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Lakes of the north eastern region of the Okavango Swamps, Botswana

by

T. S. McCarthy, W. N. Ellery and L. G. Stanistreet, Johannesburg

with 13 figures

Zusammenfassung. Die Okavango-Sümpfe im nördlichen Botswana liegen in den proximalen Teilen eines großen Schwemmfächers (20000 km²), dem endgültigen Ablagerungsraum des Okavango. Der Fluß teilt sich am Beginn des Schwemmfächers in eine Anzahl von Rinnen, die 6000 km² permanenter Sümpfe aufrechthalten. Seen bilden einen wichtigen morphologischen und ökologischen Teil dieser Sümpfe. Die Seen sind mit einem Mäandergürtel verbunden, der aber 2000 bis 3000 Jahre alt ist und nicht mit dem heutigen Netz der Rinnen verbunden ist. Die Seen entstanden durch die erneute Überflutung alter Mäanderschlingen oder durch das Abdämmen des Wassers gegen alte Mäanderuferwälle. 50 Jahre der Registrierung durch Luftbilder zeigen, daß einige Seen stabil sind, während andere verschwunden sind. Durchbrüche lenken gelegentlich Rinnen in einen See über einen Pfad von Flußpferden, wodurch eine Vegetationssukzession entsteht, die sehr schnell zu einer Auffüllung des Sees durch Vegetation führt. Dieses wird abgelöst von einer Rinne, die von einem Sumpf mit dichter Vegetation flankiert wird. Seen, die nicht durch Rinnen verbunden sind, füllen sich sehr langsam auf durch die Ablagerung von autochthonem, organischem Material.

Summary. The Okavango Swamps of nothern Botswana are situated in the proximal reaches of a large alluvial fan (20000 km²), the terminal depository of the Okavango River. The river divides into a number of distributaries at the head of the fan, which sustain 6000 km² of permanent swamp. Lakes form an important morphological and ecological feature of this swamp. The lakes are associated with a meander belt, but this belt is 2000 to 3000 years old and is not related to the present distributary channel system. The lakes have arisen from reflooding of old oxbows, or damming of water against the old meander ridge. Fifty years of aerial photographic record indicate that some lakes have been stable while others have disappeared. Avulsion occasionally diverts a channel into a lake by way of a hippopotamus trail, initiating a vegetation successional sequence which rapidly leads to closure of the lake by vegetation. It is replaced by a channel, flanked by densely vegetated swamp. Lakes not connected to channels fill very slowly by the accumulation of autochthonous organic material.

Résumé. Les marais de Okavango dans le Nord du Botswana sonst situés dans les zones proches d'un vaste cone de déjections (20000 km²), qui est le dépôt terminal de la rivière Okavango. La rivière se divise en un grand nombre de bras vers l'aval du cone, où se trouvent environ 6000 km² de marais permanents. Des laçs constituent un trait morphologique et écologique important de ces marais. Ils sont associés à un

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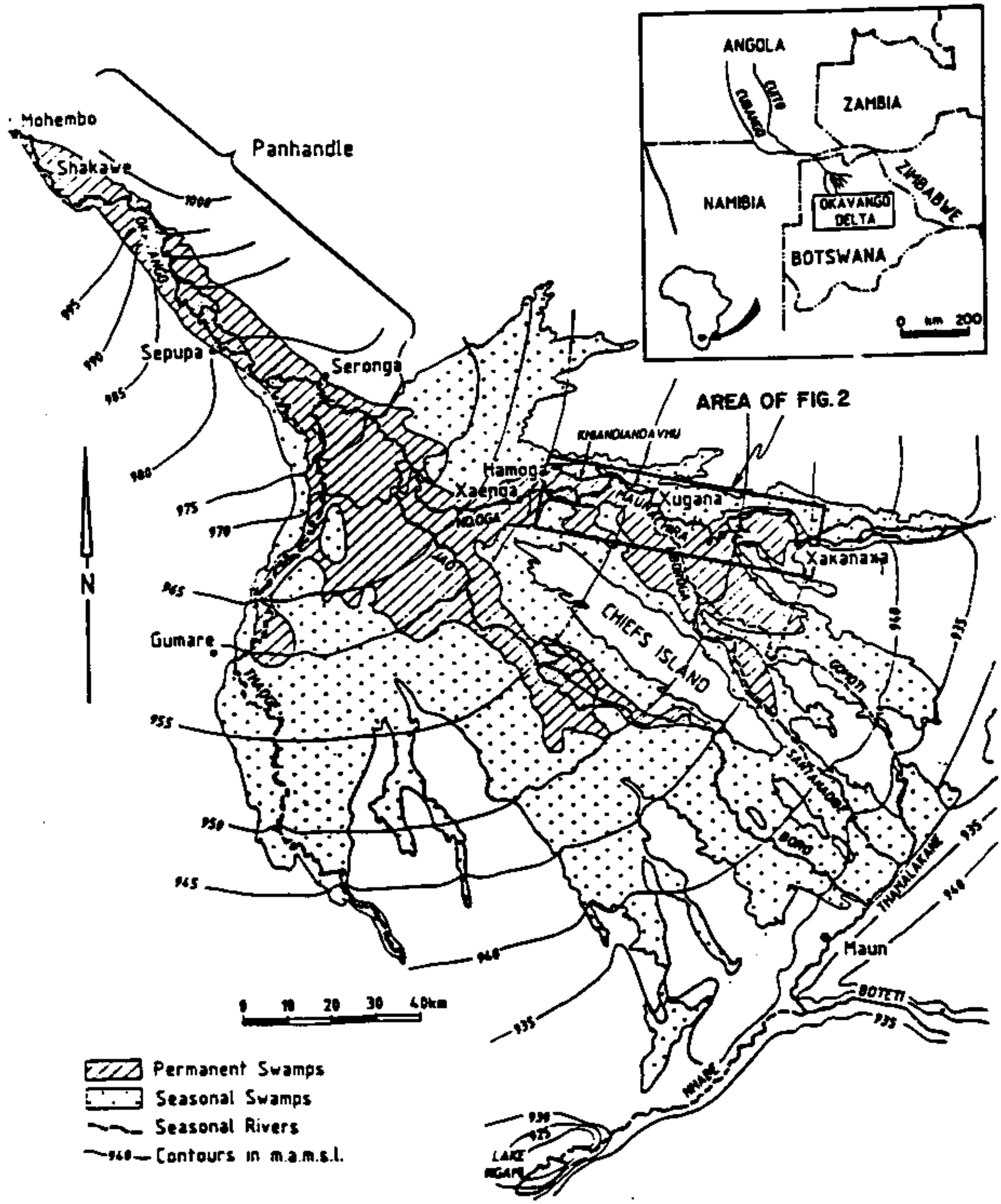

Fig. 1. The Okavango Delta.

measurements of inflow and outflow, as described by McCarthy et al. (1991a), vegetation mapping, coring and chemical and mineralogical analyses of sediment (McCarthy et al. 1989).

train de méandres, mais celui-ci a de 2000 à 3000 ans, et n'est pas en relation avec le réseau de ch
actuels. Les lacs sont nés de la réinondation d'anciens oxbows, ou par des barrages constitués p
digues d'anciens méandres. Des observations sur photos aériennes, prises au cours des cinquante der
années, indiquent que des lacs se sont maintenus, mais que d'autres ont disparu. Un déversement
occasionnellement dériver un chenal vers un lac en suivant une piste tracée par les hippopotames. C
déclenché une évolution de la colonisation végétale qui a rapidement conduit à la fermeture du lac
végétation. Le lac est alors remplacé par un chenal, flanqué d'une dense végétation de marécage. L
non reliés aux chenaux se remplissent très lentement par l'acumulation de matériaux organiques
chtones.

Introduction

The Okavango "Delta" (fig. 1) is a large alluvial fan situated within grabens fo
by a southwesterly extension of the East African Rift system (Hutchins et al. 1
The fan is the terminal depository of the Okavango River system which d
central Angola. It has a very low gradient (1:3600; Hutton & Dincer 1976)
discharge from the Okavango River spreads out on the fan, creating some 6000
of permanent swampland at the apex of the fan and in the entry corridor or "
handle" (fig. 1). A further 6000 km² to 12 000 km² area flanking the perma
swamps is seasonally flooded (Hutton & Dincer 1976). The remainder of the f
permanently dry, but historical records and geomorphological evidence indicate
these areas have, in the past, been subjected to flooding (Wilson 1972, Shaw 198
consequence of ever changing water distribution patterns on the fan surface.

The permanent swamp is a complex terrain consisting of distributary chan
flanked by densely vegetated swamp, sparsely vegetated backswamp areas, tree
vered islands and lakes or *madiba* (a Setswana word; sing. = *lediba*). There
presently three main "arms" of permanent swamp, each served by a channel system
These channels are the Thaoge in the west, the Jao-Boro in the central region and
Nqoga-Maunachira-Mboroga in the east (fig. 1). Lakes are most common around
apex of the fan and in a belt extending to the east along the Maunachira chan
system. It is in this latter region that the largest lakes occur and some attain sur
areas of up to 3 km². Studies of aerial photographs of the fan, which have been ta
at approximately five yearly intervals since 1937, have shown that several la
disappeared in the 50 years since systematic aerial photography began, while oth
remained unchanged (Wilson 1972).

The present study was undertaken to investigate the origin and especially
evolution and ultimate closure of lakes in the permanent swamps. The study
focused on the north-eastern area of the permanent swamps along the Nqo
Maunachira channel system, and one of the lakes which is currently experienc
rapid closure was studied in detail to examine the mechanisms involved.

Study methods

Analysis of aerial photographs taken in 1937, 1951, 1963 and 1983, coupled w
ground surveys, provided regional perspective on the distribution and evolution
the lakes. Detailed studies were undertaken in one of the lakes, Dxherega. Th
involved plane table mapping, bathymetric probing using steel rods, hydrologi

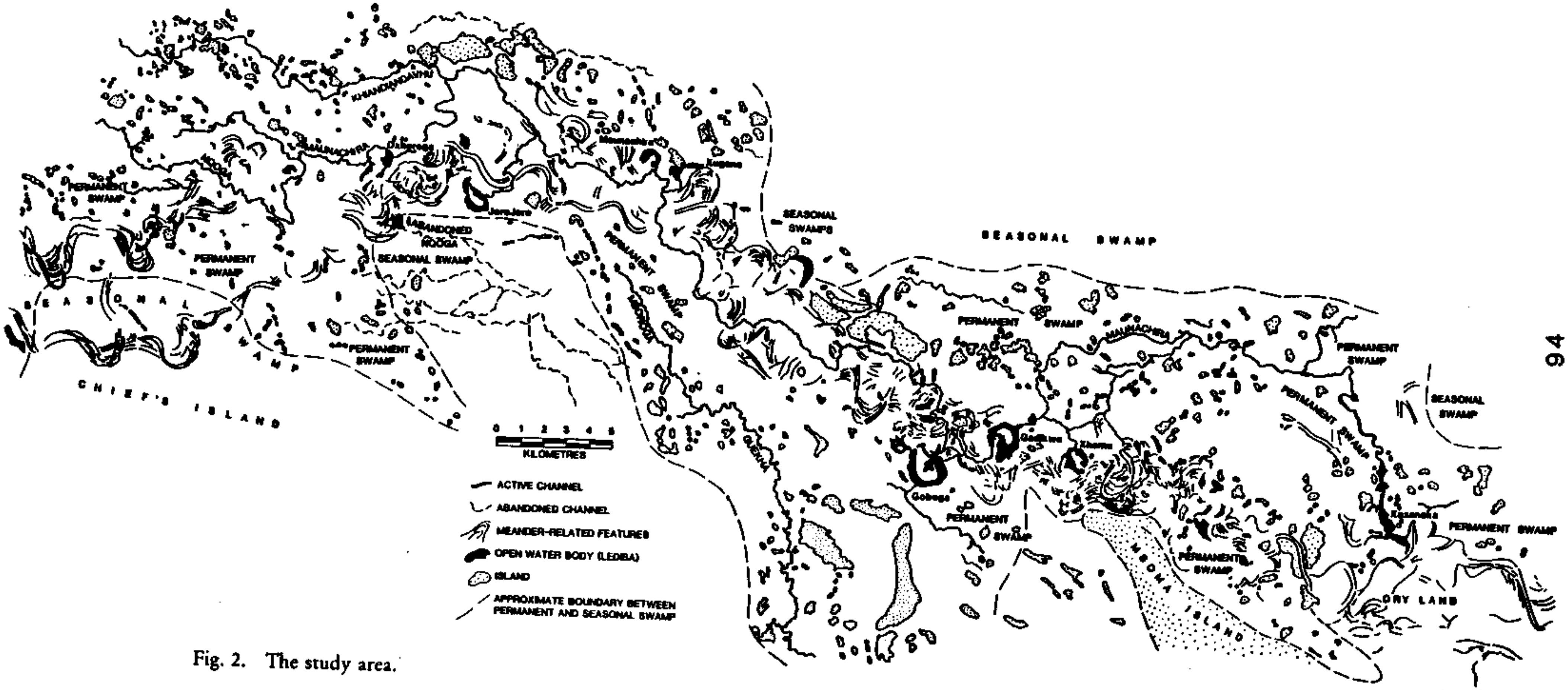

Fig. 2. The study area.

Results

Distribution and morphology of the lakes

Most of the lakes in the study area occur within a 5 km wide belt in the permanent swamp which flanks the Nqoga-Maunachira channel system (fig. 2). This belt is characterized by topographic and other photo-features indicative of a meander ridge, including point bars with scroll-bars which rise above the present water level and form tree-covered islands. Two different morphologies are evident among the larger lakes (fig. 3). The most numerous type of lake has a curved form indicative of a former oxbow, sometimes with cut-off channels across former point bars (eg Gadikwe; Jere Jere, fig. 3). All of these lakes occur within the meander belt (fig. 2). It is evident from the dimensions of these lakes that the channels which gave rise to them must have been in the order of 200 m wide. The other morphological type is represented by Xakanaxa (fig. 3), which occurs outside of the meander belt (fig. 2) and is characterized by a very irregular outline. This type of lake seems to have formed by damming of water against the topographic ridge of the former meander belt (fig. 2).

Outside the meander belt, the terrain is characterized by shallow seasonal or permanent swamp, dotted with low, irregularly shaped islands formed by subsurface precipitation of calcite and silica (McCarthy & Metcalfe 1990; McCarthy et al. 1991b). The lakes become larger and more frequent, and the inherited oxbow shape more clearly defined, towards the east (eg. Gobega, figs. 2,3). The density of swamp vegetation decreases downstream towards the east and laterally away from the present channel system, probably due to changes in resource availability. Hence large areas of sparsely vegetated swamp are common in the eastern extremity of the study area both within and adjacent to the meander belt. The irregularly shaped open water bodies of the Xakanaxa type occur in this region.

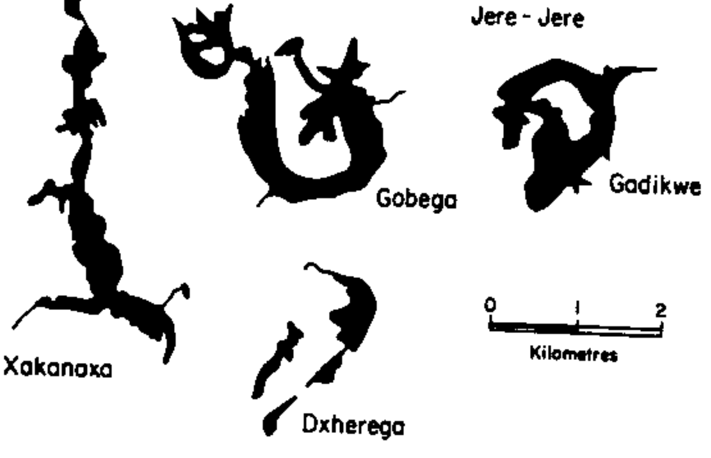

Fig. 3. Outlines of selected lakes in the study area.

The modern channel system and its relationship with the lakes

The present channels in the study area are typically less than 25 m wide (McCarthy et al. 1991a; Ellery et al. 1990), with flow velocities less than 0.5 m/s. Seasonal variations in discharge are minimal in this area (McCarthy et al. 1991a). The channels lie mainly peripheral to the meander belt. They are flanked by a 10 to 15 km wide zone of permanent swamp, which encompasses all of the meander belt except in the Xakanaxa area in the far east. In the western portion of the study area, channels lie to the north of the meander belt, cut through it in the central portion but again move to the northern margin in the east (fig. 2). These relationships indicate that the present channel system is superimposed on the older meander belt and could not have produced the oxbows and other features of the belt.

At present, only three of the lakes lie directly along the modern channel system, viz. Dxherega in the west and Gadikwe and Xakanaxa in the east (fig. 2). However, most of the larger and many of the smaller lakes are connected to the main channels by narrow channels, often no more than 2 m wide, usually with barely detectable flow. These narrow channels are hippopotamus trails. Hippopotami spend daytime in the lakes and adjacent swamp areas, but move to islands or the swamp fringes at

Fig. 4. Aerial photograph of Dxherega lake showing portion of the meander belt.

night to graze. Repeated movement between resting and feeding sites appears to maintain these narrow channels, despite extremely low current velocities (Skinner & Smithers 1990, Ellery et al. 1991).

Channel margins consist mainly of root stabilized peat (McCarthy et al. 1988a) and are permeable to water. Sediment carried by the channels consists primarily of bedload and suspended load concentration is very low (McCarthy et al. 1991a). Although the channels are sinuous (sinuosities vary from 1.2 to 1.9, mean 1.5), they are very rarely meandering. Note, for example, the exceptionally tight bend west of Dxherega lake (fig. 4), which has not changed position since at least 1937. Deposition of bedload occurs primarily on channel beds (McCarthy et al. 1986; McCarthy et al. 1988a), with only minor point bar formation.

McCarthy et al. (1992a) have drawn a distinction between channels which carry bedload sediment derived from the apex of the fan (termed primary channels) and those which do not (secondary channels). The secondary channels obtain much of their water from primary channels by flow through areas of dense, swamp vegetation, which have appropriately been termed "filters" by Wilson (1973). In the study area (fig. 2), the Nqoga is a primary channel as is that section of the Maunachira

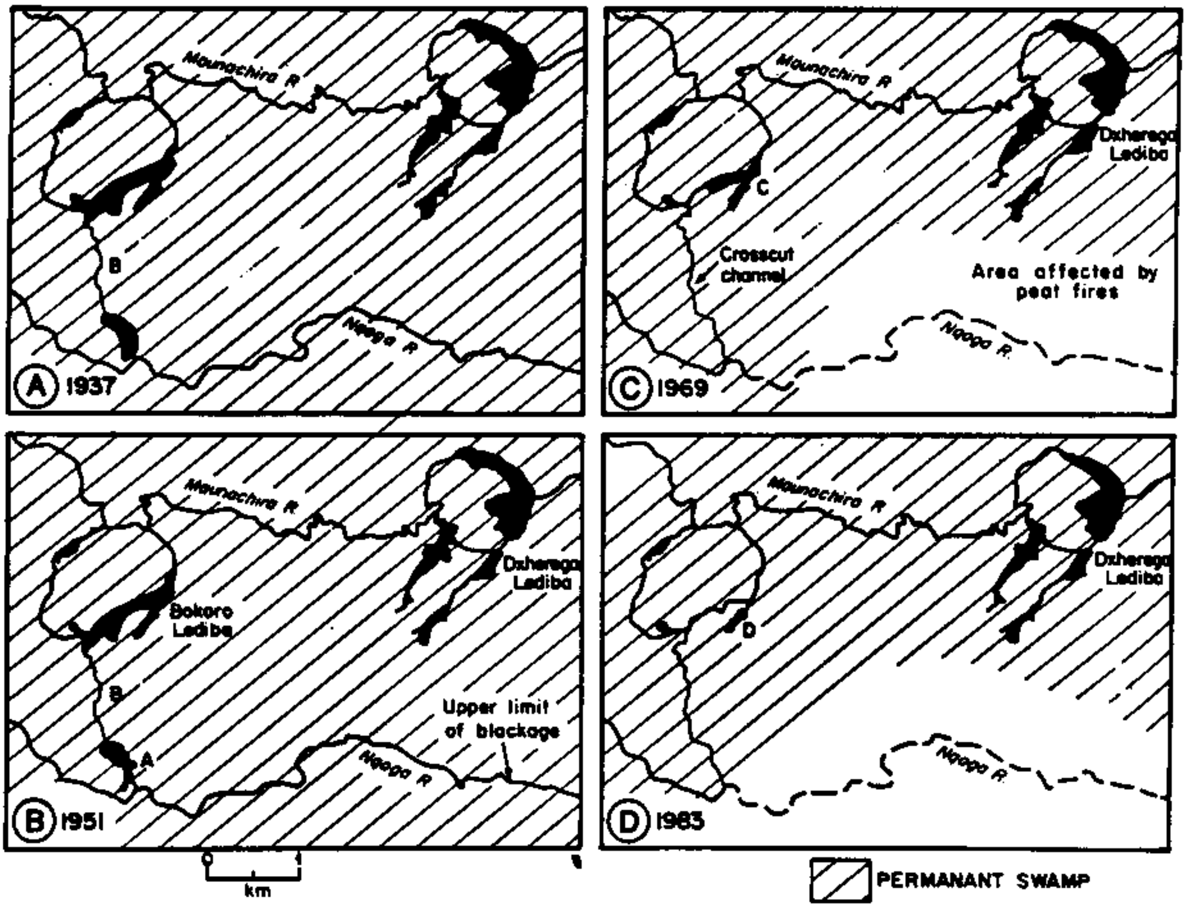

Fig. 5. Sequence of diagrams based on interpretations of aerial photographs showing the diversion of the Nqoga channel into the Maunachira channel, with the consequent closure of lakes.

channel from Dxherega lake to the Nqoga channel. The remainder of the channels in fig. 2 are secondary. The channel reach downstream of Dxherega lake is here classified as secondary because all of the bedload and most of the suspended load of the primary inlet channel is deposited in this lake (McCarthy et al. 1991a).

Primary channels are subject to progressive failure from their distal ends, caused by aggradation and vegetation blockage (McCarthy et al. 1986). This progressive failure is accompanied by headward growth of flanking secondary channels (McCarthy et al. 1992a). As the primary channels fail, the swamp desiccates and organic material is burnt off by peat fires (Ellery et al. 1989). Thus, in the past, the Nqoga channel connected directly to the Mboroga channel (Stigand 1923; Wilson 1972), but progressive abandonment and consequent peat fires have broken this connection. This failure was accompanied by an increase in flow along the more northerly Maunachria channel system (Wilson & Dincer 1976, Smith 1976).

Closure of lakes

The infilling and closure of lakes is closely associated with the evolution of primary channels, as can be seen in fig. 5, which is based on aerial photographs taken in 1937, 1951, 1969 and 1983. The sequence of events depicted in fig. 5 has been discussed elsewhere (Ellery et al. 1993; McCarthy et al. 1992a) and will only be briefly described here. By 1937, the lower Nqoga channel, which had been an important waterway, was failing at its distal end (fig. 5a). As this failure progressed upstream, an increasing quantity of water and sediment was diverted into a small lake adjacent to the channel (A in fig. 5b), by widening of a hippopotamus trail. This lake closed and by 1969 had completely disappeared, to be replaced by a typical channel. The hippo trail connected through to Bokoro lake, which also began to receive increased water and sediment input and by 1969 this lake was substantially reduced in size. By 1983 (fig. 5d), Bokoro lake had also largely disappeared.

Figure 6 shows the outline of Dxherega lake over the period 1951 to 1983. Major changes have occurred in the inlet region of this lake, especially post 1969. In contrast, the outline of the southern section of the lake has hardly changed, and intricate details have persisted. The processes which are operating at the inlet of Dxherega lake presumably also operated to close Bokoro lake and for this reason, Dxherega was studied in detail.

Dxherega lake as a case study of lake closure

a) *Morphology*

Dxherega lake has two inlets, a major one in the north where the Maunachira channel enters the lake and a minor inlet in the south from an adjoining small lake (fig. 4). Profiles across the Maunachira channel upstream of Dxherega, the southern inlet and the outlet are shown in fig. 7. The main inlet channel is approximately 15 m wide with a mean depth of 4 m, while the minor inlet is approximately 8 m wide and 2.2 m deep. Combined discharge of these channels into the lake is 28.3 m^3/s. Seasonal variations are minimal (McCarthy et al. 1992a). The outlet channel is 22 m wide and 6 m deep. Despite the larger size of the outlet, inflow exceeds outflow by 3.1 m^3/s, suggesting that some water leaks from the lake into the surrounding swamps. This is possible because the margins of the lake are identical to those of the channels and are

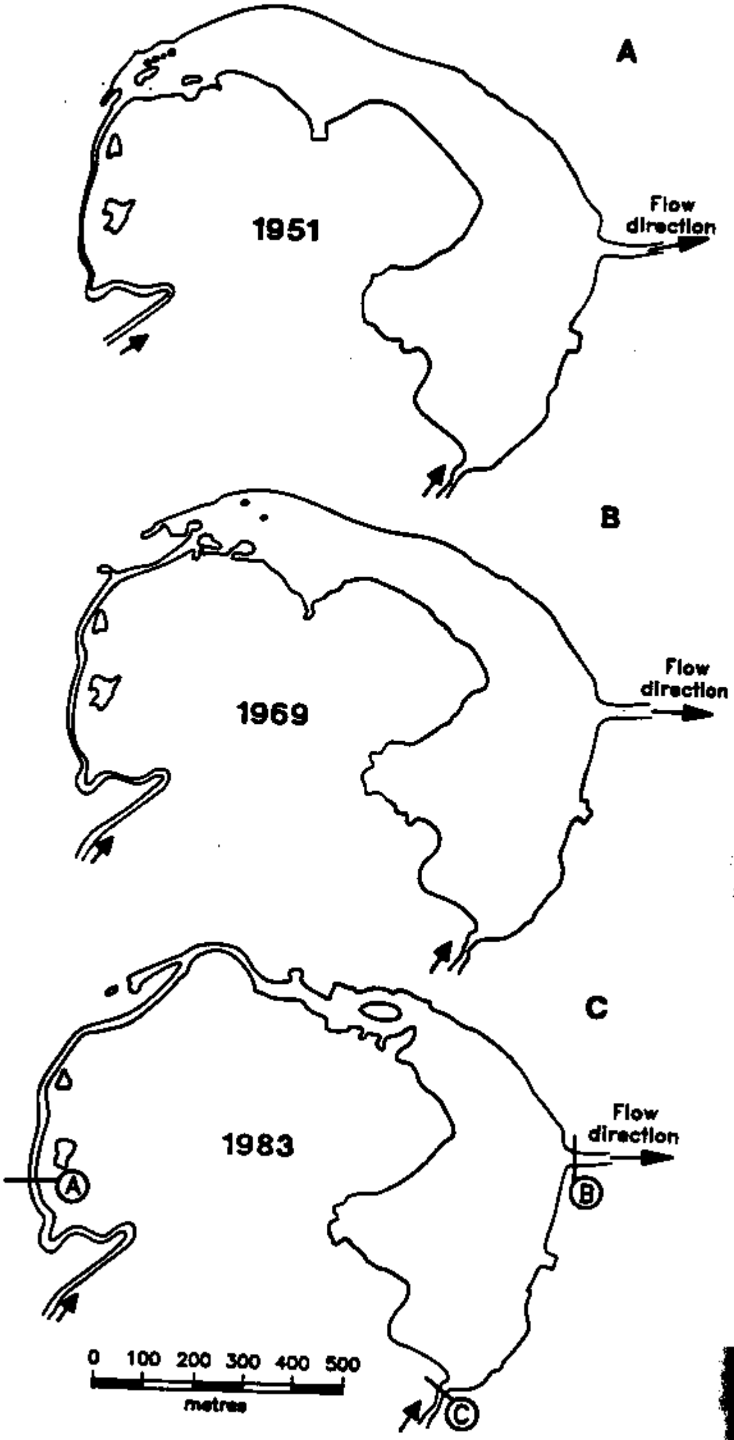

Fig. 6. Outline of Dxherega lake over the period 1951 to 1983.

formed by root stabilized peat and are therefore permeable. The bed of the lake is covered by an organic-rich ooze, which is underlain by a firm sandy substrate. Depths to this substrate are shown in fig. 8. The concave eastern margin of the lake is paralleled by a deep trough, which shallows gradually towards the west but has a relatively steep outer slope. This asymmetric form is typical of a meander bend, with the trough representing the former thalweg (e. g. Bridge & Jarvis 1969), supporting

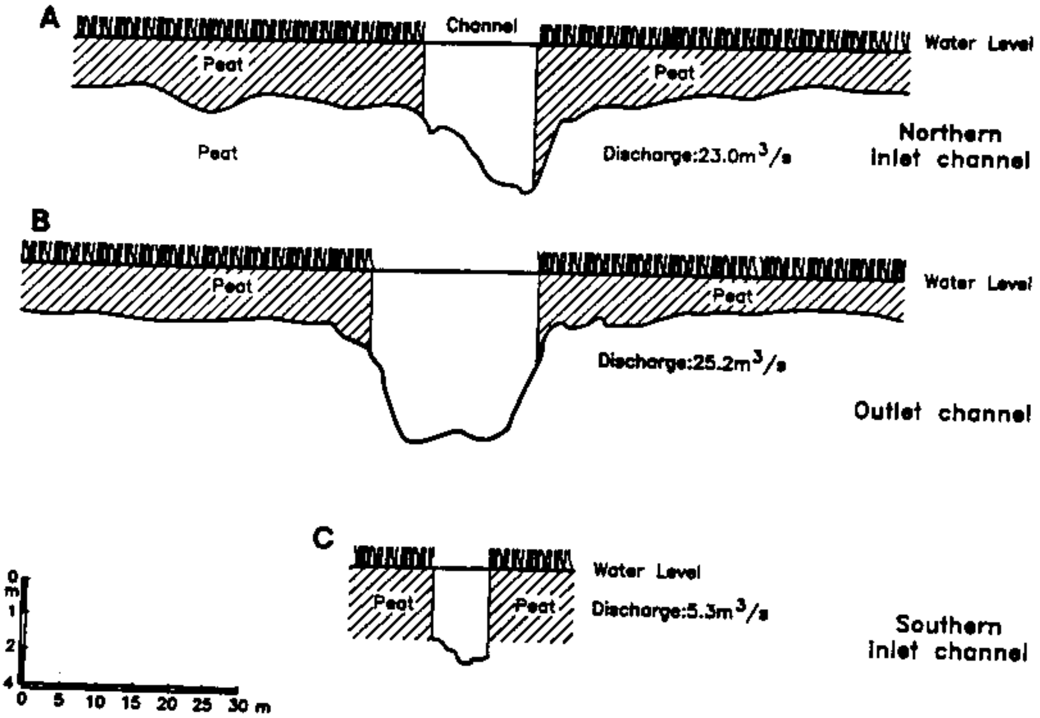

Fig. 7. Profiles across the Manuachira channel upstream of Dxherega lake (a), the outlet of the lake (b) and the southern inlet (c) (Downstream views).

the interpretation of the lake as a former oxbow. The small islands developed near the northern inlet consist of rafts of floating vegetation, while the present outline of the lake is defined by vegetation rooted in peat and only partially reflects the original form of the oxbow. A delta mouthbar developed in the northern inlet area has prograded along the deep, former thalweg of the oxbow.

b) *The major inlet*

Bathymetric profiles across the inlet area are shown in fig. 9. The active channel is flanked and underlain by a mound consisting largely of sand (mean grain size 1.6 phi). In profiles 1 and 3, this as a marked central depression beneath the zone of active flow which is flanked by submerged, shallow vegetated or unvegetated levees. Coring on these levees indicated that they consist of interlayered sand and organic debris with the proportion of sand increasing with depth. Behind these levees are depressions containing organic ooze and peat. These are usually densely vegetated in the upstream profiles, but become less densely vegetated towards the lake. The firm base beneath these marginal depressions defines the original bed of the lake. The central mound may be asymmetric, as in profile 2 (fig. 9), in which case the zone of active flow is flanked by root-stabilized peat on the outer bend and sand on the inner bend. The central depression becomes less pronounced downstream, disappearing completely near the crest of the mouth bar (profile 5, fig. 9). The mouthbar itself is asymmetric (fig. 10) due to deflection of the flow by aquatic vegetation, and is tongue-shaped, tapering into the lake. The bar appears different from the triangular or lunate bars described by Hyne et al. (1979) from a fluvio-lacustrine setting.

Moreover, bedload is spread laterally to a width of only 5 times that of the channel, as opposed to the 10 to 16 times reported by Hyne et al. (1979). The general form of the deposit at the major inlet differs substantially from those described from other lakes eg. Lake Turkana (Frostick & Read 1986) or Lake Brienz (Sturm & Matter 1978).

c) *The lake sediment*

Organic-rich ooze is not confined to the regions behind the levees which flank the channel, but extends over most of the bed of the lake, as shown in fig. 11. The greatest thickness of ooze within the lake occurs in the region ahead of the mouth bar and it is evident that the mouthbar is prograding over this material, and hence must be underlain by it, as indicated in fig. 9. A similar ooze accumulation, albeit thinner, is developed adjacent to the southern, minor inlet. Away from the inlet areas, the layer of ooze is thin, usually less than 30 cm.

Two cores taken in the organic-rich ooze were subjected to chemical and mineralogical analysis. The lowermost samples in each case are enriched in quartz, due to contamination from the substratum and probably also reflecting the effect of wind-borne material. The overlying material contains about 25 per cent (dry weight)

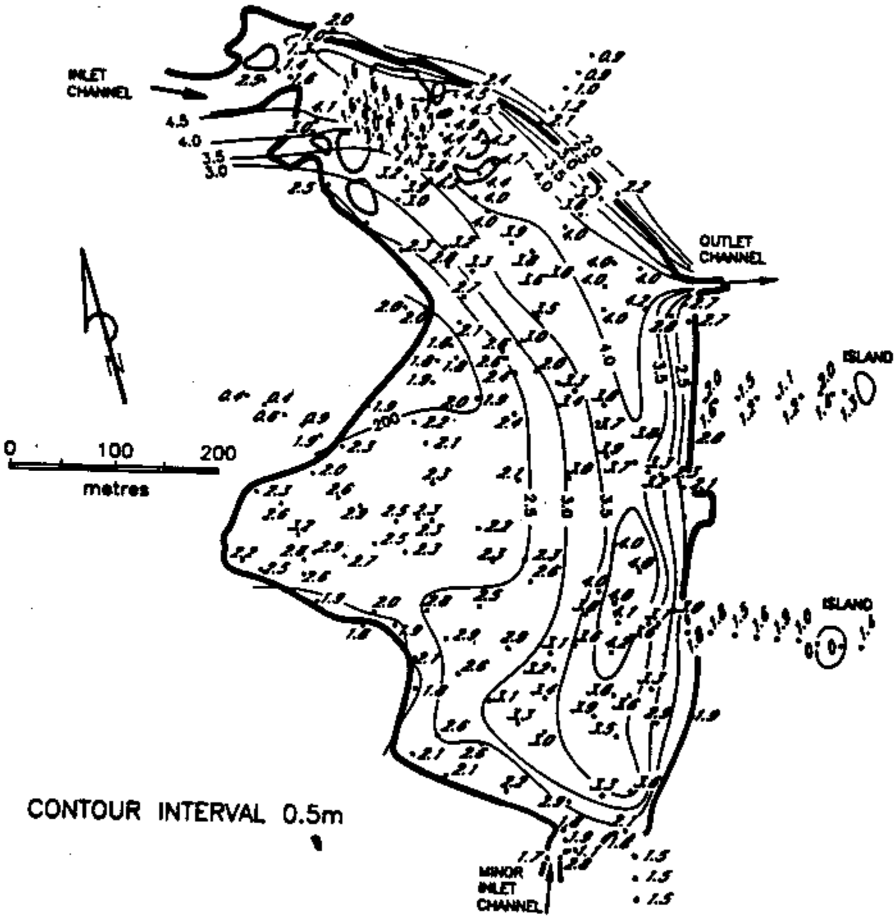

Fig. 8. Map of Dxherega lake showing depth to firm substratum beneath organic-rich ooze which forms the lake bed.

organic matter and the remainder consists of quartz, kaolin, amorphous silica (mainly phytoliths and spicules with some diatoms) and minor illite. There is an increase in alumina and iron content and a decrease in silica with height in these cores, reflecting increase in the detrital clay component during progradation of the delta.

d) *Vegetation in the lake*

The area surrounding the original lake is colonized by a mixed community of *Phragmites australis* and *Cyperus papyrus* (fig. 12), with the latter apparently superceding the former. The southern end of the lake itself is characterized by extensive stands of *Najas pectanatus*, a submerged species which is found typically where water depth

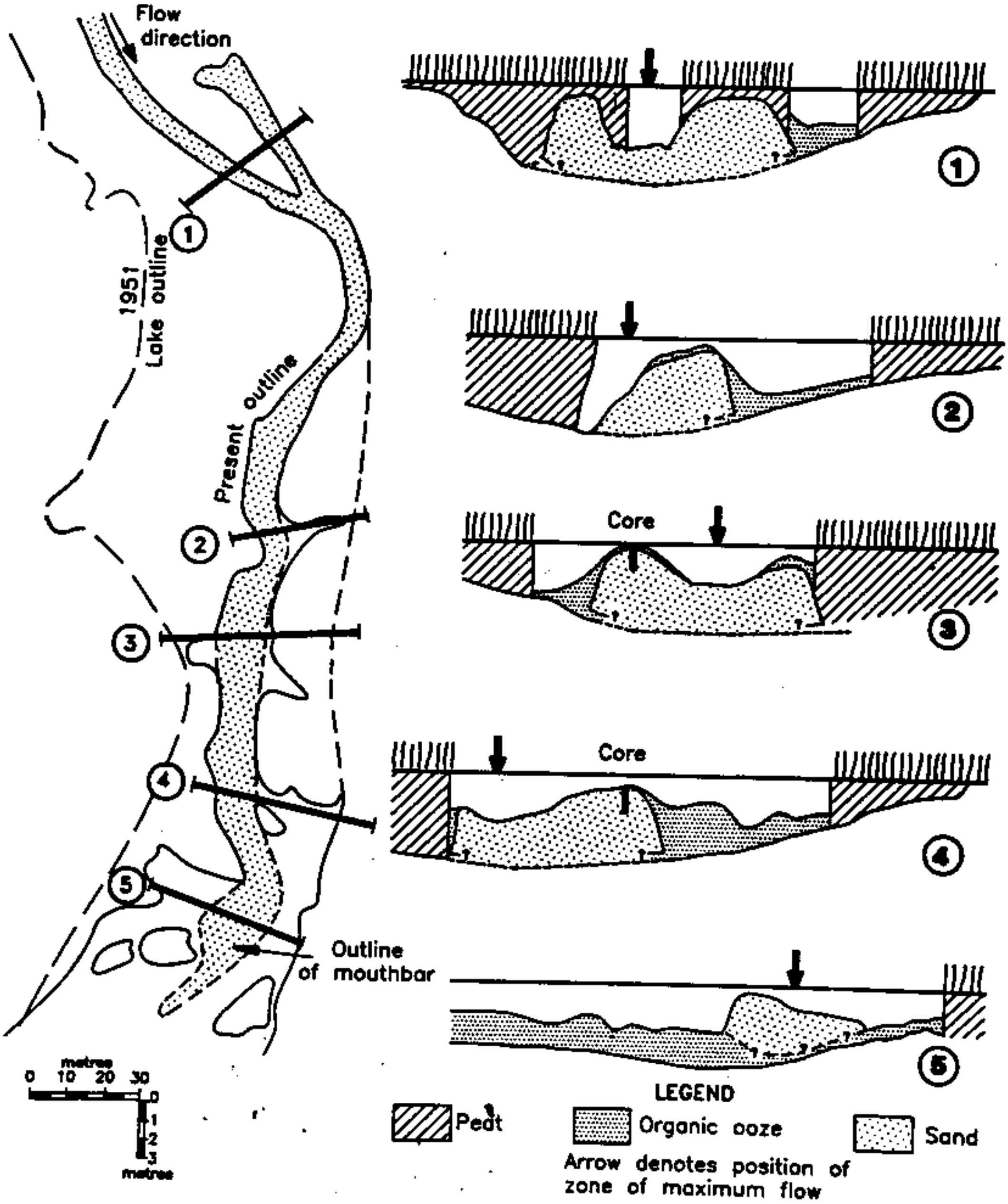

Fig. 9. Detailed map and cross-sectional profiles across the inlet area of Dxherega lake.

exceeds 2 m and where water flow is negligible. In the distal parts of the inlet region, especially adjacent to the region of slightly increased flow, *Trapa natans* (water chestnut) becomes abundant. This species is characteristic of areas of low flow, where organic detrital ooze has accumulated to substantial thickness. *Eichhornia natans* occurs close to the inlet where flow rates are moderate. It exhibits two distinct growth forms: submerged plants have long, linear leaves, whereas plants that reach the surface have leaves which are much smaller, more rounded and bear inflorescences. The distribution of these two growth forms reflects the current velocities of the habitats in which they occur. In areas of faster flow, shoots are unable to reach the water surface and only the submerged growth form is visible.

Vossia cuspidata (hippo grass) grows in luxuriant stands around the margins of the mouthbar and in the deeper water behind the submerged levees flanking the inlet channel. It is a robust, bottom rooted species with long, submerged stems (stolons) that terminate in a cluster of emergent leaves extending up to 0.75 m above the water surface. It is able to withstand relatively high current velocities (ELLERY et al. 1991). In the more proximal areas, this species gives way to *Cyperus papyrus*, especially over deep water areas, and locally to *Miscanthus junceus* on the submerged levees. Papyrus colonizes new areas of the Okavango swamps entirely by vegetative propagation (SMITH 1976, ELLERY 1988). Fragments detached from upstream banks are washed down by the current and become entangled in the robust shoots of *V. cuspidata* at the lake inlet, where they eventually grow into luxuriant stands by vegetative reproduction.

Fig. 10. Aerial photograph of the inlet to Dxherega lake showing the positions of the measured profiles and the mouth bar.

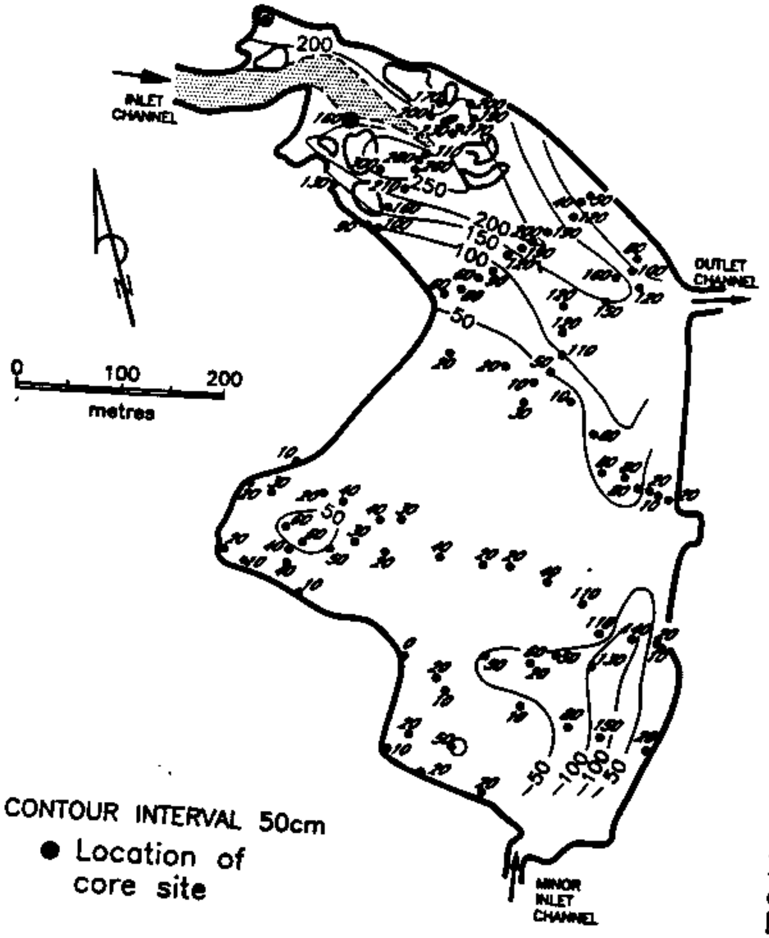

Fig. 11. Map showing the thickness of the organic-rich ooze on the lake bed.

Discussion

The age and origin of the lakes

The meander belt which gave rise to the lakes clearly represents a substantially different hydrological regime to that which exists at present. Channel widths were of the order of 200 m (fig. 3) and assuming 4 m depth and flow velocity of 0.6 m/s (equivalent to the depth and velocity of the Okavango River in the Panhandle region; McCarthy et al. 1991a), the calculated discharge is of the order of 600 m^3/s. Alternatively, discharge can be calculated from meander wavelength using relationships described by Carlston (1965). Typically, half wavelenght is about 1000 m (fig. 3), which yields a mean annual discharge of 592 m^3/s. These estimates are of the same order as present peak discharge of the Okavango River at the head of the Panhandle (McCarthy et al. 1991a). Presently, most of the Okavango River's discharge is lost from the channel system to the surrounding swamps (McCarthy et al. 1991a). The indicated discharge in the meander belt therefore implies substantially greater discharge at the head of the Panhandle during formation of the belt, and hence it must have formed during a period of much higher rainfall than at present.

Early iron age artifacts found on a scroll bar adjacent to Xugana lake have bee tentatively dated at 1070 AD (Huffman, in prep), providing a minimum age for th meander belt, but it is not possible to assign a definite maximum age. Studies o island soils in and adjacent to the meander belt have revealed that outside the belt, th island soils tend to be impregnated with amorphous silica and calcite, as a result o evapotranspiration (which is still taking place); while soils within the belt tend t have little of this material (McCarthy & Metcalfe 1990; McCarthy et al. 1991b McCarthy et al. 1992b). It has been estimated that the accumulation time of calcit in the island soils outside the belt, is of the order of 20000a (McCarthy & Met calfe 1990, McCarthy et al. 1992b), and it is therefore inferred that the meande related islands must be substantially younger than 20000a.

The increased discharge of the Okavango River indicated by the wide channel of the meander belt should be reflected in other geomorphological features of th area, especially the levels of lakes in the distal regions of the fan (currently dry which have been studied in detail by Shaw and co-workers. Their work indicates tw possibly relevant periods of lake high stand, viz. 17000–12000 B.P. and 3000–200 B.P. (Shaw 1985, Shaw & Cooke 1986, Shaw & Thomas 1988). On the basis of th low calcite content of soils on islands related to the meander belt, it seems likely tha the belt formed during the younger of these age ranges.

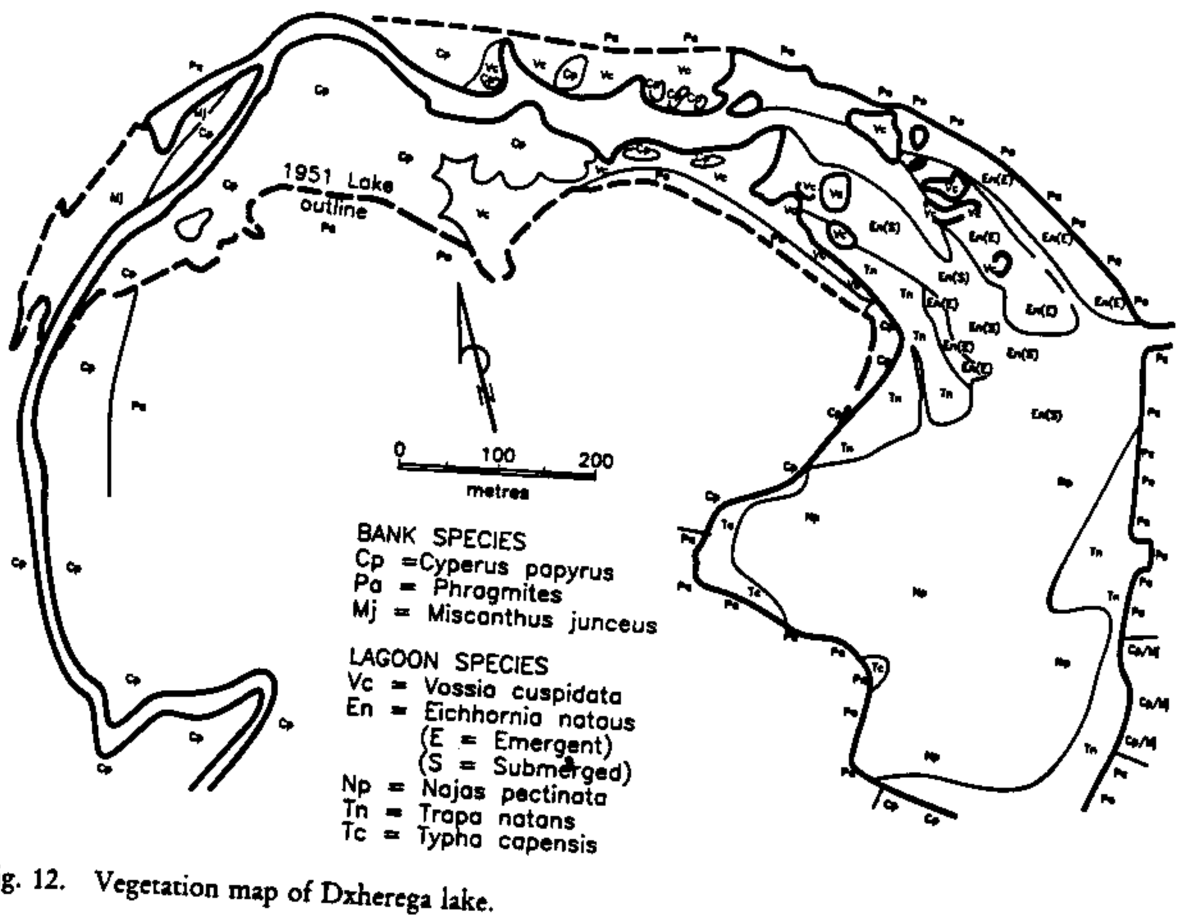

Fig. 12. Vegetation map of Dxherega lake.

The origin of the meander belt is not solely due to increased discharge. Based on studies of channel morphology and sediment dispersal of the Okavango River in the Panhandle, McCarthy et al. (1991a) concluded that this river forms a meander belt which periodically progrades out onto the fan. These episodes are interrupted by avulsion, possibly involving neotectonic activity, which causes a reorganization of the distributary system. It seems likely that the meander belt in the study area formed during such a period of advanced progradation of the meander belt.

The presently active, narrow channel system developed during the latter part of the 19th century (Stigand 1923), coincident with the failure of the Thaoge meander belt on the western section of the fan (fig. 1). It appears to represent a transitory state, characerized by erosive and depositional reaches (McCarthy et al. 1991a),

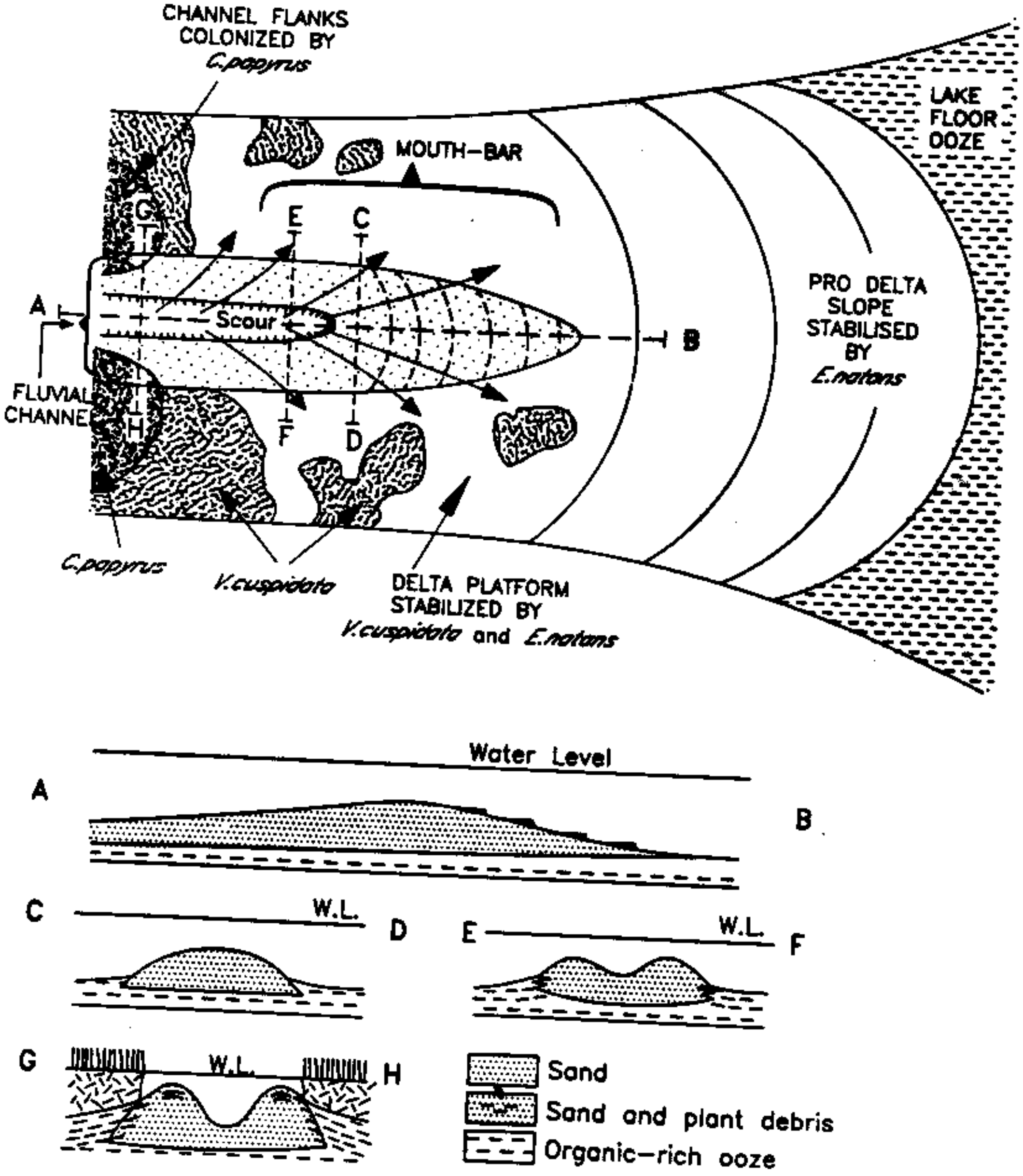

Fig. 13. Schematic diagrams showing the features of the mouthbar and channel at the lake inlet.

reflecting reorganization following an avulsion from the Thaoge channel system. It is unrelated to the older meander belt which gave rise to the depressions now occupied by lakes.

The relationships between channels and lakes

The modern channels are superimposed on the older meander belt, which in general appears to constitute a slight topographic high relative to the surrounding swampland, as scroll and point bars and other channel features form islands within this belt. Old oxbow depressions along the belt have given rise to lakes within the swamp. Although the modern channel system largely skirts the meander belt, occasional incursions are made into the belt which often involve the entry of channels into lakes (e.g. fig. 5). Studies of the avulsion process have revealed the reason for this (McCarthy et al. 1992a). Failure of a primary channel is associated with rapid vertical aggradation (5 cm/a), accompanied by a concomitant rise in water level (McCarthy et al. 1992a). This results in the diversion of flow into hippopotamus trails leading from the failing channel, which often lead directly to lakes, as shown in fig. 5.

The role of sedimentation processes in lake closure

The distribution of organic ooze on the bed of Dxherega lake (fig. 11) provides an indication of the relative importance of allochthonous and autochthonous ooze in lake filling. Greatest thickness of ooze occurs adjacent to the major inlet, where it forms a fan shaped wedge distal to the mouth bar. A similar, but thinner, accumulation occurs distal to the southern inlet. The positioning of these accumulations suggest that both represent largely allochthonous material. Accumulation in the south western section of the lake, away from inlet areas must represent mainly autochthonous material and these rarely exceed 30 cm. The rate of accumulation of allochthonous material is therefore clearly much faster than of autochthonous material.

Entry of a channel into a lake would appear to increase the rate of supply of fine allochthonous detritus and hence accelerate the rate of accumulation of the ooze. However, the present study shows that this is not sufficient to bring about accelerated closure, as is indicated, for example, by comparison of Dxherega and Gadikwe lakes. Rapid closure only occurs when a primary channel carrying sediment derived from the fan appex, enters the lake. It appears therefore that the introduction of inorganic detritus is an essential element in the events leading to lake closure.

Bedload is deposited by the inflowing channel in the form of a tongue-shaped mouth bar, shallowing and widening proximally (fig. 10). Flow is deflected by anchored, emergent vegetation causing the bar to follow a sinuous path in its advance into the lake (fig. 9), and also resulting in asymmetry in the bar form.

The morphology of the mouth bar is shown schematically in fig. 13. The bar increases in width and height from its distal end. Bedload is carried across the bar as ripples on the backs of sand waves. As the bar progrades and flanking areas are colonized by plants, a trough is scoured into the crest. Sand and organic debris which are washed oblique to the central flow accumulate as levees on either side of the trough. These become progressively higher with time, almost reaching the water surface. Very fine detritus and plant debris is transported over these levees and accumulates as a layer of organic-rich ooze in the backwater areas. As the mouth bar progrades, the lake closes, but it is evident that the fill, on a volumetric basis, consists mainly of plant material rather than clastic sediment. *E. natans, V. cuspidata* and *C. papyrus* are key species in this process, moderating flow conditions and reducing turbulence and hence oxidative decomposition of organic detritus in backwater areas.

The role of vegetation processes in lake closure

The spatial distribution of plant species in Dxherega lake indicates the temporal vegetation succession that appears to accompany closure. Initially, much of the lake would have been colonized by a monospecific stand of *N. pectinata*, and in the vicinity of the mouth, *T. natans* would have existed. The increase in sediment and vegetation debris entering Dxherega after closure of Bokoro lake appears to have resulted in an explosion of *E. natans* around the zone of active flow, of *V. cuspidata* in the area close to the inlet and around the prograding mouth bar and of *C. papyrus* immediately flanking the mouth bar itself.

The introduction of sediment from the fan apex into Dxherega is considered to promote plant growth by increasing nutrient supply. Papyrus growth flanking primary channels, which are relatively nutrient rich, is far more luxuriant than elsewhere (McCarthy et al. 1992a). Dxherega lake is currently the first lake to occur along the Okavango-Nqoga-Maunachira distributary channel system and is the final depository for sediment introduced onto the fan. The deposition of fine clays with a high cation exchange capacity in the lake would tend to promote plant growth and would explain the invasion of the inlet by *E. natans, V. cuspidata* and papyrus subsequent to the closure of Bokoro lake.

Furthermore, it would appear that the presence of dense stands of bottom rooted, floating leaved or emergent species would promote sedimentation of organic and clastic fines in the region of the inlet. This would be achieved by reducing current velocity as well as by reducing the effects of environmental factors acting on the water surface such as wind, which would reduce mixing and decomposition of organic detritus (Wetzel 1983). Plant species would in this way alter the environment, facilitating the establishment of later colonizers in the vegetation succession that accompanies lake closure.

Both *V. cuspidata* and papyrus reproduce vegetatively and are brought into Dxherega by channels from further upstream. Shoots of *V. cuspidata* become entangled in stands of *E. natans* and rapidly become rooted. Once established, this species reproduces vegetatively, rapidly colonizing the area around the initial nucleus. The circular or lobate shapes characteristic of stands of this species around the inlet of Dxherega indicate this pattern of colonization. Similarly, *C. papyrus* colonizes new areas by entrapment of floating rhizome fragments in stands of *V. cuspidata* and hence also forms circular or lobate stands. Both of these species appear to be dependent on their predecessors for colonization and eventually out compete them by shading them out. This is suggested by their distribution in the lake inlet, with papyrus more proximal than *V. cuspidata*. The final stage of the vegetative succession in a closing lake which is fed by a primary channel is therefore papyrus swamp.

In contrast to this sequence of events occurring around the northern inlet of Dxherega lake, the southern section has remained virtually unchanged. Although

C. papyrus grows along the southern margin of the lake, the plants appear small and moribund, in contrast to the vigorous growth of papyrus around the inlet. *Vossia cuspidata* is altogether absent from the distal areas. The poor performance of these two species away from the inlet probably reflects nutrient availability. Hence the lake outline changes very slowly in areas remote from the inlet.

During progradation of the mouth bar and the development of the flanking papyrus swamp, segments of the lake may be bypassed and left without vegetation cover. This has occurred near the original inlet of Dxherega lake, on its northern margin. Eventually, these become completely isolated, as can be seen in the case of Bokoro lake (D in fig. 5). Lake areas by-passed in this way persist for considerable periods.

In contrast to the events in lakes fed by primary channels, closure of open water bodies is the distal reaches such as Xakanaxa lake is slower, and the processes, which have been described by ELLERY et al. (1990), are different. Here, the dominant process is the colonization of free floating or partly attached, floating mats of accumulated autochthonous organic detritus. In the distal areas of the swamp studied by ELLERY et al. (1990), the sedge *Pycreus nitidus* is the most important colonizer, but in lakes in the upper fan, *C. papyrus* has been observed as the dominant species on floating islands (CHILD & SHAW 1990).

Regional distribution of lakes

Lakes within the upper reaches of the study area have been affected by the failure of the lower Nqoga channel and several have been partly or completely closed. Lakes in the distal portion of the study area, in contrast, have not been exposed to the influence of primary channels and can only fill by the slower accumulation of allochthonous material (ELLERY et al. 1990): It is evidently for this reason that the lakes are larger and occur more frequently in this region of the study area. Moreover, available nutrient supply presumably decreases downstream, leading to decreased productivity. Probably for this reason even shallow water bodies outside the meander belt, such as Xakanaxa lake, have persisted.

Conclusions

As part of the normal evolution of the Okavango fan, meander belts prograde from the Panhandle region onto the fan. Two such progradations have been-recognized: one in the present study area and the second in the presently failing Thaoge channel system (MCCARTHY et al. 1991a). These events are interrupted by avulsions, induced either by aggradation of the meander belt or by neotectonic activity, which leads to a reorganization of the distributary system.

Most of the lakes in the study area developed in the abandoned depressions of former oxbow lakes which formed in a meander belt which appears to have been active around 3000 to 2000a B.P., at a time which was characterized by much higher discharge than at present. This resulted in wide channels and hence large oxbow lakes. Minor lakes have also developed by flooding of the areas adjacent to the meander ridge. Another meander belt had developed down the western side of the fan (the Thaoge) prior to the early 19th century. Avulsion in the mid 19th century led to the demise of this system and a reorganization of the distributaries, which produced the present Nqoga-Maunachira channel system. This new system invaded and reflooded an older meander belt, producing the lakes.

The lakes have been filling slowly by the accumulation of autochthonous organic material and more rapidly when allochthonous detritus has been introduced. This study has shown, however, that the inflow of channels which carry sediment derived from the fan apex is the most important factor in inducing accelerated closure of the lakes. This is partly due to the introduction of sediment, but equally important is the vegetation successional sequence which is brought into play by these primary channels, possibly because of the enhanced nutrient status of the water. The plants are important because on a volumetric basis, they contribute more to the filling of the lakes than the clastic sediment component.

The closure of lakes is closely allied to the evolution of the primary channels. These channels are subject to progressive failure from their distal ends, during which rapid vertical aggradation takes place. This diverts flow into lateral distributaries. Most important in this regard are hippopotamus trails which interconnect channels and lakes. It is in this way that primary channels are diverted into lakes. As a result of this process, the lake is replaced by a channel flanked by densely vegetated swamp. During progressive closure, distal parts of lakes may be by-passed, creating isolated open water bodies. Deprived of clastic sediment and nutrient-rich water, these remain open for long periods. It is likely that the numerous small, irregular shaped lakes in the upper reaches of the permanent swamps represent such remnants.

This study has shown that the evolution of the lakes in the Okavango swamps is controlled by complex interplay involving water, sediment, vegetation and animals. While the driving agent is water and its sediment load, biota play a pivotal role in the distribution of water and sediment and in the final closure of the lakes.

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Address of the authors: T. S. McCarthy, W. N. Ellery, L. G. Stanistreet, Departments of Geology and Botany, University of the Witwatersrand, P.O. Wits, Johannesburg 2050, South Africa.