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The gradient of the Okavango fan, Botswana, and its sedimentological and tectonic implications

T. S. MCCARTHY,[1] M. BARRY,[2] A. BLOEM,[1, 5] W. N. ELLERY,[3]
H. HEISTER,[4] C. L. MERRY,[2] H. RÜTHER[2] and H. STERNBERG[4]
[1]Department of Geology, University of the Witwatersrand, PO Wits,
Johannesburg, 2050, South Africa
[2]Department of Surveying and Geodetic Engineering, University of Cape Town,
Private Bag, Rondebosch 7700, South Africa
[3]Department of Geographical and Environmental Sciences, University of Natal,
King George V Avenue, Durban, 4001 South Africa
[4]Institüte für Geodasie, Universität der Bundeswehr Munchen,
D-85577 Neubiberg, Germany

Abstract—The Okavango alluvial fan of northern Botswana supports the largest wetland in southern Africa (*ca* 25,000 km^2). It is situated in a tectonically active extension of the East African Rift system. Only limited topographic information is available in the area because of its remoteness. The water surface gradient down the axis of the wetland was measured using a differential Global Positioning System. Two discrete gradients occur: 1:5570 on the upper, confined flood plain, and 1:3400 on the lower, unconfined alluvial fan, with a slight downstream steepening of gradient on the fan. The change in gradient is a consequence of the loss of confinement of the seasonal flood water. Historical records indicate that distributary channels are able to meander at both gradients. Gross fluvial characteristics may mainly depend on bedload. The regional gradient on the fan represents a balance between clastic sedimentation on the proximal fan and chemical sedimentation on the distal fan. Although a distributary channel system occurs down the central axis of the fan, it is presently poorly developed, because of low sediment load, with much of the water dispersal occuring by overland flow, forming extensive wetlands. The regional gradients show local, small scale perturbations and satellite images and aerial photographs indicate that these are associated with lineaments representing active faults. Changes in channel character are associated with these faults and emphasise the sensitivity of the fluvial system to subtle changes in gradient. *© 1997 Elsevier Science Limited.*

Résumé—Le cône alluvial de l'Okavango dans le nord du Botswana correspond à la plus vaste étendue de marécages de l'Afrique australe (*ca* 25.000 km^2). Il se trouve dans un prolongement tectoniquement actif du système du Rift de l'Afrique Orientale. Suite à son isolement, il n'existe que peu d'informations topographiques sur la région. A l'aide d'un GPS différentiel, le gradient de la surface des eaux le long de la zone axiale des marécages a été mesuré. Deux gradients discrets s'observent: 1:5570 dans la partie amont confinée de la plaine d'inondation et 1:3400 dans la partie aval non-confinée du cône alluvial, avec au niveau du cône une faible augmentation de gradient vers l'aval. Les variations de gradient résultent de la disparition du confinement des crues saisonnières. Des relevés historiques montrent que les chenaux de distribution des eaux peuvent développer des méandres dans les deux cas. Les caractéristiques fluviales générales peuvent dépendre principalement de la charge des eaux. Dans le cône, le gradient régional correspond à un équilibre entre une sédimentation clastique de cône proximal et chimique de cône distal. Quoiqu'un

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[5]Permanent address: Mappa Remote Sensing (Pty) Ltd, PO Box 62269, Marshalltown 2107, South Africa

système de chenaux distributeurs existe le long de l'axe central du cône, celui-ci n'est que faiblement développé à ce jour suite aux charges sédimentaires limitées. En fait, l'essentiel de la dispersion des eaux se fait par inondation des terres, à l'origine des vastes marécages. Les gradients régionaux montrent des perturbations locales de faible amplitude. Les images satellite et les photos aériennes indiquent que celles-ci se marquent à hauteur de linéaments correspondant à des failles actives. Des modifications des caractéristiques des chenaux sont associées à ces failles et soulignent la sensibilité du système fluvial à des changements de gradient subtils.

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INTRODUCTION

The long term conservation of wetland ecosystems depends on a comprehensive understanding of their hydrology, biology, sedimentology and geomorphology. Topographic information forms an essential data set for all of these disciplines, but has been very difficult to acquire, especially in large, remote wetlands. The Okavango alluvial fan, a unique wetland situated in northern Botswana, is a case in point. Conventional surveying is almost impossible in the Okavango, because of the remoteness of the area, the low relief, the high density of vegetation and the extensive development of swamps. Only eight survey beacons have been established in the wetlands of the Okavango, in an area of some 25,000 km^2. All of these are confined to Chief's Island, a tract of higher ground extending up the centre of the fan (Fig.1). However, the western margin of the fan is more accessible and more populated, and surveys have extended via this route to the apex of the Panhandle region, providing information on the relative elevations across the fan.

The development of the Global Positioning System (GPS) and especially the differential GPS, has made it possible to establish, with high precision, the relative heights of points in the absence of line-of-sight communication. This technique was used to measure the water surface elevation down the axis of the fan, an undertaking not previously possible. This was supplemented by hydrological measurements, aerial photographs and satellite imagery to provide a spatial perspective. Knowledge of the water surface gradient provides an insight into several important aspects of the functioning of this wetland, namely response to local tectonism, causes of changes in channel morphology, local water dispersal patterns and the relative contributions of different sedimentation processes to the overall aggradation of the fan and to the general functioning of the wetland ecosystem.

METHODOLOGY

GPS Survey

The survey was carried out down the length of the fan along the Okavango, Nqoga, Jao and Boro distributary channels (Fig. 1). Stations were selected on elevated land, usually small islands on the flood plain. A 1.5 m steel stake was hammered into the ground at each site to serve as a survey monument. The water level at each site was measured relative to the monument using conventional survey techniques.

Five dual frequency GPS receivers (Leica Wild GPS-System 200) were used for the survey; one of these was set up as a continuously operating reference station at Jedibe, while the remaining four occupied sites sequentially along the route for a minimum of two hours at each site. Redundant measurements were made so as to provide a check on the results. Altogether, 27 stations were observed, of which 20 were distributed within the delta. From all the simultaneously sampled GPS-data, 109 baselines could be derived, with an average length of 14.5 km. The measurements were processed using two different software systems. An excellent agreement between the two sets of results was obtained (RMS fit of 5 mm, Merry 1995a) and the final ellipsoidal co-ordinates (WGS84) yielded a standard deviation in position Sp = 5 mm and in height SH = 14 mm.

Unfortunately, GPS provides height or height differences with respect to a mathematical reference frame ellipsoid defined by the World Geodetic System 1984 (WGS84). For the purposes of determining water gradients it is essential that the heights are referred to a level surface — the geoid. Geoidal height corrections were obtained from a tailored geoid model (Merry 1995b) and applied to the data. A comparison with three points of known geoidal height indicates an accuracy of approximately 5 cm for the water surface elevations.

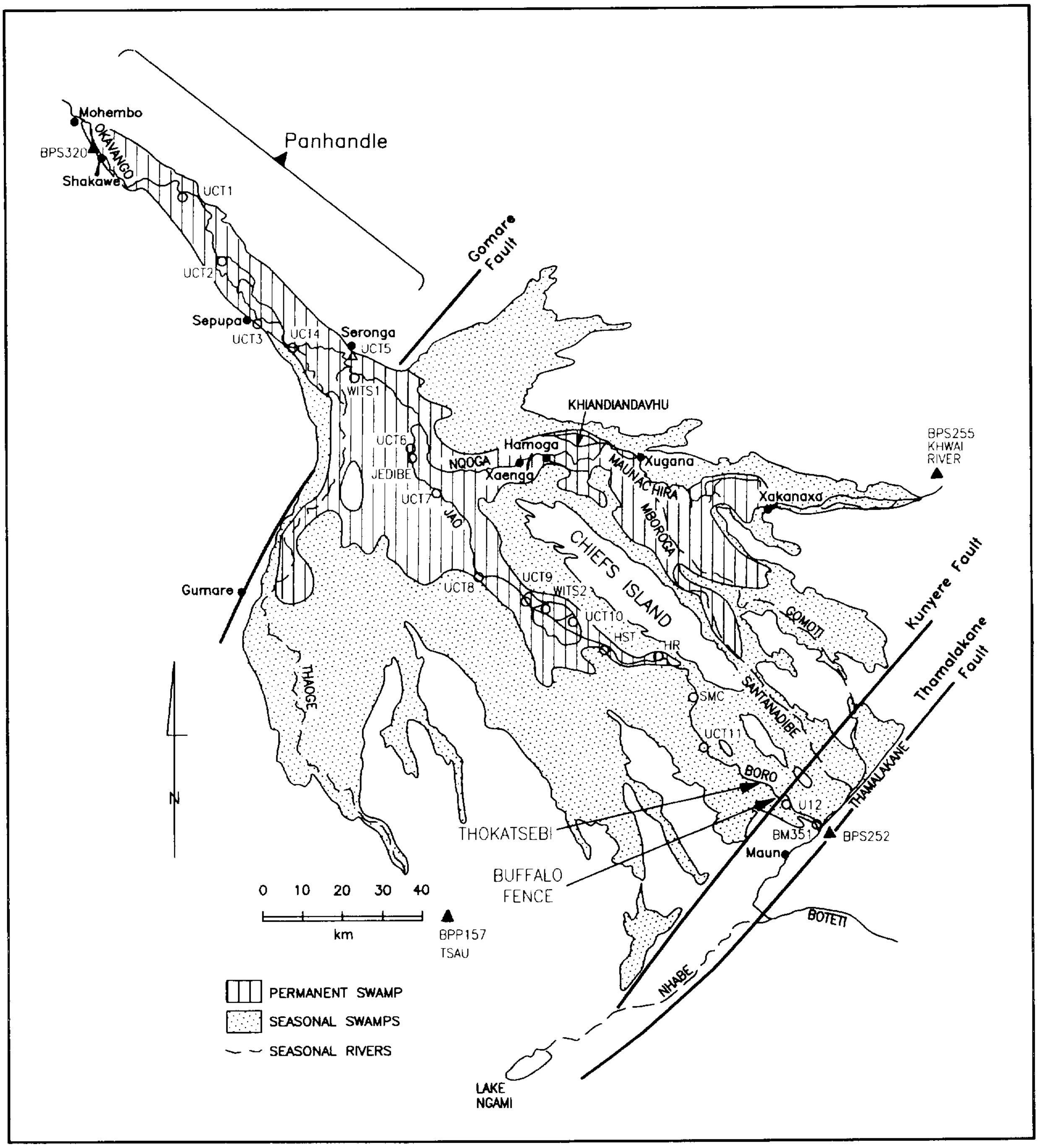


Figure 1. *The Okavango fan, showing the locations of the survey sites.*

Channel characteristics

At selected survey sites the dimensions of the channel and discharge were measured using techniques described by McCarthy *et al.* (1991). Turbidity was measured on site with a portable turbidity meter.

Satellite imagery

The Advanced Very High Resolution Radiometer (AVHRR) on-board the NOAA-11 (National Oceanic and Atmospheric Administration) Polar Orbiting Environmental Satellite provides daily synoptic Earth observations at various wavelengths. The AVHRR has five bands of data: channel 1 (0.58-0.68 mm; visible green); channel 2 (0.725-1.05 mm; near infrared); channel 3 (3.55-3.92 mm; hybrid of reflected and emitted thermal infrared [TIR]); channel 4 (10.3-11.3 mm; TIR); and channel 5 (11.5-12.5 mm; TIR). Relative radiant temperature differences

Table 1. Survey data

	Latitude (South) day min sec	Longitude (East) day min sec	Location	Land elevation (m)	Water level (m)	Distance from Shakawe (km)
BPS320	-18 21 56.8821	21 50 43.2841	Shakawe	999.70	991.69	0.0
UCT-1	-18 27 29.5535	22 2 1.1007	bef.Red Cliff	988.19	987.74	22.4
UCT-2	-18 35 39.3737	22 7 7.1568	Phillipo	988.47	984.97	38.4
UCT-3	-18 44 40.5714	22 11 48.2579	Wenela 1	981.54	980.99	56.0
UCT-4	-18 48 57.1681	22 17 22.4089	Wenela 2	980.53	979.05	68.4
UCT-5	-18 49 14.3552	22 24 57.9456	Seronga	984.13	977.31	78.5
WITS-1	-18 52 41.4616	22 25 43.8261	bef.Clover Leaf	977.39	976.67	83.7
UCT-6	-19 2 9.9830	22 33 37.7785	Kwihum	972.24	971.75	105.8
Ref-Jed	-19 3 20.8454	22 33 4.6494	Jedibe	972.45	971.31	106.7
UCT-7	-19 7 58.7883	22 36 59.5595	Matsupatsela	968.77	-	117.6
UCT-8	19 19 46.6661	22 42 33.3957	Txichira	962.28	961.83	140.3
UCT-9	-19 23 7.4290	22 49 22.5739	Palm Tree	959.16	958.51	152.8
WITS-2	-19 24 55.3385	22 51 53.9431	bef. Chao	957.44	956.98	158.3
UCT-10	-19 26 12.3335	22 55 56.3202	Chao	955.41	954.10	164.9
HST	-19 30 6.1087	23 0 16.0500	Xakue	952.07	951.54	175.3
HR	-19 32 9.7166	23 7 35.6719	Moomo	949.61	948.04	187.1
SMC	-19 37 33.7226	23 12 37.6227	Mporota	945.62	944.32	200.4
UCT-11	-19 44 0.6411	23 14 38.9450	Collins Zebra	943.31	940.72	211.2
UCT-12	-19 51 40.6588	23 26 6.4856	Boro Landing	936.10	935.17	235.5
BM351	-19 54 57.2680	23 30 47.4467	Boro junction	933.33	931.77	245.5
BPP084	-19 58 25.2126	23 26 0.8494	Maun	946.40	-	-

between quartz sands and water of the Okavango swamps peak pre-dawn and post-noon in the TIR (channels 4 and 5 and, to a lesser extent, channel 3). The radiant temperature contrast between water and quartz sands enables the mapping of the water in the Okavango fan. AVHRR data from NOAA-11 were acquired on the mid-day descending trajectory on the 8th of March, 7th of May and 7th of August during 1992. The dimensionality of the data for channels 3, 4 and 5 (10-bit, High Resolution Picture Transmission) were reduced using Principal Components Analysis (Kaneko, 1978). For all three data acquisitions, the first component explained more than 98% of the input variance. In the representations used in this study, low values (dark) are relatively cool radiant temperatures while high values (light) are warm.

The Landsat-5 Multi-spectral Scanner (MSS) has three bands of data in the visible and one in the near infrared (NIR) portion of the electromagnetic spectrum (band 4 from 0.5-0.6 mm, band 5 from 0.6-0.7 mm, band 6 from 0.7-0.8 mm and band 7 from 0.8-1.1 mm). Data (World Reference System: path 175, row 74) acquired on the 11th of November 1989 were processed using the tasselled cap transformation (Kauth and Thomas, 1976). This orthogonal transformation converts four MSS bands into vegetation and soil brightness indices. The soil brightness index (SBI) easily distinguishes clear water (low values, dark) from increasingly dry soils (high values, light).

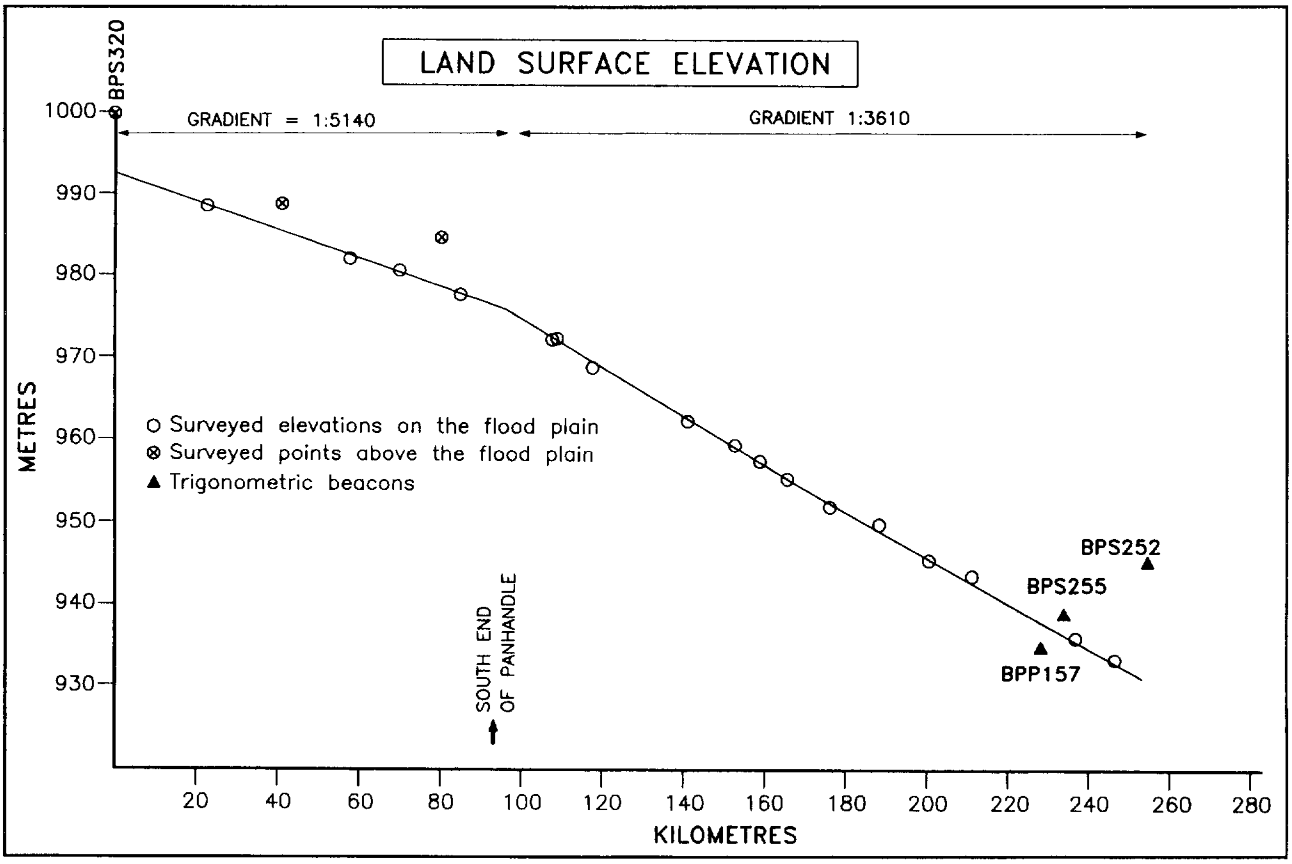
These data (AVHRR and MSS) were geometrically corrected to the Universal Transverse Mercator projection (zone 34, Clark 1880 spheroid) and re-sampled to a ground resolution of 1.1 km and 82 m, respectively.

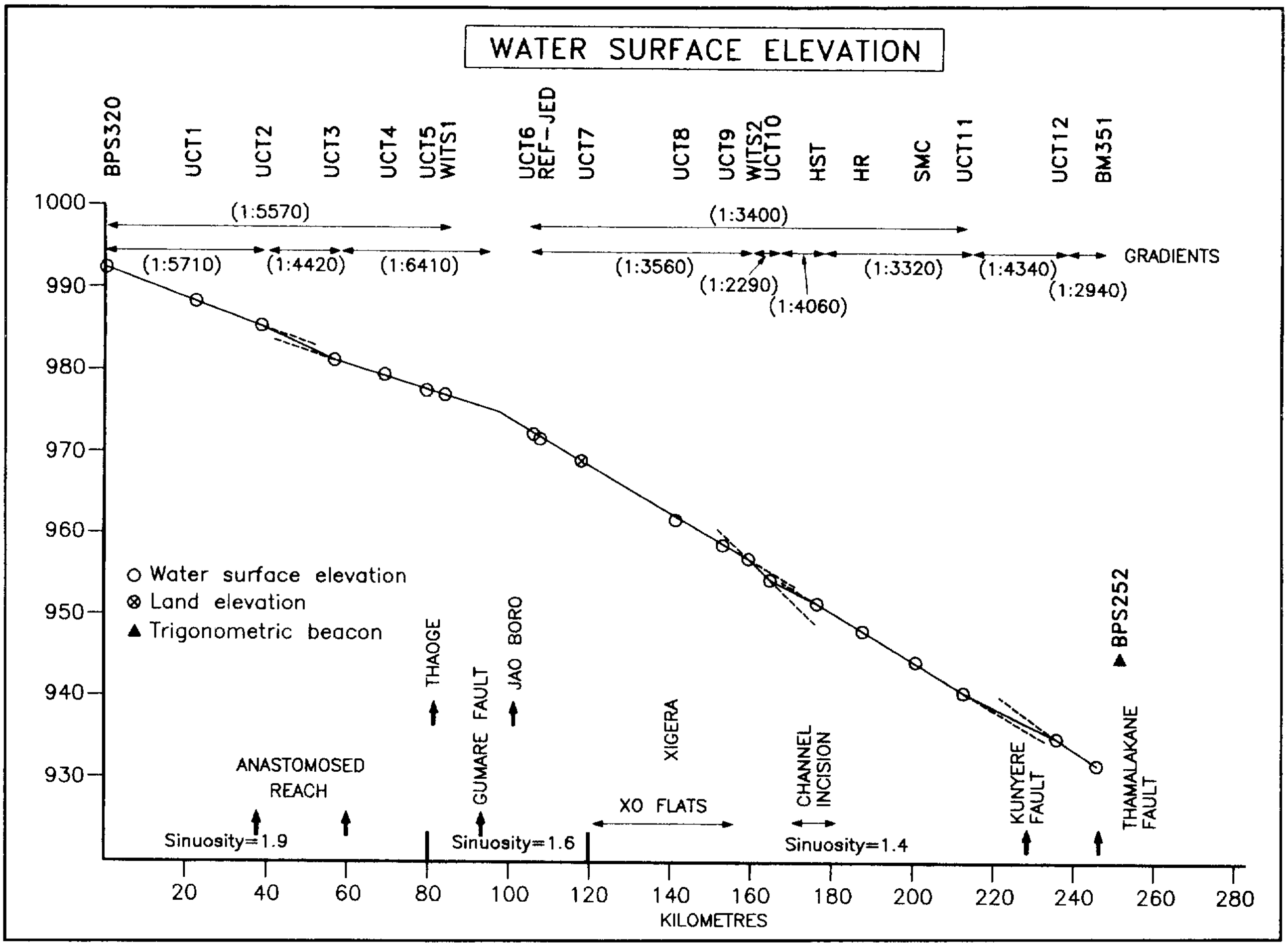
RESULTS

Topographic elevation

The results of the topographic survey are listed in Table 1 and are plotted as a function of linear distance from station BPS320 in Fig. 2. The land surface profile (Fig. 2a) is irregular, especially in the upper reaches where several stations were established above the level of the floodplain. If only elevations on the floodplain are considered, two distinct slopes are evident: the Panhandle region, with a mean slope of 1:5140; and the fan, with a mean slope of 1:3610. The southern end of the fan is defined by the 12 m scarp of the Thamalakane Fault, as indicated by the elevation of BPS252, which is located on the upthrown side of the fault. The elevations of trigonometric beacons at Tsau (BPP157) and the

Figure 2. *(a) Land and (b) water surface elevations down the axis of the fan.*


LAND SURFACE ELEVATION
BPS320
GRADIENT = 1:5140
GRADIENT 1:3610
METRES
1000
990
980
970
960
950
940
930
○ Surveyed elevations on the flood plain
⊗ Surveyed points above the flood plain
▲ Trigonometric beacons
SOUTH END OF PANHANDLE
BPS252
BPS255
BPP157
20
40
60
80
100
120
140
160
180
200
220
240
260
280
KILOMETRES


WATER SURFACE ELEVATION
BPS320
UCT1
UCT2
UCT3
UCT4
UCT5
WITS1
UCT6
REF-JED
UCT7
UCT8
UCT9
WITS2
UCT10
HST
HR
SMC
UCT11
UCT12
BM351
(1:5570)
(1:3400)
(1:5710)
(1:4420)
(1:6410)
(1:3560)
(1:2290)
(1:4060)
(1:3320)
(1:4340)
(1:2940)
GRADIENTS
1000
990
980
970
960
950
940
930
○ Water surface elevation
⊗ Land elevation
▲ Trigonometric beacon
THAOGE
GUMARE FAULT
JAO BORO
XIGERA
CHANNEL INCISION
KUNYERE FAULT
THAMALAKANE FAULT
BPS252
ANASTOMOSED REACH
Sinuosity=1.9
Sinuosity=1.6
XO FLATS
Sinuosity=1.4
20
40
60
80
100
120
140
160
180
200
220
240
260
280
KILOMETRES

Khwai River (BPS255) (Fig. 1) are plotted in Fig. 2a: distances from BPS320 in these two cases were measured down the axis of the Panhandle and radially from the apex of the fan to the beacons. It is evident that the radial slope across the fan is remarkably uniform.

The gradient on the water surface is shown in Fig. 2b. The "valley" distance is plotted here, rather than channel distance, partly because of the sparse data set, but also because for much of the year the flood plain is inundated, especially in the Panhandle and upper fan. A major change in slope occurs at the lower end of the Panhandle, with the average slope increasing from 1:5570 to 1:3400. This coincides with the trace of the Gumare Fault and represents the point where the flood plain loses lateral confinement and expands to form the apex of the fan (Fig. 1). In detail, the Panhandle reach consists of two segments: an upper section with a gradient of 1:5710; and a lower section with a gradient of 1:6410. Major anastomosis occurs in the reach between these two segments (i.e. between UCT2 and UCT3).

Several subtle changes in gradient also occur on the fan itself. A major perturbation occurs in the vicinity of station UCT10. Upstream of this, there is a uniform slope of 1:3560, while downstream, the gradient is slightly steeper, *viz.* 1:3320. A second perturbation occurs between UCT11 and UCT12, which coincides with the trace of the Kunyere Fault. Downstream of this (UCT12 to BM351), the gradient is 1:2940. Overall, there appears to be a downstream steepening of the gradient of the fan.

Distributary channel characteristics

In the Panhandle, the main channel (the Okavango River) is broad and meandering, with a sinuosity of 1.9. The channel width near Shakawe (BPS320) exceeds 100 m, but narrows downstream (UCT1, UCT2, UCT4; Fig. 3, Table 2). In these lower reaches, channel banks consist of permeable, vegetation stabilised, mud-rich peat through which water leaks into backswamp areas (McCarthy *et al.*, 1991). The Jao/Boro distributary channel separates from the main Nqoga channel near the fan apex and diverts about 30% of the channel flow to the south (McCarthy *et al.*, 1991). The Nqoga channel carries the remainder to the east of Chief's Island. Additional water enters the Jao from lakes to the north (Porter and Muzila, 1989), which are supplied by leakage from the upstream reaches of the Nqoga channel. The region between UCT6 and UCT10 is characterised by extensively flooded areas, often with multiple channels. Where present, the channels are narrow (eg. UCT7, Fig. 3) with peaty, vegetation stabilised margins. Most of the discharge is by overland flow, with channels accounting for little

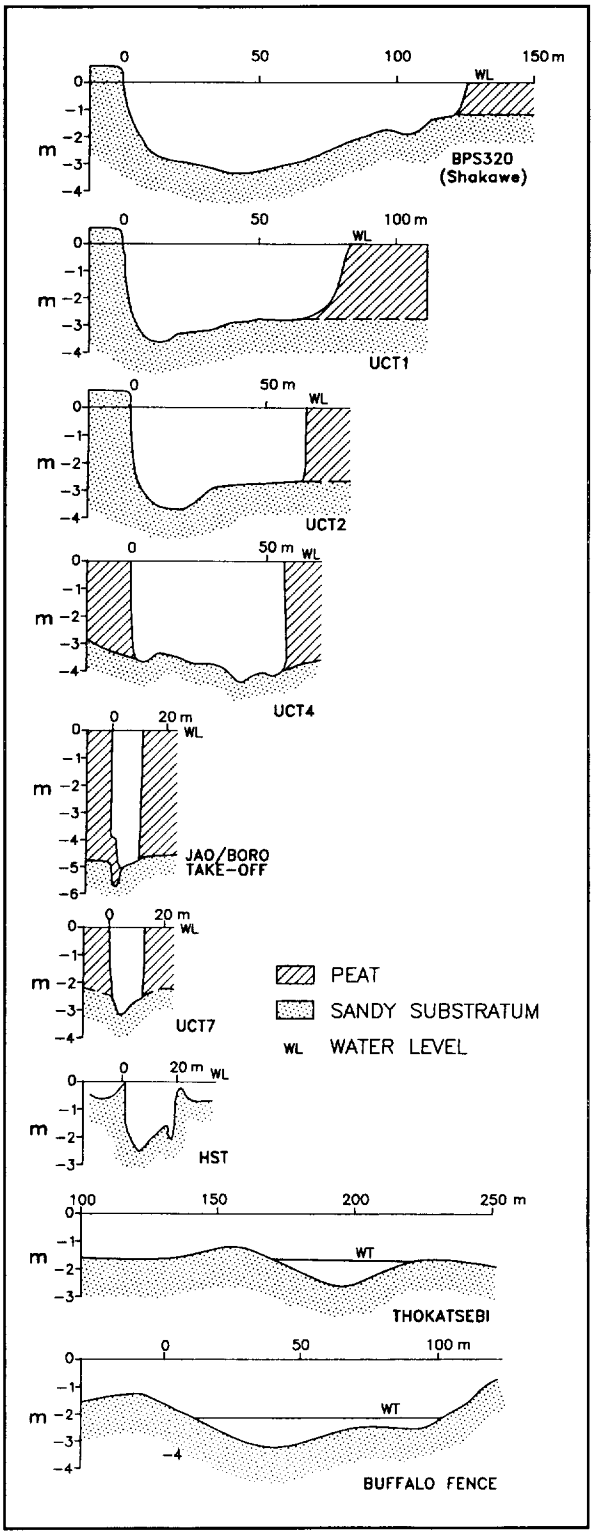


Figure 3. Cross channel profiles down the fan. See Fig. 1 for locations.

Table 2. Channel characteristics along the study profile

Site	Turbidity (NTU)	Suspended* load (kg m^{-3})	Channel width (m)	Mean Depth (m)	Area (m)	Mean Velocity (m s^{-1})	Discharge (m^3 s^{-1})
BPS320	3.2	0.0035	154	1.90	293.2	0.47	131.0
UCT1	3.3	0.0036	82	2.78	227.8	0.50	112.9
UCT2	3	0.0033	64	2.98	190.4	0.66	125.5
UCT4	2	0.0022	57	3.77	215.1	0.58	124.1
UCT7	1	0.0010	14	2.41	33.7	0.31	10.5
HST	1.5	0.0016	19	1.99	37.8	0.41	15.4
Jao/Boro take off	-	-	11	4.41	48.5	0.46	22.3**
Buffalo Fence	2.1	0.0023	95	0.75	71.5	0.0084	0.6

*Calculated from turbidity using calibration of McCarthy *et al.* (1991)

**From McCarthy *et al.* (1991). This site was measured at a different time (Jan, 1988) and hence these data may not be entirely comparable. However, in January 1988, site UCT 4 had a discharge of 117.9 $m^3 s^{-1}$ (Site H of McCarthy *et al.*, 1991) compared to 125.5 in the present study, therefore the discharge of Joa/Boro quoted here is probably roughly comparable.

of the total discharge. In certain sections there is no defined channel at all, especially in the vicinity of UCT8, the so called "Xo flats", where extensive, sparsely vegetated water bodies occur with scattered islands. Water depth is typically between 1 and 2 m. In these areas the navigation route is defined by hippopotamus trails through the aquatic vegetation. The sinuosity along the navigation route is 1.6, but the use of the term sinuosity is inappropriate in a fluvial sense, because of the poor definition of the channels.

In the vicinity of UCT10, and especially downstream of this station, the channel becomes clearly defined. For a distance of about 10 km south of UCT10, the Boro channel is incised into the sandy substratum where small, sand levees have developed (e.g. HST; Fig. 3). These levees are submerged during the seasonal flood. Downstream of HR, the Boro channel consists of a sinuous depression (Thokatsebi, Buffalo Fence, Fig 3) with a sinuosity of 1.4. Extensive flooding occurs lateral to the Boro channel, especially during high flood years.

Suspended load, as measured by turbidity, is low throughout the Okavango (Table 2). Turbidity was converted to suspended load (kg m^{-3}) using the calibration established by McCarthy *et al.* (1991). This calibration is only approximate because both organic (low density) and inorganic (high density) material contribute to the turbidity and cannot be differentiated. The relative proportions of these two components probably varies down the channel. Compared to other rivers (Milliman and Meade, 1983), the suspended load of the Okavango system is exceptionally low. Suspended load decreases downstream, reaching a low at UCT7, indicating the declining contribution of unfiltered source water to water flows downstream. Thereafter it rises slightly, probably due to anthropogenic influences such as boating, livestock watering, etc.

Satellite imagery

Seasonal variations in water distribution in the Okavango wetland are illustrated by three NOAA satellite images in Fig. 4. Figure 4a shows the situation in March (8/3/1992) as the seasonal flood water enters the Panhandle. By May (7/5/1992; Fig. 4b), the area of inundation has greatly expanded, especially across the central region of the fan (Jao/Boro channel system). Near maximum flooding occurs in July or August and is illustrated in Fig. 4c (7/8/1992). Chief's Island forms a prominent divide, separating the Jao/Boro system in the west from the Nqoga/Santantidibe system in the east.

The extensive lateral flooding, which occurs in the upper reaches of the Jao/Boro channel system terminates abruptly along a linear feature (A in Fig. 4a, b) with only a single major distributary (the Boro channel) extending southwards beyond this terminus. The terminus coincides with the perturbation in gradient in the vicinity of station UCT10. An aerial photograph of this reach is shown in Fig. 5a. Extensive, shallow swamp is developed in the northwestern portion of the scene, but this terminates against a northeasterly trending lineament (A-A; Fig. 5) with several irregular overspills, the most prominent of which is the Boro channel. The Boro shows marked incision for a distance of about 10 km downstream of the lineament. A second, sub-parallel lineament is developed to the northwest (B-B, Fig. 5b), also with limited incision of the Boro channel in its vicinity. A Landsat MSS image of the terminus region is shown in Fig. 6. Although this image was acquired at a time of greater inundation, the lineaments referred to above are nevertheless clearly visible. The most distal distributary channels and overspills terminate along the Thamalakane fault scarp (Fig. 4) along the southeastern edge of the Okavango.

DISCUSSION

Channel morphology

The Okavango system within the swamps is an alluvial river. Its gradient is the consequence of sedimentation, modulated by a variety of extraneous factors, and presumably represents a quasi-equilibrium state. The river has established two discrete gradients: in the Panhandle, where the flood plain is laterally confined, the gradient is 1:5570 and the channel is meandering. This occurs in spite of the fact that the river is bedload dominated, with a bedload to suspended load ratio of about 6, and as much as a five-fold difference in discharge between seasons (McCarthy *et al.*, 1991). The meandering fluvial style, rather than braiding, as may have been expected (e.g. Leopold and Wolman, 1957), is due to the stabilising effect and bank-forming ability of the vegetation (Stanistreet *et al.*, 1993; McCarthy *et al.*, 1988).

On the fan itself, the gradient is steeper (1:3400). This appears to be primarily due to the lack of confinement of the flood plain, and the river has created an extensive, gently sloping, alluvial fan of remarkably uniform gradient (Fig. 2a). The channels are not meandering at present. In the past, however, the meander belt of the Panhandle has prograded out onto the fan, and the Thaoge channel (Fig. 1), which was active up until a few decades ago, was meandering but has since been abandoned (McCarthy *et al.*, 1991; Stanistreet *et al.*, 1993). The gradient along this former channel was about 1:3200 (from fan apex to BPP157; Fig. 2a).

While the slope has been recognised as an important factor in determining the tendency of a river to meander (e.g. Schumm, 1977), it is evident that rivers in the Okavango are able to meander over a substantial range of regional gradients. The reason the channels on the fan are not presently meandering may be due to the loss of bedload within a region of anastomosis in the Panhandle and meanders downstream of this reach are incised (McCarthy *et al.*, 1991). Within the upper reaches of the fan, along the Jao channel system, channels are narrow with most of the discharge occuring through the

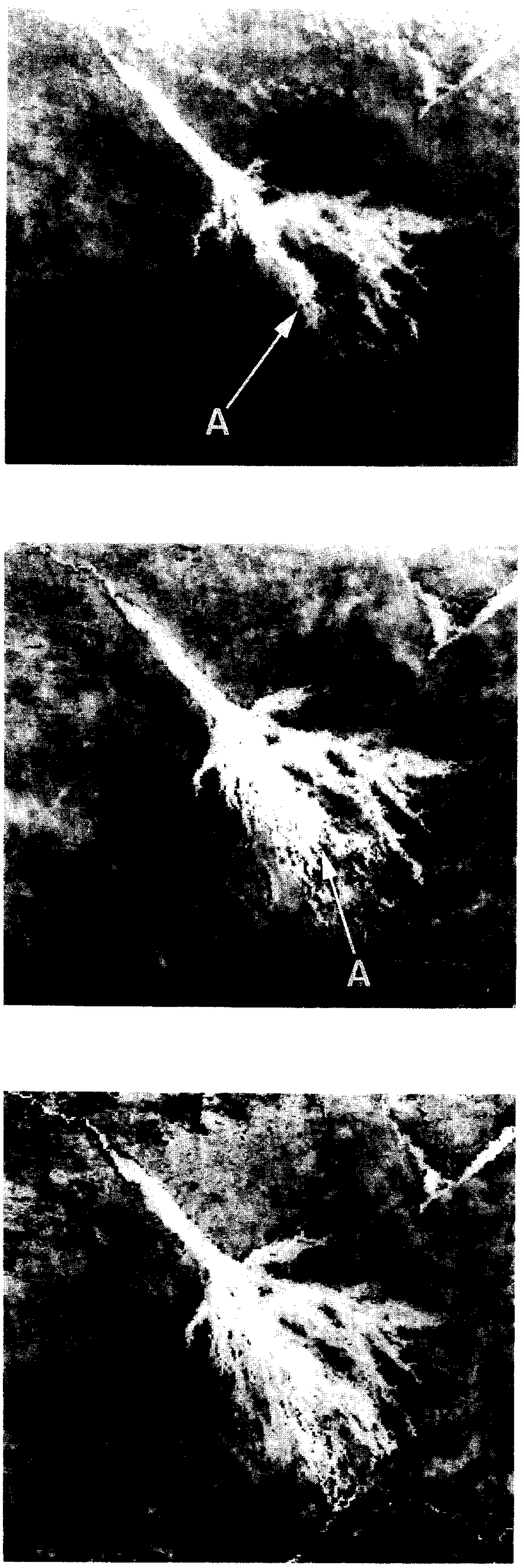


Figure 4. NOAA satellite images showing the distribution of water (white in the images) on the fan surface on 8 March, 1992 (a), 7 May 1992 (b) and 7 August, 1992 (c). A: the position of the lineament in the vicinity of UCT10.

swamp rather than in channels, despite the substantial volume of water discharging down the central region of the fan (Fig. 4b). This contrasts markedly with the situation in the northeastern section of the fan, where the Nqoga channel serves as a major artery of the swamp, discharging much of the water in this section (McCarthy *et al.*, 1992). The contrast between these two sections of the swamp suggests that channels have a function other than simply the transfer of water, possibly confirming the suggestion of Wilson and Dincer (1976) that an important function of major channels in the Okavango is the conveyance and dispersal of bedload. Where sediment load is high, as at present in the Panhandle, a meandering system develops and bedload accumulates on point bars, ultimately forming a sand dominated alluvial ridge. Under conditions of reduced bedload, bedload deposition results in vertical aggradation of the channel bed and, ultimately, channel abandonment, as for example on the lower Nqoga channel (McCarthy *et al.*, 1992).

In contrast to the well defined channel system of the Okavango and Nqoga Rivers, the Jao-Boro system is very different. The Jao channel system receives very little bedload at present, as the channel at the distributary head is small (Fig. 3). Most of its water is derived from overspill from the Okavango River in the lower reaches of the Panhandle (Porter and Muzila, 1989). The network of channels in this area seem almost superfluous from a fluvial perspective, being very small in relation to the flooded area (Fig. 4), and most of the discharge is by overland flow. Indeed, the channels are locally prone to vegetation blockage, particularly the reach between UCT6 and UCT8, indicating that they are redundant. This is further emphasised by the fact that discharge at UCT7 is only 10.5 m^3 s^{-1}, lower than that at site HST some 60 km downstream (Table 2). Channels in this region seem to have one primary function, namely the movement of hippopotami and, to a lesser extent, elephants through the swamps, and may thus be no more than a network of animal trails, locally widened by flow.

Fan gradients

The nature of the sediment load entering the Okavango Delta has been quantified by McCarthy and Metcalfe (1990). They showed that the solute load is twice that of the clastic load and, from hydrological considerations, have deduced that all of the clastic load and most of the solute load are deposited in the delta. Water distribution on the fan is largely by unchanneled surface flow (Fig. 4). The upper fan is permanently inundated and supports dense aquatic vegetation. The vegetation traps suspended load, hence the turbidity declines down fan (Table 2). Most of the suspended load is therefore deposited in the upper fan. The solute load is mainly deposited in the distal, seasonal swamps (McCarthy and Ellery, 1995), although a minor amount is deposited on islands in the permanent swamps of the upper fan.

Reference to the water surface profile in Fig. 2b indicates a slight tendency of the fan to steepen distally (between UCT6 and WITS2 the gradient is 1:3560; between HST and UCT11, 1:3320; and between UCT12 and BM351, 1:2940). This situation is therefore different from debris flow or glacial outwash fans, which tend to have a decreasing gradient down fan (e.g. Bluck, 1964; Boothroyd and Nummendal, 1978). It seems that the gradient of the Okavango fan steepens because the clastic load is deposited around the fan apex over a restricted area, while the solute load is spread over a far greater area on the distal floodplain and hence aggradation in this latter area tends to be slower than in the proximal areas, even though the dissolved load exceeds the clastic load. Such a system may, however, be self regulating: if the gradient becomes too steep, the permanent swamp would tend to prograde over the seasonal swamp, moving the zone of clastic sedimentation down fan and increasing the water supply to the distal reaches, increasing chemical sedimentation and thereby restoring the gradient.

On a local scale, the gradient, or more correctly the relief, is also self regulating. Lower areas receive more water and hence are inundated for longer periods, permitting an aquatic plant community to establish. These areas would tend to aggrade faster, due to enhanced transpiration, generation of phytolithic silica and the entrapment of suspended particulates from swamp water (McCarthy and Ellery, 1995). Islands, which represent higher ground, only aggrade around their margins, while the centres of islands experience little or no aggradation (McCarthy *et al.*, 1993a; McCarthy and Ellery, 1995). The overall effect of these various processes is to keep local relief within a narrow range (generally less than 1.5 m) and the regional gradient at 1:3400.

Gradient perturbations

Local perturbations of the water surface gradient occur (Fig. 2b). These are less evident on the

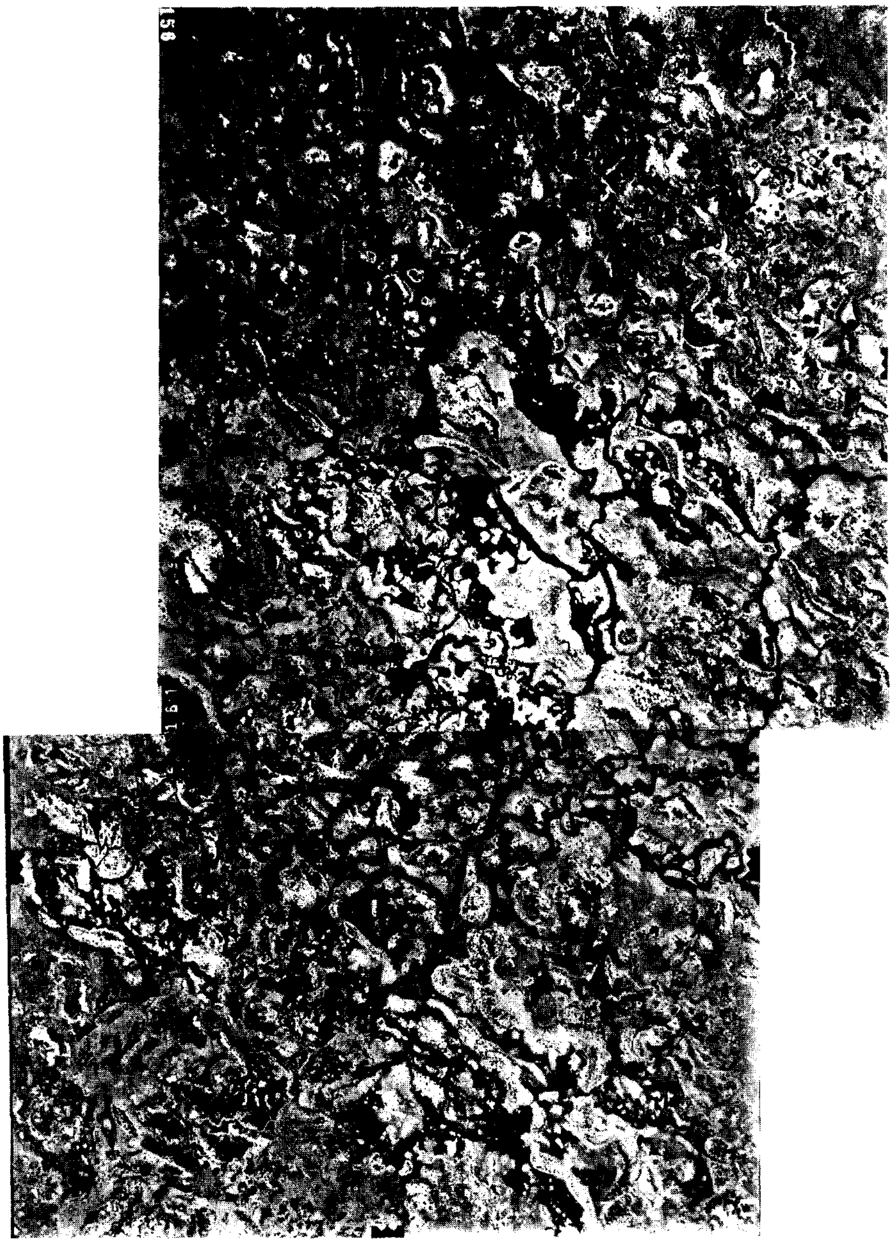


Figure 5. *(a) Aerial photograph of the region of the fan above where the surface gradient is perturbed.*

topographic profile (Fig. 2a) because they are subtle and tend to be masked by local topographic effects. The first of these is located in the Panhandle and is associated with major channel anastomosis. Others occur on the fan itself. Studies of satellite images of the Okavango have shown that the entire area is transected by numerous lineaments (Hutchins *et al.*, 1976) and some of these have been observed to limit the extent of inundation (McCarthy *et al.*, 1993b) and are inferred to represent the scarps of minor faults. The area is also seismically active (McCarthy *et al.*, 1993b).

The steepening of the gradient between stations UCT2 and UCT3 in the Panhandle is likely to be tectonic in origin. Extrapolating water surface gradients above and below this reach suggests a total offset in the order of 1.5 m with the downthrow to the southeast (Fig. 2b). This faulting appears to have initiated anastomosis in this region. A detailed study of this reach has been completed (N.D. Smith *et al.*, *in press*).

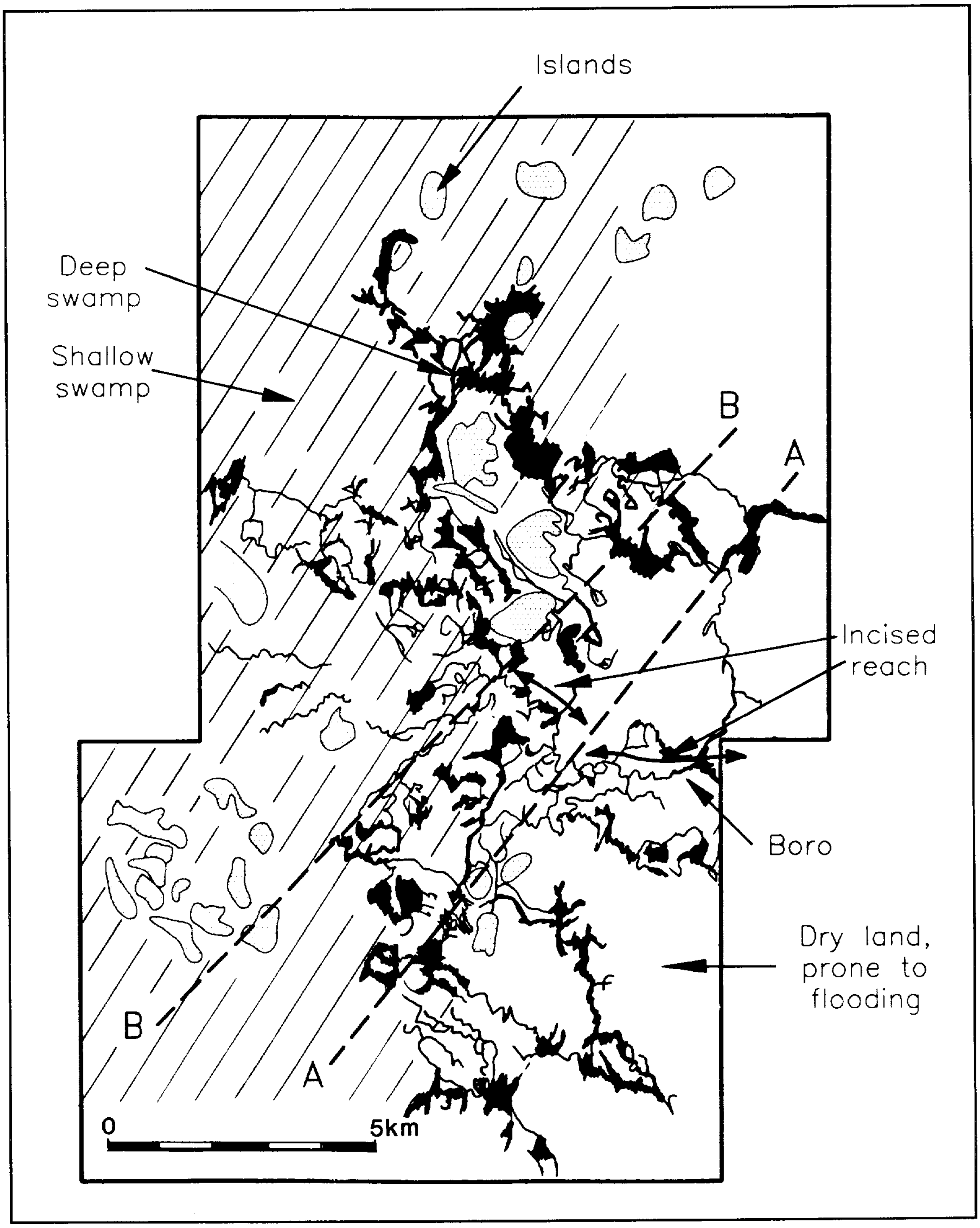


Figure 5. (b) An interpretation of the surface features visible in the aerial photograph.

The change in gradient between UCT11 and UCT12 coincides with the trace of the Kunyere Fault, which has an upthrow to the southeast (Hutchins *et al.*, 1976; McCarthy *et al.*, 1993b). The scarp height is of the order of 2 m (Fig. 2b). The water surface gradient flattens towards the scarp, indeed, much of the seasonal swamp is distally limited by this scarp. Extensive flooding occurs against the scarp in particularly wet years (McCarthy and Ellery, 1995).

The perturbation in gradient at UCT10 is also inferred to be the result of faulting and is associated with a photo lineament (Figs 5 and6). The offset across the entire zone (i.e. between stations WITS2 and HST) can be inferred by the projecting gradients from up and down stream

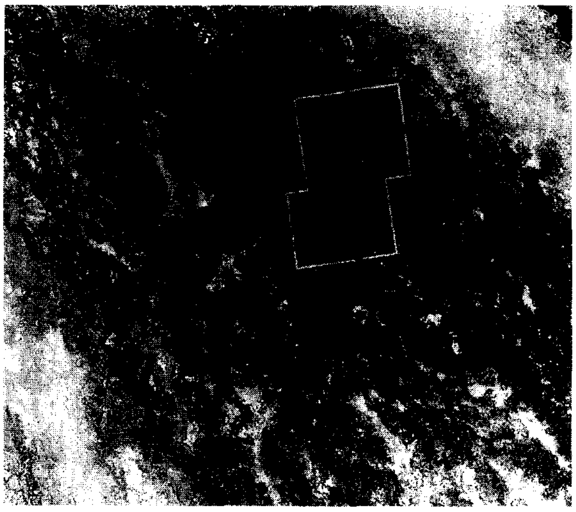


Figure 6. Landsat MSS image covering the region shown in Fig. 5.

and appears to be less than 1 m, with the downthrow to the southeast. The disturbed zone at UCT10 appears to be a small graben structure (less than 10km wide) with a local scarp height of approximately 1.5 m. The aerial photography of this region (Fig. 5), shows it to be a composite structure, more in the nature of a complex fault zone. The associated graben temporarily retards the advance of the seasonal flood as can be seen in the satellite images in Fig. 4a, b.

The Boro channel is incised for a short distance within the fault zone and for a distance of about 10 km downstream, as is shown by the channel profile at HST (Fig. 3), where the incision is approximately 2 m. Incision commences abruptly at a position coinciding with the photo lineament (Fig. 5) and is probably a consequence of downstream uplift, which has been observed to cause incision in other fluvial systems (e.g. Schumm, 1986). It is of note that a 6.7 magnitude earthquake, with an epicentre in the centre of the fan, occurred in 1952 (Reeves, 1972). Some observers (e.g. Wilson, 1973) maintain that the Boro channel became a major distributary following this event.

Incision in the reach below station UCT10 results in a more clearly defined channel than those developed upstream of this station. The major channel is currently the Boro, as this extends the greatest distance downstream, but reference to Fig. 5 shows that other overspills are developing across the scarp. In years of exceptional flooding, the entire area downstream of the scarp is inundated as far as the Kunyere Fault scarp. The Boro has undoubtedly attained its premier position because of the incision which has occurred there, as this means that it carries discharge during low flood years and also sustains flow for a longer period during the waning of the seasonal flood.

The origin of the levees along the incised reach (HST, Fig. 3) deserves comment. The channels in this reach contain very little suspended load and the levees are constructed of fine-grained sand rather than silt. Turbulent flow in the channels, especially during the seasonal flood, creates boils, which bring fine sand to the water surface. Some of this material is washed over the banks and becomes trapped in the flanking vegetation, where it accretes to form the levees.

In contrast to the above, channel incision has not occurred downstream of the Kunyere Fault scarp. At the fault trace, the channel becomes extremely shallow and widens. The lower channels are broad and shallow (Thokatsebi and Buffalo Fence, Fig. 3) and are heavily vegetated. Flow velocities in this reach are generally less than 0.03 m s^{-1}, which is insufficient to cause incision. Indeed, downstream from the region of station HR, the Boro channel generally lacks fluvial features and consists of a shallow sinuous depression with extensive lateral flooding. The channel is vegetated by a variety of aquatic species and the thalweg is defined by the ever present, vegetation free, hippopotamus trail. It appears that sand eroded from the incised section of the Boro has accumulated against the fault scarp.

CONCLUSIONS

Topographic information forms an essential data set in the study of wetlands, but it has been very difficult to acquire, especially in large, remote wetlands such as the Okavango fan. The development of differential GPS in accurate 3d point positioning and advanced methods in geoid determination (Merry and van Gysen, 1987; Heister *et al.*, 1991) makes it possible to acquire accurate elevation information routinely, as this study has demonstrated.

This study has revealed that the Okavango wetland has two discrete gradients: one in the Panhandle region (1:5570) and one on the alluvial fan (1:3400). The change in gradient occurs at a major fault and is due to the loss of confinement of the flood plain, which results in wide dispersal of the sediment load and hence a steepening of the gradient. The channel is potentially able to meander on both of these gradients, possibly influenced by bedload availability. Although sedimentary processes on the proximal and distal reaches of the fan are fundamentally different (clastic and chemical sedimentation, respectively), the overall gradient is maintained within narrow limits. Clastic sedimentation occurs in a restricted area in the upper fan, while chemical sedimentation occurs over a wide area. Aggradation on the upper fan is evidently slightly more rapid and hence there is a tendency for gradient to steepen down fan.

The overall gradients are locally disturbed due to active faulting. These disturbances result in changes in channel character. In the Panhandle, this results in anastomosis. A narrow graben has formed in the mid-fan region, the scarp of which tends to retard the advance of the seasonal flood. Overspill occurs across this scarp and has locally caused incision along the Boro channel. On the distal fan, the Kunyere Fault scarp does not induce incision, but is associated with shallowing of the channel against the scarp. This is due to the very low flow velocity in the distal channel.

The Okavango is a dynamic system, but there is an underlying uniformity in its overall structure. Small perturbations have occurred, to which the system has responded because of the generally low gradients. This emphasises the potential sensitivity of the ecosystem to small changes in elevation, whether induced by tectonics, by endogenous agencies such as sedimentation, or by anthropogenic interference. Before human intervention is even contemplated in a system such as this, a thorough knowledge and understanding of the topography is essential, as the topography has a critical control over the hydrology.

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