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The Okavango Fan and the classification of subaerial fan syste

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ABSTRACT

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Controversy exists over the classification of fluvially formed subaerial fans. Authors either restrict alluvial fans to deb flow dominated types or extend the spectrum to fans dominated by braided rivers. The Okavango Fan provides an e member which extends this spectrum to fans dominated by meandering and low sinuosity rivers. The fan is a large (150 radial axis) shallowly sloping (0.00036), highly vegetated subaerial fan, which can be subdivided into four subenvironmen These are: (1) the entry corridor or Panhandle characterized by single and anastomosing meander belts; (2) the upper f characterized by meander belts diverging from the fan apex, comprising peat-confined meandering channels, with intercha nel swamps forming thick peats; (3) the middle fan with highly confined single and anastomosing low sinuosity rivers and l common prograding meander belts whose channels are confined by thick peats with, however, little chance of pe preservation; and (4) the lower fan in which annual floods from relatively unconfined channels spread over the fan surfa and interact with pre-existing aeolian and lacustrine deposits.

With the recognition of this new fan type, the spectrum of subaerial fan types can be expressed in terms of: (1) deb flow dominated fans of which the Death Valley fans are a member; (2) braided river dominated fans of which the Kosi F is a member; and (3) low sinuosity/meandering (losimean) river dominated fans of which the Okavango Fan is a memb This spectrum can be expressed in terms of variation in slope, maximum size and percentage of surface vegetation, b crucial to the evolution of the various fan types is variation in the flashy to continuous nature of the discharge and t degree of channel confinement evident on the fan surface. Comparable ancient examples of the three fan types a recognizable, many of which provide intermediates between the ideal end members.

Debris flow dominated and braid dominated fan types are known from throughout earth history. However, the losime fan type, because of its reliance on confining vegetation, may only have developed after the Devonian Period.

The spectrum of subaerial fan types can be expressed on a triangular field of variation with the vertices defined by t relative importance of the processes which shaped a particular fan system be they debris flows, processes associated wi braided rivers or processes associated with meandering and low sinuosity rivers.

Introduction

The Okavango Fan has been intensively studied over the past five years by the Okavango Research Group at the University of the Witwatersrand, particularly from the point of view of the interaction between sedimentation and vegetation in the evolution of the system. The fan has developed where the Okavango River, which rises in the Central Highlands of Angola 1000 away, encounters the southwestward extensio the African Rift System (Fig. 1). The river cut erosional groove into the low northern shou of the graben, referred to as the Panhandle, (2). The area is semi-arid and forms part of Kalahari "Desert" (actually a semidesert) though a more humid microclimate is devel in the area of the fan.

On entering the rift system sedimentatio spread out (McCarthy et al., 1991) throug peated bifurcation of the river channels to fo "birds foot" channel pattern on the large

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gradient fan system. This "birds foot" pattern led to the erroneous naming of the area during the colonial period as the Okavango "inland delta". Such a classification cannot be maintained because the fan (initially recognized as such by UNDP, 1977) does not debouch into a major water body. The diminutive Lake Ngami at the foot of the fan was, in the last century, a solitary small permanent lake, fed by the Thaoge River (Anderson, 1856; Chapman, 1868; Livingstone, in Schapera, 1961) whose existence was due to the damming effect of the Okavango Fan across the rift system and does not represent a water body into which the depositional system is prograding. Abandonment of the Thaoge River has reduced Lake Ngami to little more than an ephemeral pan. Interestingly, the Kosi Fan of northern India was similarly initially referred to as an "inland delta" (Gole and Chitale, 1966) and went through a similar phase of reclassification as a fan system (Gohain and Parkash, 1985; Wells and Dorr, 1987a, b; Gohain and Parkash, 1990).

The Okavango Fan is the largest subaerial fan yet identified, extending 150 km in radial extent, and is unusual in that it supports an amazingly lush vegetation, perennially in areas referred to as the permanent swamps and annually in association with the annual flood in areas referred to as the seasonal swamps. The fan has been relatively little disturbed by man because of the depredations of the malarial mosquito, but more importantly the tsetse fly, which renders cattle farming impossible. It is therefore presently in a pristine condition for scientific study. The system records the lowest gradient of any previously described subaerial fan system of 0.00036 average on the fan itself (McCarthy et al., 1991). Its recognition impacts greatly on our understanding of the classification of subaerial fans in general and it is to this end that this paper is directed.

Controversies in the classification of subaerial fans

The "Glossary of Geology" (Bates and Jackson, 1987) defines a fan as "a gently sloping, fan-shaped mass of detritus forming a section of a very low cone commonly at a place where there is a notable decrease in gradient" whereas an alluvial fan is recognised as being a specific type of fan. It was with the study of glacial outwash fans by Gustavson (1974) and Boothroyd and Nummedal (1978) that there was a realization that fans could be grouped into at least two types.

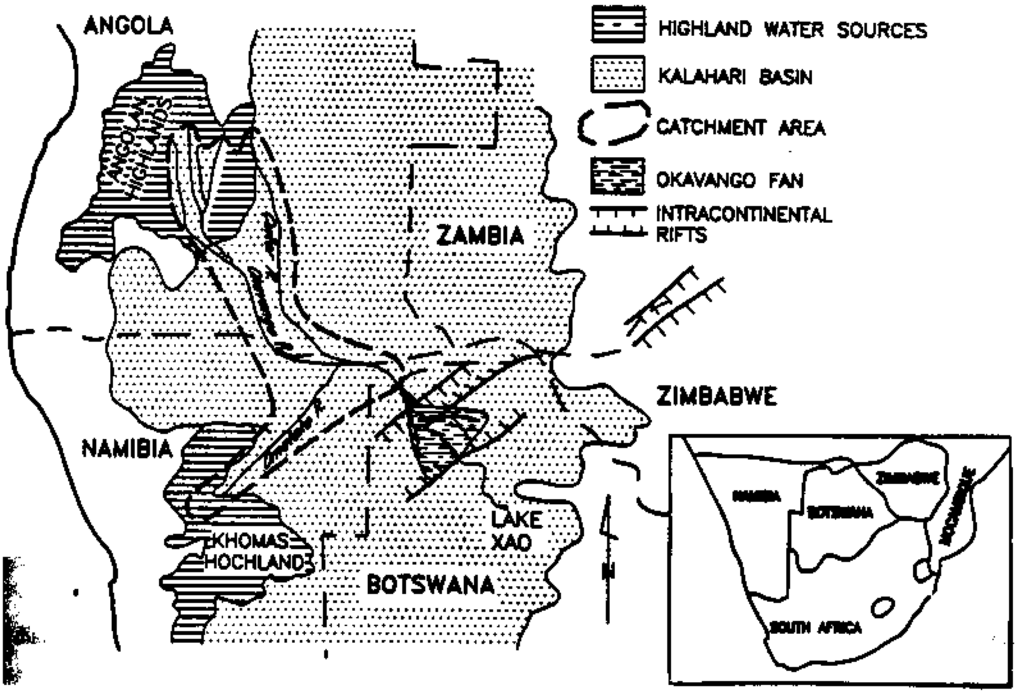


Fig. 1. Geological and geomorphological setting of the Okavango Fan.

These were referred to initially as "arid" and "humid" fans, although it was soon realized that factors other than climate, such as tectonic stability of the source area and the nature of the source materials, particularly the clay content (e.g. Gloppen and Steel, 1981; Maizels, 1990), were also extremely important. These ultimate controls on fan geometry affect the sedimentary processes which operate on a fan surface and ultimately, therefore, the morphology and type of fan produced. The recognition of fans which are dominated by braided fluvial processes has meant that the identification of such fans in the
becomes problematic, with the resultin
difficult to distinguish from those deve
braided rivers on a fluvial plain. Such a
tion requires the geometry and areal pa
rent variations to be taken into accou
distinction may be particularly difficult
when it must be made solely on the
subsurface information such as that of
core. McPherson et al. (1987), in the
specifically directed at fan deltas and bra
have tended towards a reductionist appr

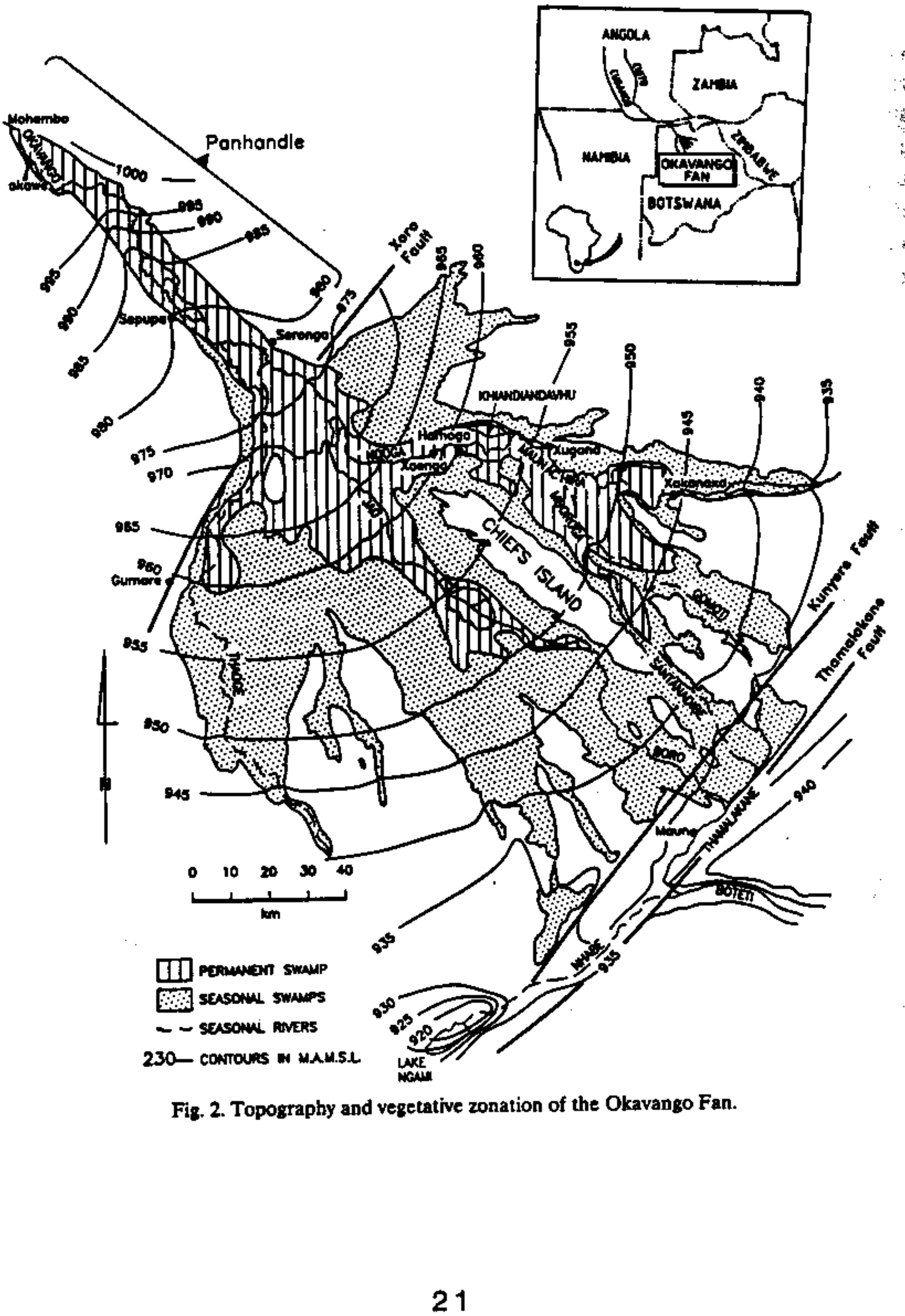


Fig. 2. Topography and vegetative zonation of the Okavango Fan.

seem to imply that most sedimentary bodies made up entirely of braided alluvium should be classified as braidplains, restricting the term fan to bodies in which debris flow processes are a major factor. In respect of this Wells and Dorr (1987a) agonize over whether the Kosi Fan is a fan or an alluvial plain. They conclude that the Kosi is a fan but hedge with their comment that the Kosi is a "huge, flat and wet end member in the spectrum of alluvial fans, although it is clearly also allied with alluvial plains". In a subsequent paper Gohain and Parkash (1990) define the Kosi Fan as a "megafan". In the present paper we agree with Wells and Dorr (1987a) about the spectrum of alluvial fans, but we "raise the stakes" by recognizing fans such as the Kosi Fan, not as an end member, but as an intermediate point in the spectrum of subaerial fan types. We therefore believe that the spectrum of fan types needs to be extended rather than reduced in order to encompass the full variation of subaerial fan characteristics. For that reason we will describe the Okavango Fan and make new proposals for criteria for fan classification. Because of the controversies surrounding the use of the term "alluvial fan" the more general term "subaerial fan" will be initially applied in this paper.

Characteristics and subenvironments of the Okavango Fan

For a more detailed account of previous work involving the detailed hydrological statistics of the active fluvial channels which operate presently on the Okavango Fan surface, the reader is directed to McCarthy et al. (1991). For the purposes of the present paper it is important to know that the fan is supplied from a catchment (Fig. 1) which extends back to the Central Highlands of Angola from where the perennial Okavango River (referred to as the Cubango River in Angola) and its perennial tributary, the Cuito River source. Ephemeral river tributaries such as the Omatako begin in the Khomas Highlands of Namibia, but their contribution to the discharge of the system is of less significance. Run off from the Angolan Highlands reaches a peak during the summer rains and this causes a flood maximum in the Panhandle in March or April. It takes four months for the flood water to pass through the panhandle and across the vegetated fan surface to arrive at the base of the fan at Maun (McCarthy et al., 1991). The total catchment of the Okavango Fan is 180,000 km^2 in size (UNDP, 1977) and the area of the fan itself is 18,000 km^2.

It has been calculated (Wilson and Dincer, 1976) that only 2% of the water which enters the fan system via the Panhandle exits from the system via the Boteti River towards Lake Xao (Fig. 1) and this reduction is gradual as shown by the decrease down-fan of water discharge in the active channel system (McCarthy et al., 1991). Water loss from the swamps is through evapotranspiration associated with the swamp vegetation and through seepage into the groundwater system. Thus, the fan comes within a close margin of being classified as a terminal fan system. At times of extremely dry interpluvials it may actually become a terminal fan, although for the majority of the time water exits seasonally from the down-fan end into the northern Botswana inland drainage system which has the Makgadikgadi Pans at its centre.

Very little clay enters the fan system, so the majority of the fines encountered on the fan surface is represented by naturally macerated plant material and other organic material generated within the swamps themselves. This is because the major part of the catchment area comprises loosely consolidated, chiefly aeolian sand of the presently active Kalahari Basin (Fig. 1). Only a very little sand is derived directly from crystalline bedrock. Grain size characteristics of sand samples throughout the channel system compare (Fig. 3) with Kalahari sand characteristics defined by Lancaster (1986). No statistically significant changes occur in sand sample parameters down the entire system. The presently active channel system changes in style from meandering to low sinuosity down-fan (Stanistreet et al., 1993) and there is a concomitant change from low width/depth ratios to high width/depth ratios (Fig. 4).

As suggested by McCarthy et al. (1991) the Okavango Fan is in a mode of changeover of primary distributary channels from the Thaoge

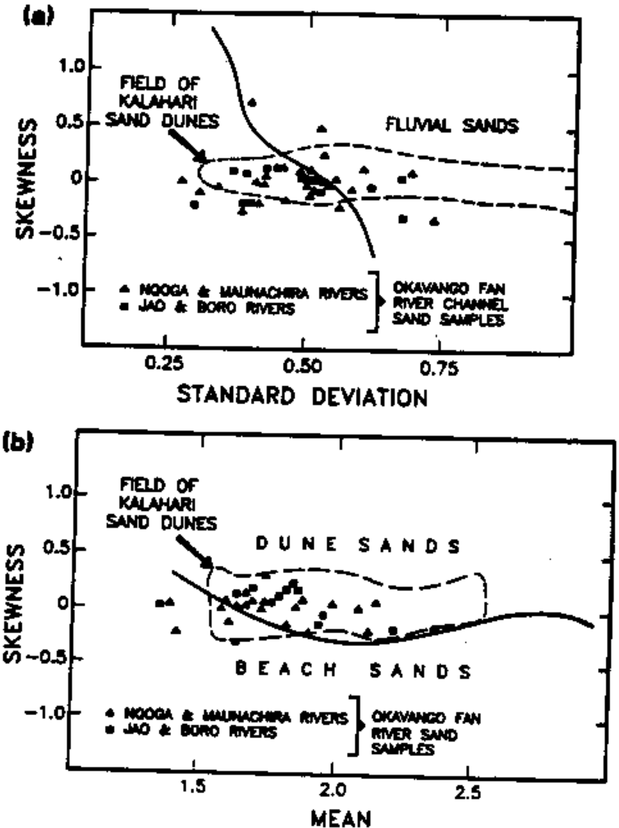


Fig. 3. Grain size distribution parameters: (a) skewness vs. standard deviation and (b) skewness vs. mean of active river channels on the Okavango Fan. Solid lines are environmental discrimination lines defined by Friedman (1961) for reference purposes only. Dashed lines bound fields defined by Lancaster (1986) for Kalahari aeolian sands in general for comparison.

River channel system on the west side of the fan which was the major distributary when Livingstone first visited the area (Schapera, 1961) to the presently active Nqoga–Maunachira–Khwai channel system on the east side. The latter follows the eastern side of an extensive previously abandoned Xugana meander belt which was probably the precursor to the Thaoge channel system, and which is possibly 2000–3000 years old (McCarthy et al., 1993). The newly activated channel has reflooded old oxbows associated with this ancient system to generate lakes locally called *lediba*. The present changeover in main distributary patterns allows a fortunate insight into the various types of fluvial channels of the Upper, Middle and Lower Fan and the Panhandle areas at various times in the fan's evolution. These areas will be described in detail.

The entry corridor or Panhandle

This erosive corridor to the fan is a shallow notch (up to about 5 m deep at the fan apex near Seronga) which broadens towards its downstream end. Its position is thought to be controlled by NW-trending faults as shown on the geologica

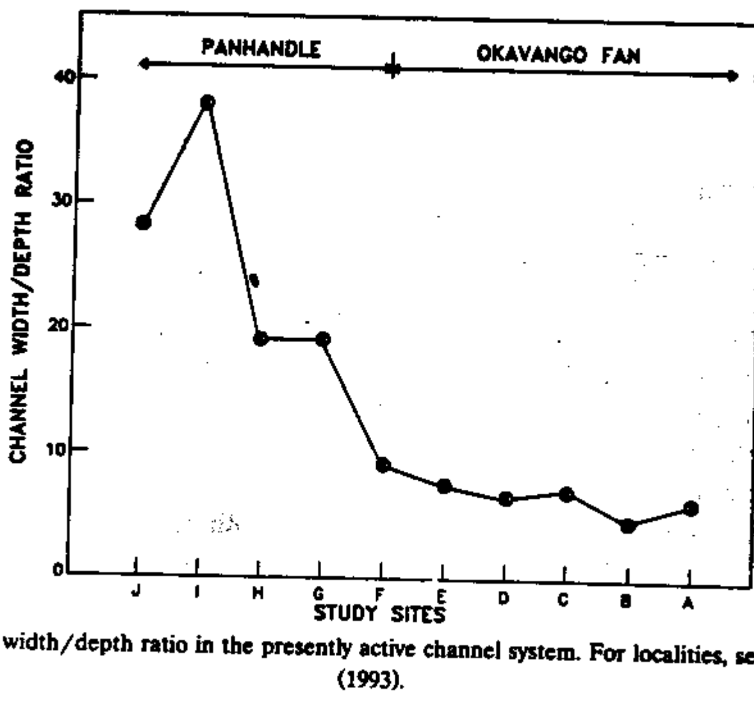
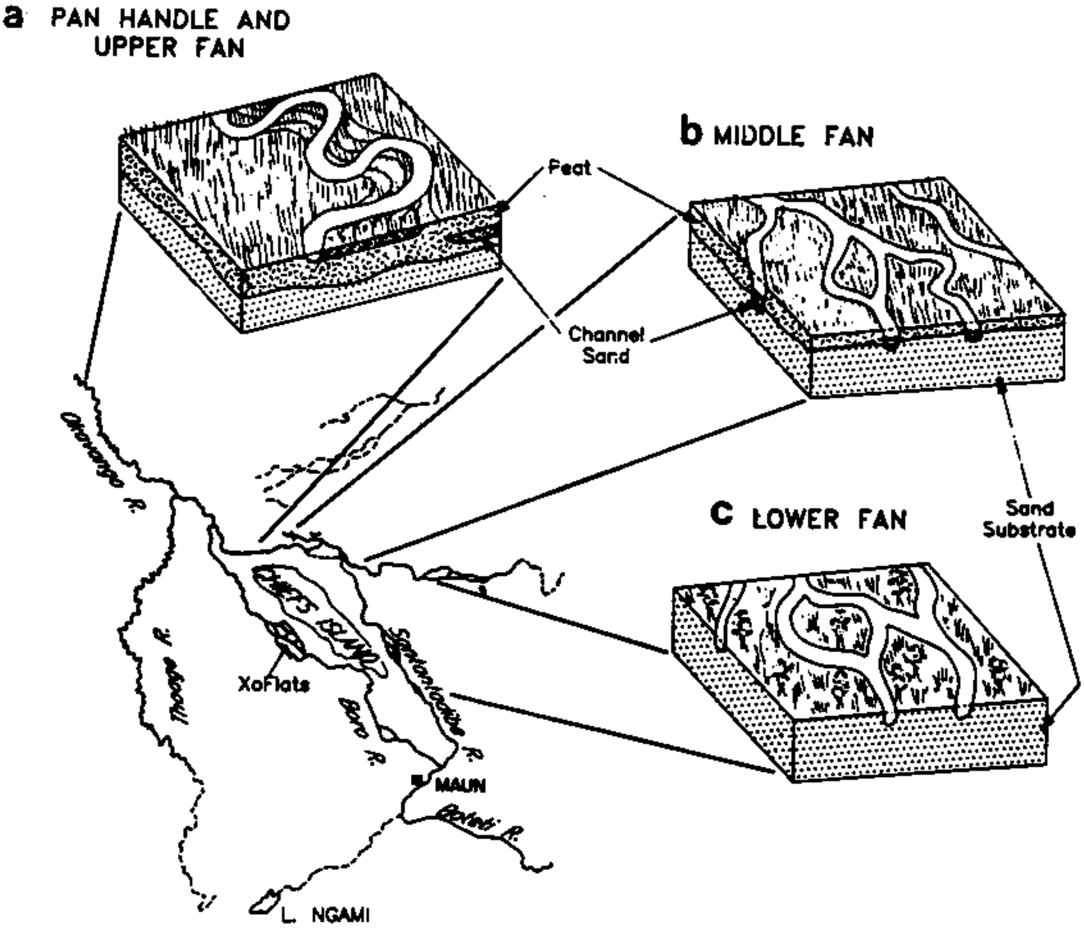


Fig. 4. Down-fan changes in width/depth ratio in the presently active channel system. For localities, see Fig. 1 of Stanistreet et al. (1993).

map of Botswana (Geological Survey of Botswana, 1984). Within the corridor the Okavango River has developed a confined meander belt (Fig. 5) whose oxbows locally abut against and have eroded laterally into the shoulders. The channel margin is raised above the surrounding floodplain or flood basin and is not confined by a levée of fine sediment, as is usually the case, but by a vegetative levée comprising mainly peat, topped and stabilized by living plant communities dominated by *Cyperus papyrus*, or *Phragmites Spp*. As with similar channel margins on the fan surface (McCarthy et al., 1988a), these margins may be permeable even during non flood periods. This is shown by a decrease in water discharge from the top to the bottom of the panhandle of 20% during a particular measurement period (McCarthy et al., 1991).

The average water discharge measured in the Okavango channel in the middle part of the Panhandle for December 1987/January 1988 was 130.8 m^3 s^{-1} with a bedload discharge of 2.38 kg s^{-1}. At flood peak during 1989 the average water discharge was 186.2 m^3 s^{-1} with a bedload discharge of 2.7 kg s^{-1}. During high discharge the water floods the surrounding flood basin which acts as a reservoir for later flooding downstream, as described by Wilson and Dincer (1976). Any fines which might be brought into the system tend to settle out at this stage. The return of flood water into the Panhandle channel system causes an increase of suspended load (mainly organic particles) downstream (McCarthy et al., 1991). In the lower half of the panhandle, the channel system anastomoses (Fig. 2) as two meandering channels, the Western Pass and the Eastern Pass. Previously abandoned meander belts in various stages of abandonment are common throughout the panhandle and these are illustrated and described in Stanistreet et al. (1993).



ig. 5. Schematic diagram showing the varying style of river channel and overbank sediments in the (a) panhandle and upper fan, (b) middle fan, and (c) lower fan subenvironments of the Okavango Fan.

The upper fan

The upper fan area is limited southwards approximately by the 960 m contour (Fig. 2) and has a slope of about 0.0004. As with the panhandle it is dominated by meandering channels (Fig. 5a) forming meander belts. In the past, point bar accretion has been an active process operating in this area in the present Nqoga channel, the recently abandoned Thaoge channel and an earlier abandoned meander belt which preceded the Nqoga channel named here the Xugana meander belt (Fig. 6). With the present state of avulsion from the Thaoge to the Nqoga channel, bedload sand which has previously been provided to the upper fan is being trapped in the lower Panhandle (McCarthy et al., 1991). This seems to have momentarily stabilized (Wilson, 1972) and slightly incised the channel system. The major distributary channels of the Okavango Fan subdivid from the presently dominant Nqoga/Maunachira/Khwai channel, mainly in the upper fan bu also in the lowermost panhandle. The Thaog distributary (Fig. 2) is virtually moribund, however, and it diverts only 16% of the total wate discharge. The Boro take off is more active an 25% of the total water discharge is diverted by i

In the upper fan the channel banks are colonized almost exclusively by lush growth of th papyrus dominated plant community. These margins are described in detail by McCarthy et a (1988a). The lack of fine suspended load in th system means that a negligible amount of sed ment leaves the active channel system (McCarth et al., 1988b). The interchannel areas receiv considerable amounts of water, however, as percolates through the vegetated peat levées eve during low flood periods and flows between th

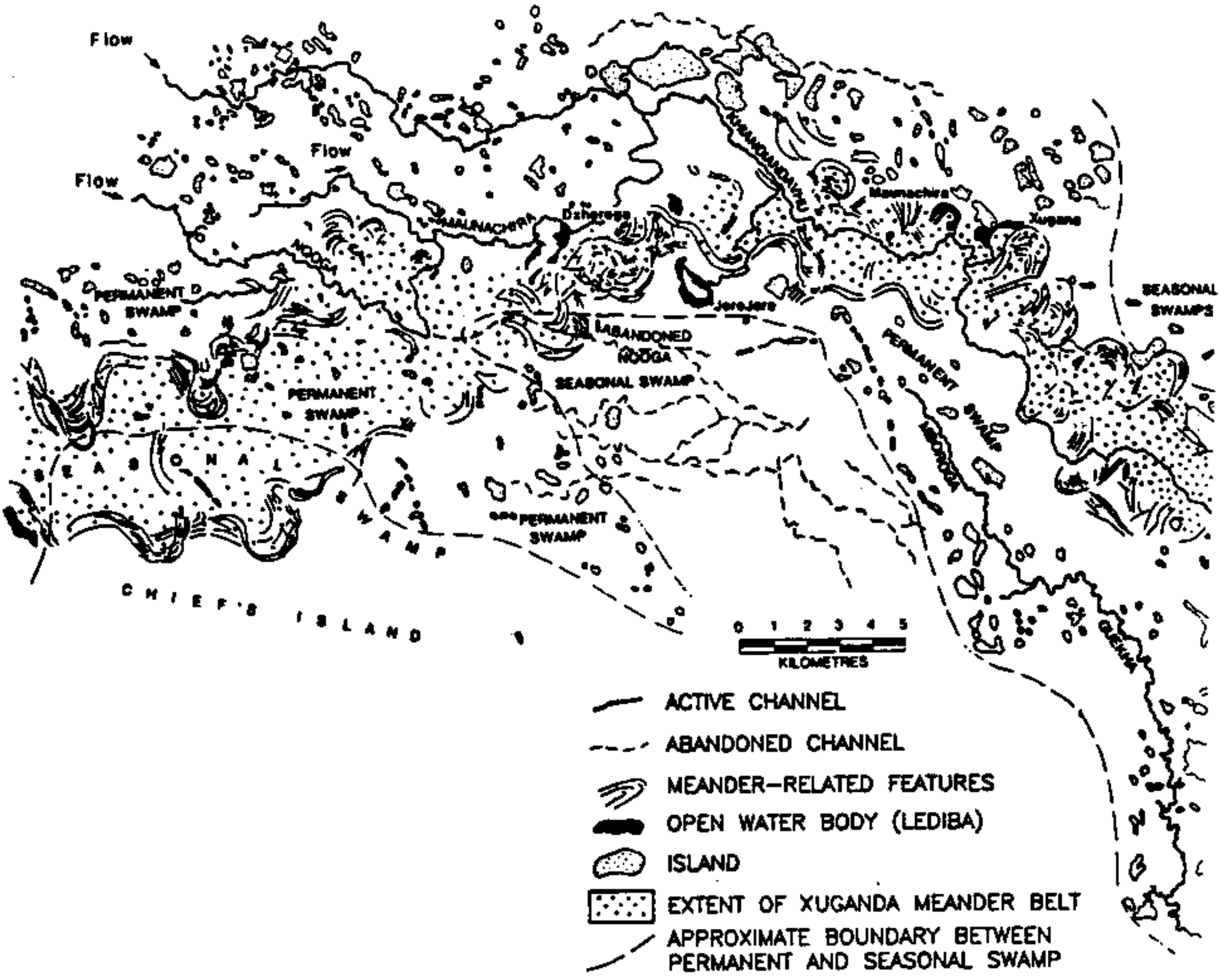


Fig. 6. Details of sedimentary features of the active part of the middle fan subenvironment showing the position of the lo abandoned Xugana meander belt.

plant stems of the levée top during flood period. This supports the permanent swamp vegetation which dominates the floodplain in this area and peat is the only sedimentary material accumulating in the interchannel areas. The permanent nature and constant wetting of the swamps means that this peat is less affected by fires which are a major factor in peat degradation in the sedimentary system as a whole (Ellery et al., 1989).

The middle fan

This area is developed between the 960 m and 945 m contours (Fig. 2) and has a slope of about 0.00035. Within this area the presently active and the most recently abandoned fluvial channels leave a variable sedimentary record. During pluvial periods or at times of fluvial channel equilibrium during periods of lower fluvial discharge, meander belts prograde over the fan surface. The former situation is represented by the down-fan extension of the long abandoned Xugana meander belt situated to the south of the present Nqoga/Maunachira/Khwai channel system (Fig. 6). The meander belt is up to 5.5 km wide and more than 70 km long and is believed to have experienced fluvial discharges on the fan surface of up to 200 $m^3 s^{-1}$ to produce meanders up to 1.1 km radius and channels 200 m wide McCarthy et al. (1993). It has been dated as prior to 1070 a, and has been associated with a pluvial period in Botswana of 2000–3000 a. An example of an equilibrium fluvial condition at lower discharge is provided by the presently abandoning Thaoge system which produced meander belts up to 3.5 km wide and up to 160 km long with channel widths up to 100 m and meander radii up to 750 m.

Presently active fluvial channels in the middle fan (Fig. 5b) are, however, of a different character. They are chiefly narrow, low sinuosity river channels described in detail by Stanistreet et al. (1993) of low water discharge (25–50 $m^3 s^{-1}$) which may occasionally produce meander bends. The channels may form anastomosing networks such as that described by McCarthy et al. (1993) from the Maunachira River or, an excellent example, the Xo flats, developed at the junction between the Jao and Boro rivers. The channels are less than 27 m wide and 3–4 m deep and like the larger meandering channels are confined by permeable vegetated peat levées (McCarthy et al., 1988a). The lack of fine sediment in suspension, the absence of crevasse splays and the relatively small change in discharge during flood means that siliciclastic deposition is virtually confined to the channel and most proximal levée. Only peat is deposited in the interchannel areas close to the active channel, sustained by water percolating through the peat levée at low water levels, with overbanking occurring during flood periods.

Aggradation in these low sinuosity river channels results in the development of ribbon sands, and although these are individually unimportant volumetrically, channels are abandoned repeatedly especially in areas of anastomosis. As a result, abandoned ribbon sand bodies are to be found scattered over the middle fan surface (McCarthy et al., 1988b). The interchannels are not favourable areas for peat preservation because abandonment leads to dehydration of the peat, and, ultimately, fire reduces even thick peat layers to thin layers of siliceous ash (Ellery et al., 1989).

Evaporation becomes an important component of the system in the middle fan. Small islands are developed within the flanking swamps near active channel systems and these are loci of evaporative pumping (McCarthy and Metcalfe, 1990), especially because of transpiration. These islands are characterized by precipitation of salts, including trona (sodium carbonate–bicarbonate) near the surface and calcite and silica at shallow depths near the top of the water table.

The lower fan

This area lies between the 945 m contour (Fig. 2) and the Thamalakane Fault. Presently active fluvial channels of the lower fan have typically vegetated beds and experience little active sediment transport, none of which is derived from outside the fan system (McCarthy et al., 1991). Channels are incised into the substrate and levées are either not developed or only poorly developed. River channels are not flanked by papyrus dominated communities, but by *Miscanthus junceus* with occasional woody species, including the fig *Ficus verruculsa*. The incoming flood during May/June is therefore unconfined and floods laterally (Fig. 7) into neighbouring hollows (Melapo), which are used, particularly near centres of populations such as Maun, for seasonal farming. In some areas these hollows represent the interdune areas of degraded dunefields, particularly well shown between the Kunyere and Thamalakane faults, which probably developed during a previous interpluvial. In contrast, during previous pluvial maxima this area was inundated by a lake whose geomorphological effects have been recognized by Shaw (1988).

The base of the fan is defined at the present day by the Thamalakane and Nhabe rivers which follow the Thamalakane Fault on its northwestern (downthrown) side. Rivers along the base of the fan are celebrated in geomorphology as being some of the few rivers with such a low gradient that they can flow in either direction depending on the axis of flood input. These rivers rework sediment along the fan base before entering a notch through the NE-trending Ghanzi Ridge, a horst of Precambrian basement defining the southwestern shoulder of the graben. Within the notch the outflows from the fan combine to constitute the Boteti River which flows further to the southeast to Lake Xao.

Although little external siliciclastic sediment is being brought into the lower fan at the present time, this has clearly not always been the case. The Thaoge River provided sand to the Lake Ngami area prior to its abandonment. This and other previous meander belts, such as the Xugana meander belt would have episodically provided abundant siliciclastic sediment to the lower fan surface. The lower fan is, however, presently a major site of water seepage into the groundwater system during flood and, after plant transpiration, this groundwater system provides solutes for subsurface chemical precipitation of calcite and silica. The area is characterized by a patchwork of pallisaded "islands" defined by a fringe of arboreally dominated vegetation with interchannel areas vegetated by grassland and thorn scrub (Fig. 5b). These mark the sites of excessive transpirative and evaporative pumping and the islands are apparently produced by the chemical swelling effect of subsurface calcrete and silcrete

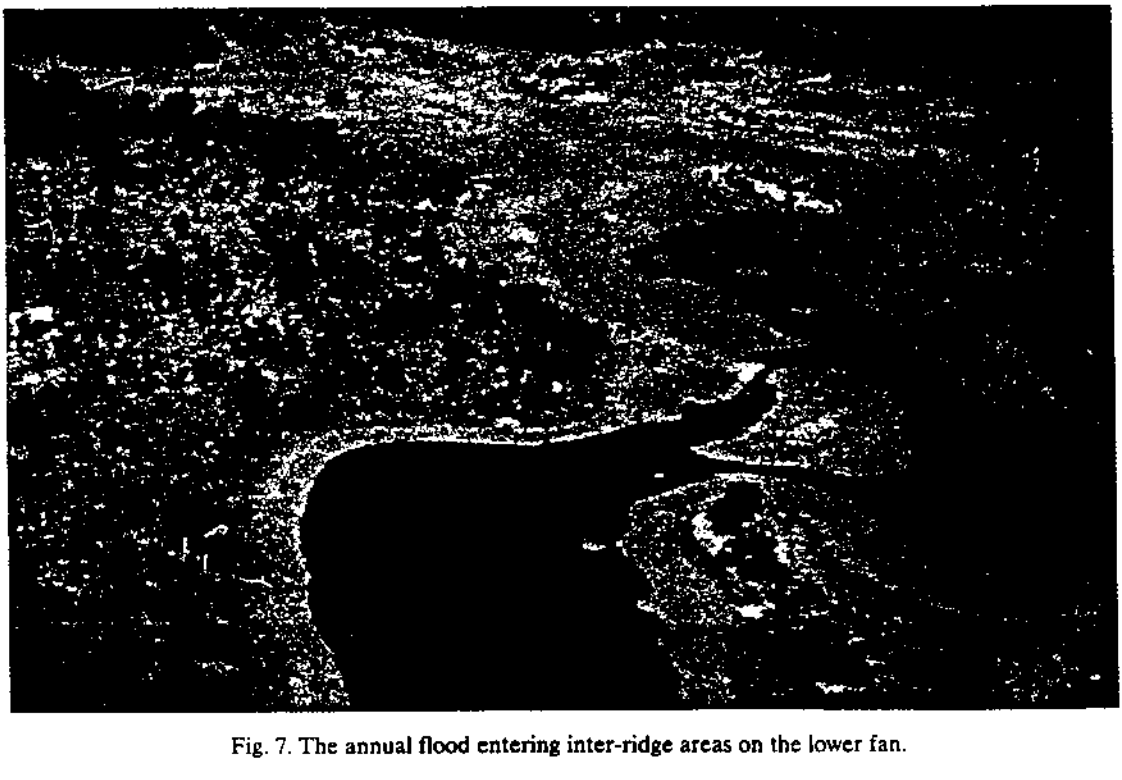


Fig. 7. The annual flood entering inter-ridge areas on the lower fan.

precipitation, a larger-scale version of the effects produced in the smaller and more restricted islands of the middle fan (McCarthy and Metcalfe, 1990). The latter authors calculated that solutes entering the Okavango Fan represent volumetrically five times the amount of siliclastic sediment being brought into the system. The vast majority of this is being precipitated as calcrete and silcrete in the subsurface of the middle and lower fan, but particularly in the lower fan where surface wetting and replenishment of groundwater is distinctly seasonal in nature.

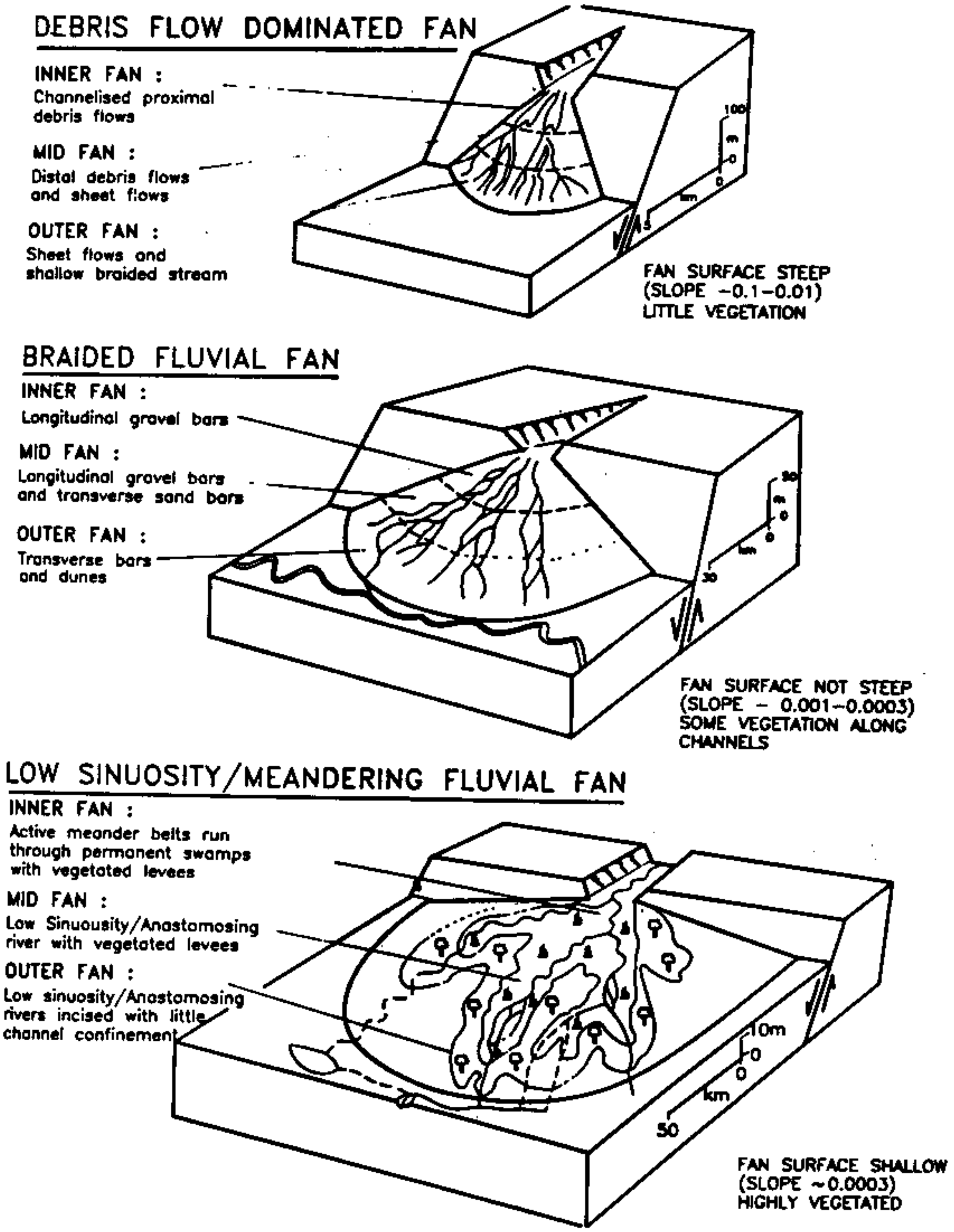


Fig. 8. Classification of subaerial fans.

Comparison with other fans and the subaerial fan spectrum

Fan types

The Okavango Fan considerably extends the presently known spectrum of subaerial fan types, representing an ultra low gradient, meandering/low sinuosity dominated, highly vegetated fan system. For convenience this fan type will be named a "losimean" fan, from the initial letters of *lo*w *si*nuosity *mean*dering. In order to reassess the spectrum of subaerial fan types, comparison needs to be made with other previously recognised fan types to highlight the differences (Fig. 8) and recognize possible points of overlap.

An early fan type to be recognised was the "alluvial" fans of the Death Valley type (e.g. the Hanaupah Fan), described particularly by Bull (1963, 1972), Denny (1965) and Hooke (1967). They were originally classified as Arid Fans and are dominated by debris flow deposits interbedded with alluvial deposits particularly those of shallow braided streams or sheetflows, the latter two typically characterized by plane laminated and some cross-bedded sands and layered gravels. Blair and McPherson (1992) in their reassessment of the Trollheim Fan bring into question the action of sheetfloods on this particular fan. They clearly document the action of fluvial processes in reworking debris flow deposits to generate clast-supported gravels on the present fan surface. Recent fans of the debris flow dominated type have been described by Derbyshire and Owen (1990) in the Gilit area of the Karakoram Mountains. Such fans will be described here as Debris Flow Dominated Fans emphasizing the primary importance of processes in shaping them rather than the many ultimate controls such as climate, source, tectonics, etc., as the controlling feature of a particular fan type. In suggesting a renaming of these fans, we agree with Leece (1990) that the term "alluvial fan" should be retained to include all fans deposited by fluvial and combined fluvial/debris flow processes. One of the major characterizing features of such fans is the total lack of channel confinement associated with the extremely "flashy" nature of their discharge.

A second type was recognized initially in situa-

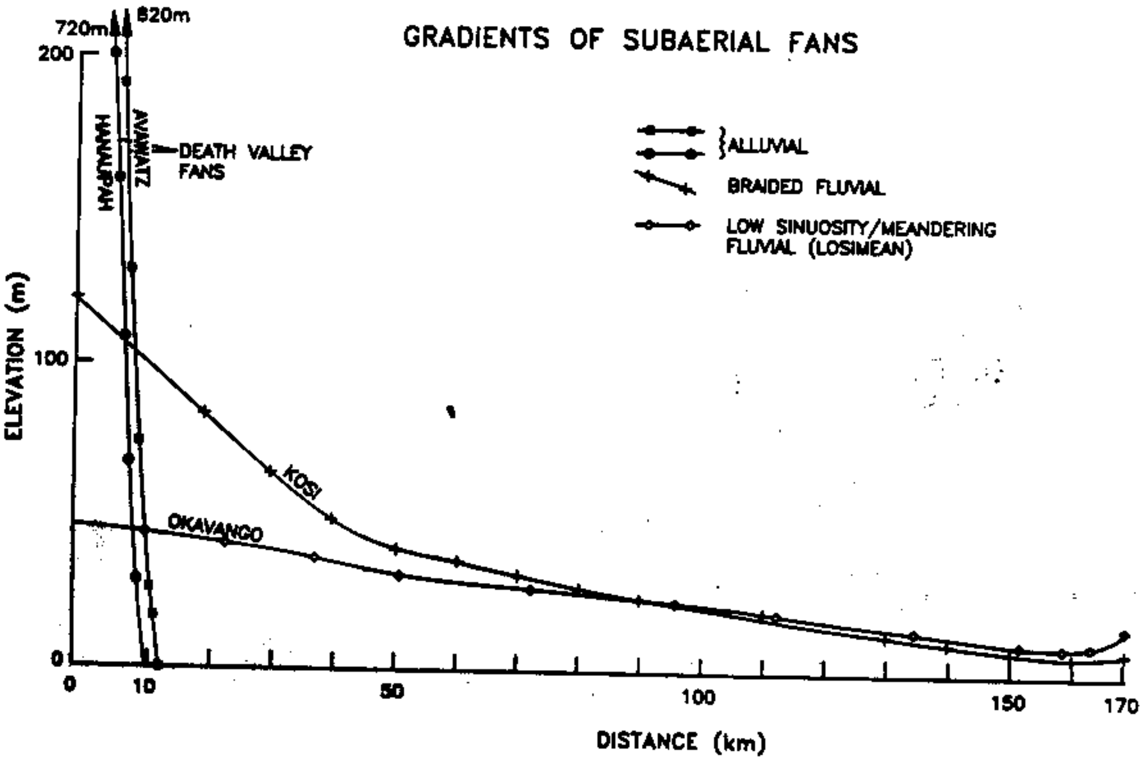


Fig. 9. A comparison of down-fan slopes on various Recent subaerial fan systems.

tions of glacial outwash (Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978; Kochel and Johnson, 1984) where both fluvial plains and fluvial fans may form (Rust, 1978). Here fans, initially referred to as Humid Fans, are dominated by braided fluvial river processes, particularly in their upper and middle parts, with the formation of well defined channel systems, longitudinal bars, transverse bars and dunes on the fan surface. Sands are typically cross-bedded and vegetation plays only a subservient role on the fan surface, particularly in the active channels where they may, for instance, stabilize individual fluvial bars. Harvey (1984) has attempted to statistically distinguish these fans from debris flow dominated types in small subaerial Quaternary fans of SE Spain. The Kosi Fan of India (Gole and Chitale, 1966) is a large member of this type of fan, where vegetation of the distal channels is a recognized feature (Wells and Dorr, 1987a, b). The case for this type of fan has been stated also by Dunne (1988) who points out that discharge is characteristically more continuous and less flashy. In these fans a degree of channel confinement of flows becomes a factor in fan evolution.

A third type is represented by the Okavango Fan described in this paper and is referred to as a losimean fan type. It is dominated by meandering fluvial belts with or without low sinuosity river channels. Channel characteristics may distinctly change down-fan if water discharge is lost due to groundwater seepage or they may maintain their characteristics if this does not occur. An example of the latter type of losimean fan is the Portage la Prairie Fan described by Rannie (1990). In this fan suspended load meandering rivers are the main agents in forming the low (slope = 0.0005) fan geometry with a maximum diameter of 50 km. In losimean fans vegetation is an important sedimentary control on the fan surface, stabilizing the positions of channels and meander belts. This aspect of total channel confinement represents an important factor in fan evolution and water discharges are far more continuous.

Vital statistics

The slopes of the three subaerial fan types are one of their characterizing features (Fig. 9). Debris flow dominated fans have high depositional

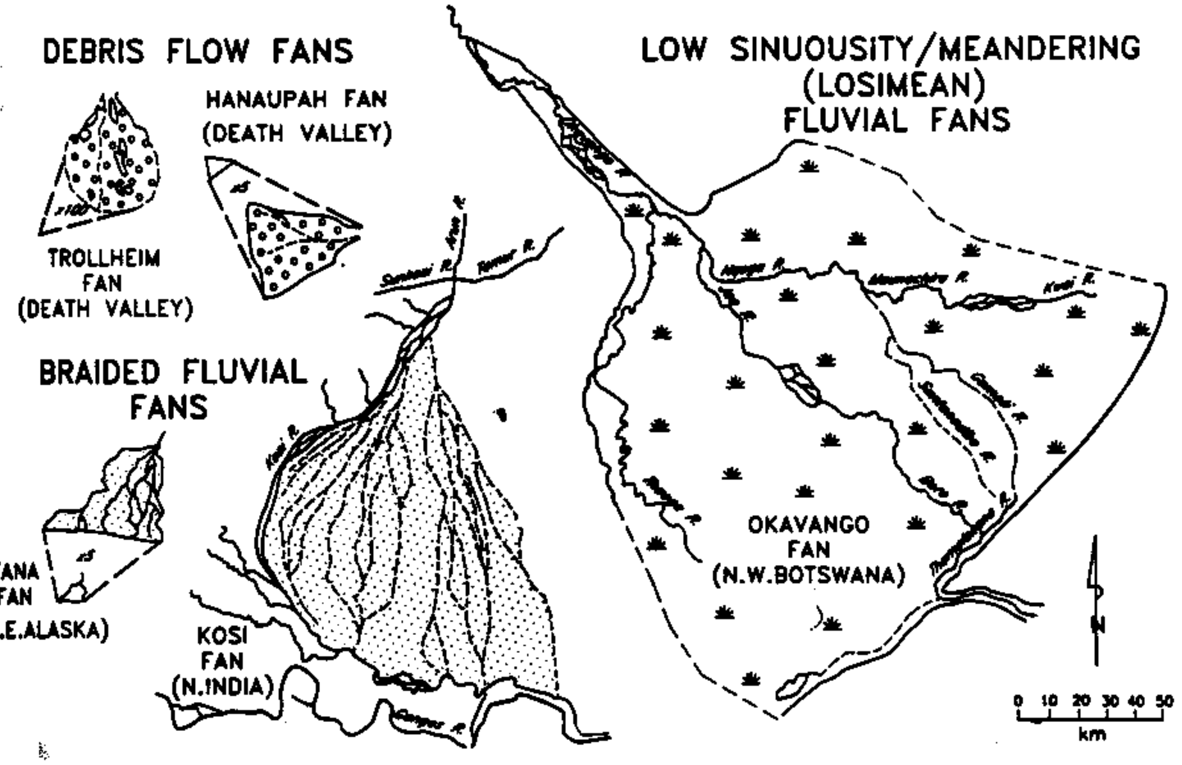


Fig. 10. A comparison of the sizes of recent subaerial fan systems.

slopes between 0.1 and 0.01, whereas the slopes of braid dominated fans are less than 0.001 and are as low as 0.00034 in the case of the Kosi Fan. This is not an order of magnitude different from the slope of the Okavango Fan (Fig. 9) which has an average slope of 0.00023. The range of braid dominated fans may therefore be taken as 0.001–0.0003. Meander/low sinuosity dominated (losimean) fans may be considered to be characterized by the lowest slopes so far recorded as low as 0.00023.

Maximum fan size is another characterizing feature. Alluvial fans range in axial fan length up to 10 km (Fig. 10). Braid dominated fans are developed up to 120 km in axial length and meandering/low sinuosity dominated fans may be greater than this value at least up to 150 km.

The percentage of vegetation cover is potentially an important characterizing parameter for subaerial fan types, but one which may be difficult to assess from published examples. Debris flow dominated fans are renowned for their lack of vegetation, with only hardy or scrub-like plant species present, perhaps covering 0–5% of the fan surface. On the Kosi Fan, wet flood areas represented by marshes of water hyacinth, constitute a minor environment (Wells and Dorr, 1987b), although their extent was not quantified. On the Yana Fan (actually a proglacial fan delta) vegetation covers perhaps 40% of the fan surface by estimate. In contrast, in the case of the vango Fan, about 70% of the fan surface is l vegetated at least once each season and th mainder is grassland with acacia thorn bush that well over 90% of the fan surface is v tated.

Subaerial fan versus submarine fan sizes

Subaerial fans of the size of the Okavango and the Kosi Fan finally provide subaerial tems which comprise a sediment volume and ometry comparable with those more usually a ciated with submarine fan systems. Previou subaerial fans have been considered too smal warrant such comparison. To illustrate this 11 shows the mapped extent of subaerial fans a a selection of their submarine counterparts. T Okavango and Kosi fans provide a link in spectrum of fan body size on the Earth's surfa as a whole; there is no "gap" between continen and submarine fans in this size spectrum.

The spectrum of subaerial fan types in ancie rock sequences

Debris flow dominated fans in the ancient

The facies associations and sequences deve oped in debris flow dominated fans are the mo

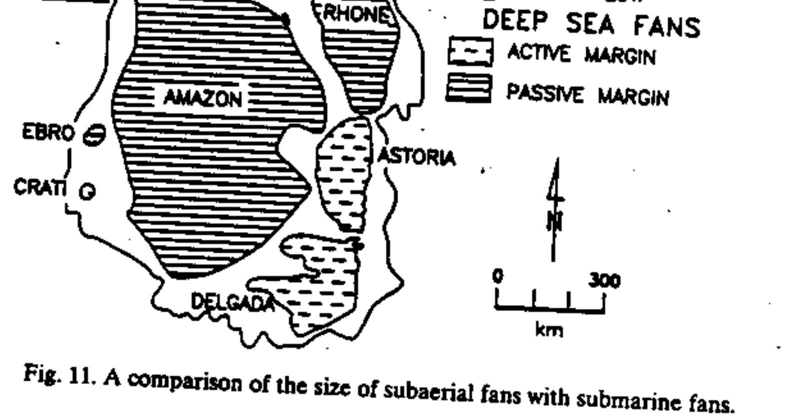


Fig. 11. A comparison of the size of subaerial fans with submarine fans.

readily identified in ancient rock sequences. They have been identified in all ages of sedimentary rock strata including: Archaean (e.g. Buck, 1980; Kingsley, 1984; Stanistreet and McCarthy, 1991); Proterozoic (Middleton and Trijillo, 1984; Ruxton and Clemmey, 1986; Von Veh, 1988; Master, 1991); and Phanerozoic (e.g. Bluck, 1967; Steel and Aasheim, 1978; Shultz, 1984; Hayward, 1983; Wells, 1984; Derbyshire and Owen, 1990).

The braid dominated fan type in the ancient

These are not as easy to identify in ancient depositional systems as the previous type because they cannot be identified merely by facies associations or facies sequences. Over and above this, the geological data set must also include palaeocurrent information or trend surface plots over an area in order to pinpoint the apex of the system and the radial pattern of the drainage system on the fan surface. Relatively few studies have achieved this, but examples are available (e.g. McGowen and Groat, 1971; Minter, 1978; Kingsley, 1984). Some studies pinpoint braid dominated fans on the basis of gravelly sedimentary bodies depositing off structural uplifts or orogenic fronts which extend into the basin for tens of kilometres before being reworked by axial fluvial plains developed parallel to the orogenic grain (e.g. Gloppen and Steel, 1981; Hobday et al., 1981). Recently, Maizels (1990) has described a Plio–Pleistocene Fan of this type from the Barzaman Formation of Oman (Barzaman Fan II). Barzaman Fan I represents a probable intermediate between braid fans and losimean fans.

Depositional systems which warrant classification as single or coalesced braid dominated fan bodies have been recognized throughout earth history. Archaean examples include those from the Witwatersrand Basin, South Africa (e.g. Minter, 1978; Kingsley, 1984), Proterozoic examples include those from the Belt Basin, Montana (Winston, 1978) and the Van Horn Sandstone, (McGowen and Groat, 1971) and Palaeozoic examples include those from post-orogenic Devonian basins of Europe (Gloppen and Steel, 1981; Graham, 1983). The Mesozoic is represented by Jurassic/Cretaceous Rocky Mountain molasse (Hobday et al., 1981) and the Cainozoic by fans off orogenic fronts in Turkey (Hayward, 1983), and Oman (Maizels, 1990).

The low sinuosity / meandering (losimean) fluvially dominated fan type in the ancient

Identifying fans similar to the Okavango Fan in the ancient is more problematic. The dependence of the stability of the system on plant species, whether stabilizing sediment or vegetative levées to provide channel confinement, means immediately that the development of such fans should not be expected before the invasion of the land by plant life during the Devonian Period (see similar reasoning for the importance of plants in confining channelized fluvial plain systems by Schumm, 1968). One ancient depositional system, although in reality a deltaic system debouching into a lake, shows features which indicate it to be a system partially comparable with the Okavango Fan. The Luna depositional system described by Nichols (1987) was deposited in the Ebro Basin during the Miocene off its northern orogenic margin producing a fluvial depositional system that extended nearly 40 km from its point source to the region where it interacts with a lacustrine water body. Gravelly braided rivers developed at the apex of the system within 5 km of it, but these gave way rapidly down-fan to sheet and then ribbon sand bodies representing the deposits of confined river channels of low sinuosity type. Such sand ribbons have been described and figured previously (Friend, 1978; Friend et al., 1979) and are similar to those studied on the Okavango Fan (Stanistreet et al., 1993). In the Luna depositional system channels become less confined in lower parts of the system. Nichols (1987) further states that the characteristics of the Luna depositional system are consistent with progressive evaporation and infiltration of water down the system in a manner similar to that described for the Okavango Fan. Nichols (1987) is reticent to call the depositional system a fan because he cannot apply the debris flow dominated model. There are no doubts, however, that the subaerial part of the system satisfies all the necessary attributes to allow comparison with equivalent fan systems with a recognizable apex, a conical shape and a radial distributary system. Although the Luna System is a half-cone shaped deltaic system debouching into a lake, McPherson et al. (1987) have shown that fan types in general have deltaic counterparts: debris flow dominated fans have fan delta equivalents; braid dominated fans would be equivalent to braid deltas; and the Okavango Fan type also appears to have this deltaic counterpart. In fact, the subaerial part of the Luna System seems to be an interesting case representing an important intermediate between a losimean fan and a braid dominated fan. Another fan which may hold an intermediate position between losimean and braid fans is the Plio–Pleistocene Barzaman Fan I of Oman described by Maizels (1990).

The triangular field of subaerial fan types

A triangular field of subaerial fan types can be defined by the proportional importance of: (1) debris flow, (2) braided fluvial, and (3) low sinuosity/meandering (losimean) fluvial processes in depositing the sedimentary fan bodies. The vertices of the triangular field represent idealized situations in which the respective processes
100% responsible for a particular fan body
12). Only one of these vertices, that of low sin
ity meandering fluvial processes, is so far o
pied by examples, i.e. the Okavango and Por
la Prairie fans. Otherwise, fields have been
fined to encompass the plotted examples,
recent and ancient. The braided fluvial fan
can conveniently be defined to include those
in which braided fluvial processes deposit at l
50% of the accumulated sediment body (Fig.
Debris flow and losimean dominated (losim
fans occupy fields outside the one defined a
in which, respectively, the ratios of braide
losimean fluvial processes and braided fluvia
debris flow processes are less than 1:3 in
constitution of the fan body deposits. The res
ing pattern represents the fact that all fans in
mediate between debris flow and losimean do
nated fans so far recognized incorporate a h
proportion of braided fluvial deposits. Altho
the point might be made that the spectrum of
types could be equally well represented b
linear variation rather than as the two-dim
sional diagram shown in Fig. 12, a triangular f
does allow for a fan example in which debris fl

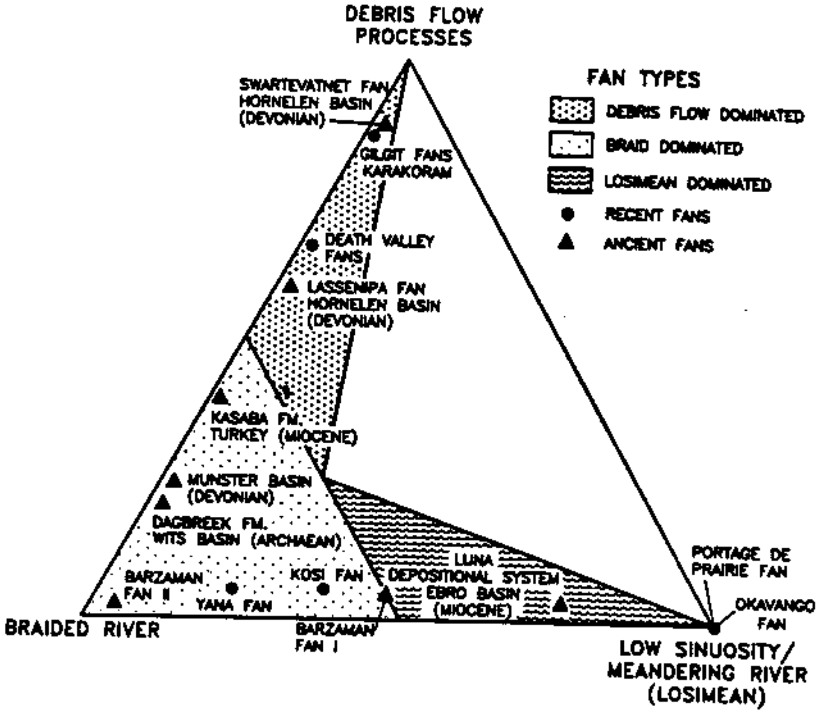


Fig. 12. Triangular field for the plotting and comparison of ancient and modern subaerial fans. Subfields representing the thr different fan types are delineated.

braided river and meandering/low sinuosity river processes may all operate in a single system. Although such an example might be presently considered idealized, in reviewing modern and ancient fans in the literature we have been impressed by the possibility that such a coexistence of the three styles is a possibility. The apparent linear array of fans may be just that, apparent, limited only by our present scientific perceptions. The aim of this paper is to open up possibilities rather than to close them down and for this reason the triangular field is presented.

Conclusions

The Okavango Fan represents a new type of subaerial fan in which meandering and low sinuosity rivers dominate in the shaping of the depositional system. It is distinguished by the large percentage of areas supporting lush vegetation. This vegetation is, in turn, important in confining the fluvial channel systems. A partially comparable modern depositional system is the Portage de Prairie Fan of the U.S.A. An ancient partial analogue is the Miocene Luna depositional system of the northern part of the Miocene Ebro Basin. The subaerial part of the latter appears to have had characteristics intermediate between losimean and braid dominated fans.

The Okavango Fan is an end member of a spectrum of subaerial fan types which can be represented by three main types: (1) debris flow dominated fans (of which Death Valley fans are a member); (2) braided river dominated fans (of which the Kosi Fan is a member); and (3) meandering/low sinuosity river losimean dominated fans (of which the Okavango Fan is a member). Intermediates between all these fan types have been recognized. Previous attempts to relate these entirely to climate are incorrect. The Okavango Fan with all its "humid" features is developed in an overall semi-arid setting. It is, however, the perennial nature of the river and its confinement which gives it these characteristics. Other factors such as tectonic stability and source material may have equally important primary roles in controlling the fan system; however, it is the depositional processes ordained by these primary controls which shape the fan body.

The three fan types can be characterized by differences in slope, maximum size and vegetation cover. Important differences are how "flashy" or continuous are discharges on their surface and to what degree flows are confined and channelized on their surface. Debris flow dominated fans are steep, small, poorly vegetated systems; braid dominated fans are shallower, larger fans which support vegetation; but meander/low sinuosity dominated fans are very low gradient and can be very large fans which are highly vegetated. Large subaerial fans such as the Kosi and Okavango fans provide a link in the size spectrum between subaerial fans and submarine fan systems.

Identification of facies and facies sequences by themselves are inadequate to differentiate fluvially shaped subaerial fans and alluvial plains. Additional information in the form of palaeocurrent variation or trend information such as that of grain size or average channel thickness is required to establish whether the fluvial system was distributary (fans) or through-flowing (plains).

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