped loop toward its base, before flowing toward the southeast, and along the current day Msunduze River course. This alluvial ridge is visible in floodplain surface particle size distributions (Fig. 7) as a coarse SE-trending silt ridge on the floodplain surface that is parallel to the western edge of the Uloa peninsula. The parallel orientation of the ridge and the Uloa peninsula may also have been responsible for the original surface water pattern of Lake Futululu, which was also SE-trending (Fig. 2).

![Maps showing river channels and avulsions](image)

**Fig. 13.** Interpreted recent avulsion history of the Mfolozi River: A–C — prehuman intervention, D — 1937, E — post 1937, and F — following Cyclone Domoina.

At some stage, aggradation on the SE-trending ridge resulted in channel longitudinal gradients that were exceedingly low as compared to the gradient away from the alluvial ridge in a fashion described by Heller and Paola (1996). This resulted in a channel avulsion toward the east at what is now called the Uloa loop (Fig. 13B), resulting in an actively meandering river flowing due east from the location of avulsion. Eastward of the Uloa peninsula, the newly formed sinuous Mfolozi River flowed in the centre of the floodplain, north of its previous position. The following avulsion (Fig. 13C) resulted in a
portion of the river being directed even farther north, with reduced sinuosity. This early sequence indicates a series of avulsions progressing northward, suggesting that the floodplain surface dipped toward the northeast at this stage.

Between 1910 and 1937, sugar cane farmers began cultivating the floodplain, and began to straighten portions of the channel to improve channel efficiency. It appears that the first major alteration was the movement of the channel toward the extreme north such that it flowed around the Uloa peninsula and then hugged the floodplain boundary. It then occupied the existing channel ~ 4 km downstream of the Uloa peninsula (Fig. 13E). This was followed by the complete removal of the Uloa loop from the rivers course between 1937 and 1960 (Fig. 13E).

Continual aggradation on the northern region of the floodplain resulted in slopes toward the south becoming steeper than the channel longitudinal slope, bringing the system close to an avulsion threshold. The threshold was crossed in 1984, when floods associated with Cyclone Domoina completely altered the course of the Mfolozi River (Fig. 13F). The progressive northward migration of the Mfolozi River in previous years had resulted in the floodplain surface gently dipping toward the southeast (Fig. 6). The suddenly high discharges and sediment loads overwhelmed the existing channel, and existing gradients favoured an avulsion at the floodplain head. The Mfolozi River switched from hugging the northern floodplain boundary to flowing to the south and occupying the existing Msunduze River course, which had been substantially straightened by agriculturalists.

The resulting location of an avulsion is a combination of superelevation of the channel above the floodplain (Heller and Paola, 1996), the relative channel versus crossvalley gradient, the occurrence of previous avulsions (Mackey and Bridge, 1995), and also stochastic events. Simulation models of rising sea level have suggested that in such settings, avulsion probabilities increase downstream, with subsequent avulsions tending to occur progressively upstream from the initial avulsion (Mackey and Bridge, 1995). On alluvial fans, avulsions are likely to occur at the apex because of rapid superelevation of the channel (Bryant et al., 1995), a finding consistent with the study of Törnqvist (1994) in the Rhine-Meuse delta.

Despite the limited availability of information regarding the Mfolozi River's avulsion history, these models provide insight into the dynamics of the Mfolozi River floodplain. The floodplain's current geomorphic state suggests two main nodes of ongoing sedimentation. The first is at sea level, where
the floodplain is under ongoing adjustment. As the river approaches the sea, gradients decrease, the river loses both capacity and competence, and aggradation of the channel occurs. The result of aggradation at the coast is further lowering of the river's longitudinal gradient, which in turn causes feedback that further encourages sedimentation. Unless the estuary and lower floodplain area are scoured, as described by Cooper (1993), aggradation on the lower floodplain channel may reach a critical elevation causing local avulsion. Thus, the lower floodplain is a region of frequent avulsion as the channel jostles the effects of transgression and loss of sediment transport capacity. The evidence for frequent avulsions in this region is the large number of preserved abandoned channels in the lower floodplain region, which are also indicative of low rates of overbank aggradation.

The second node of enhanced aggradation, and thus avulsion frequency, is on the alluvial fan at the floodplain head. The majority of alluvial fan building is not through gradual (daily) channel aggradation, but rather through sudden rapid aggradation associated with infrequent flood events. During Cyclone Domoina, discharges well exceeded the channel's flow capacity, causing the river to overtop its banks and deposit sediment on the alluvial fan as it flowed southward toward the Msunduze River course. Deposition occurred as a series of lobes that were deposited and subsequently eroded, disrupting the characteristic flood sequence of upward coarsening followed by upward fining as the flood waned. The result is a varied sequence of upward coarsening and/or fining within the Domoina flood deposits, as shown in Fig. 8. At core B3, only a portion of the Domoina deposit is represented; while at core B2, only the upward coarsening unit is visible. At core B1, a thin unit of upward fining is visible, indicating the waning flow. Using this information, the sediment lobe was eroded and redeposited at least twice between cores B1 and B3 during the flood. The current topography of the upper alluvial fan is also indicative of the process of deposition followed by scour, where the sediment lobe is transported progressively farther from the avulsion node. This suggests that episodic scour is an important part of alluvial fan evolution, particularly during large flood events.

Superelevation of the abandoned and active alluvial ridge prevents reoccupation of abandoned channels in the upper to central floodplain region, and instead, once the channel has avulsed at the floodplain head, a completely new channel must be generated for almost the entire length downstream. As a result, the avulsion style is contrary to that reported by Jerolmack and Paola (2007), in that the channel is generated in long reaches, rather than short segments. Furthermore, deposits associated with nodal avulsions at the floodplain head contribute significantly to the volume of sediment stored in the
floodplain, in contrast to a study by Taha and Anderson (2008), which found avulsion deposits to be insignificant relative to the total volume of valley sediments. Toward the ocean, the floodplain becomes constricted and the channel is not significantly elevated above the surrounding floodplain. In this region, channels may form to increase flow capacity, occasionally becoming the main conduits of flow through headward incision, and thus causing local avulsion as described by Slingerland and Smith (2004). In this region, channel reoccupation is likely to be common, and new channel reaches are probably generated in short segments.

6. Conclusions

The Mfolozi River Floodplain is characterized by two avulsion styles that predominate in two different regions of the floodplain. At the floodplain head, avulsions occur primarily during extremely infrequent, large flood events, where the stream flow capacity of the channel is insufficient. As a result, flow is forced out of the channel and down the steepest slope, from the alluvial ridge to the surrounding floodplain. The resulting avulsion is regional, and affects the location of the channel from the floodplain head to the river mouth. Deposits resulting from such avulsions contribute significantly to the total volume of sediment stored in the floodplain, and tend to persist for long periods after the avulsion.

In the lower floodplain region, avulsions tend to be local, and channel is generated in short segments rather than long reaches. In contrast to the nodal avulsions of the upper floodplain, deposits from these local avulsions are generally negligible.

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