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The great inland deltas of Africa

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Abstract - At least three large (> 30000 km²), low gradient alluvial fans, termed "Inland Deltas" by early travellers, are developed on the African continent. They have several features in common: (i) all occur in half-graben structures and are fault-bounded at their distal ends; (ii) they have low topographic gradients (0.2 to 0.05 m/km), and an extensive network of distributary channels on the fan surface which sustain vast wetland systems; (iii) all occur in semi-arid settings in which evapotranspiration greatly exceeds rainfall and inflow is derived from high rainfall sub-tropical areas; between 50 and 95 % of inflow is lost to the atmosphere; (iv) the feeder rivers are low in suspended load and water chemistry is dominated by bicarbonate and silica; (v) they have extensive seasonal swamps, vegetated by grasses and sedges with numerous tree-covered islands, and variable areas of permanent swamp. Sedimentation is dominated by clastic accumulation in and near channels and by chemical sedimentation (calcrete and silcrete) in the seasonal swamps. Organic material is not preserved because of destruction by fire. The occurrence of these features is a result of the geomorphic influences of plate tectonics and global climatic structure.

INTRODUCTION

The classic deltas of the Nile and Niger Rivers are well entrenched in the sedimentological literature as a result of intensive study in recent decades. But geographers early in this century also recorded the existence of delta-like features within the continent, which, because of "birds-foot" or anastomosing distributary systems, were termed "Inland Deltas". These are of comparable area to their marine counterparts, but all lie in remote, relatively inaccessible regions of the continent and have therefore not been accorded the same degree of attention as the marine deltas.

Three of these features are known and occur on the Niger River in Mali (the Niger Inland Delta), on the Nile River or Bahr el Jebel in the Sudan (the Sudd) and on the Okavango River in Botswana (the Okavango Delta) (Fig. 1). A possible fourth example occurs on the Chari River south of Lake Chad. This paper compares the geological and geomorphological environments of these widely separated features in an attempt to discern their sedimentological and geomorphological significance. The comparison is carried out from the following perspectives: morphology, hydrology, climatic setting, water chemistry, sediment load, geological setting and vegetation cover as these parameters completely constrain the depositional setting. Although the use of the term "delta" to describe these features is inappropriate (Bates and Jackson, 1987), it will nevertheless be used here because of well entrenched usage in the literature.

THE SUDD

Morphology

The Sudd is a vast wetland located on the Nile River or Bahr el Jebel on extensive plains of southern Sudan. It has the shape of an isosceles triangle approximately 520 km from apex to base and a base length of 120 km (Fig. 2). It contains some 16600 km² of permanent swamp, flanked by 14000 km² of seasonally flooded grassland (Sutcliffe and Parks, 1987). The northern boundary is marked by an uplift, the Nuba Mountains (Salama, 1987). The gradient across the Sudd is between 0.052 m/km (Rzoska, 1976) and 0.1 m/km (Howell *et al.*, 1988).

North of Juba (Fig. 2), the Bahr el Jebel is incised and confined to a narrow flood plain by elevated banks, with a gradient of 0.21 m/km. The distance between the banks increases northwards and their height decreases. North of Bor, the eastern bank disappears and the flood plain widens while the western bank disappears at Shambe, resulting in a dramatic widening of the flood plain (Sutcliffe, 1974; Howell *et al.*, 1988).

South of Bor, the river itself is confined by levees and flows at a higher elevation than its flood plain. Seasonal flood water overtops the levees or discharges through crevasses onto the flood plain (Sutcliffe, 1974). Downstream of Mongalla, the levees become less distinct and the river becomes increasingly anastomosed. North of Bor, the

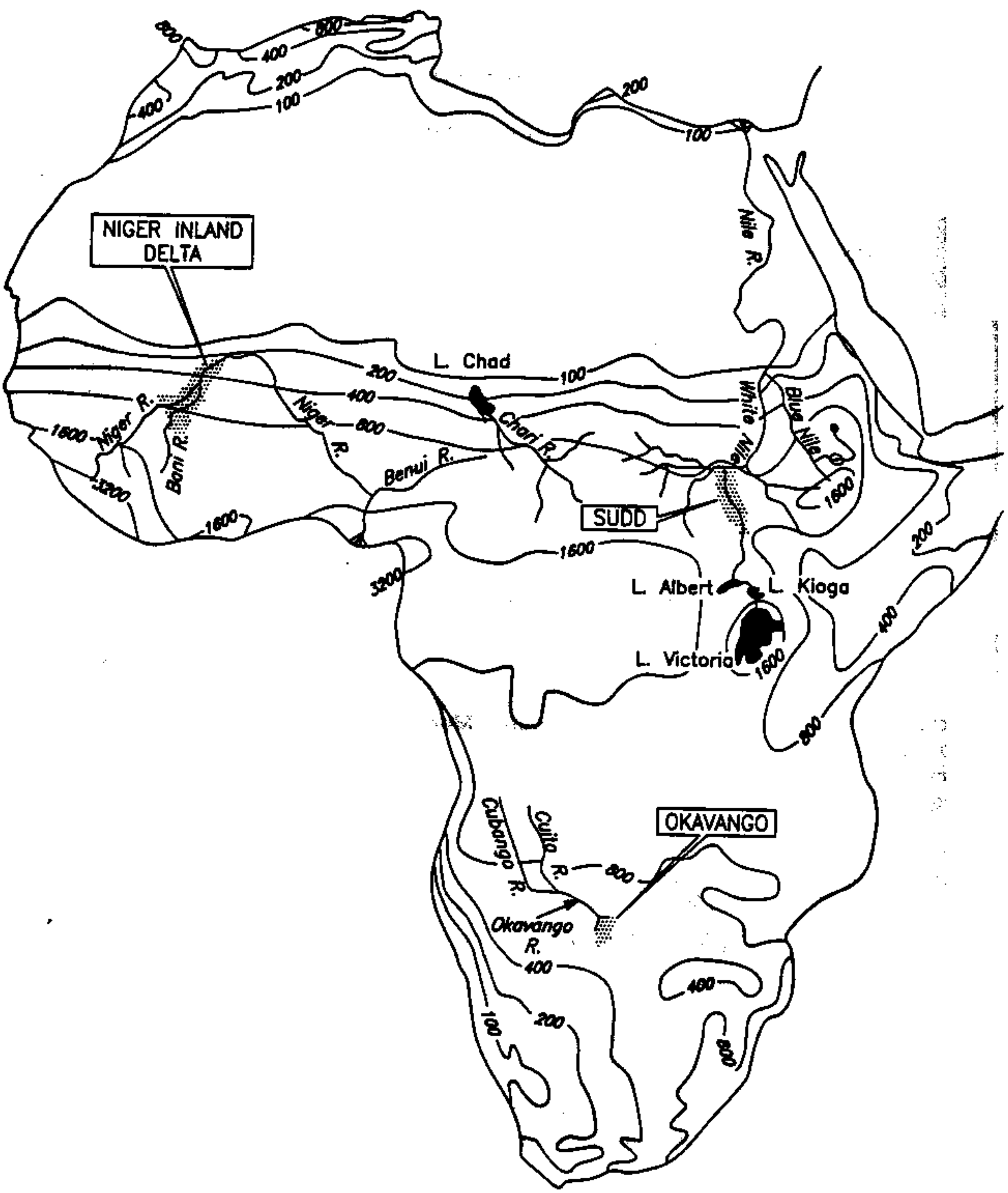

Fig. 1. Rainfall map of Africa showing the Inland Deltas (Thompson, 1965; Nicholson, 1980; Thomas and Shaw, 1991).

sinuous, anastomosed channels form a complex system of channels and interconnected lakes (Howell *et al.*, 1988) about 15 km wide, flanked by permanently inundated swampland. The area of swamp attains its greatest width north of Shambe (Fig. 2). The Bahr el Zeraf distributary channel rises in this extensive swamp and is connected to the Bahr el Jebel by artificial canals (the Zeraf cuts) dredged in 1910 and 1913 (Howell *et al.*, 1988). The Bahr el Zeraf and Bahr el Jebel diverge to the north, separated by permanent and seasonal swamp (Fig. 2). At the northern end of the Sudd, both make an abrupt eastward turn and are joined by the Bahr el Ghazal via Lake No from the west. Most of the inflow from this latter source is believed to be derived from swamps west of the Bahr el Jebel (Howell *et al.*, 1988).

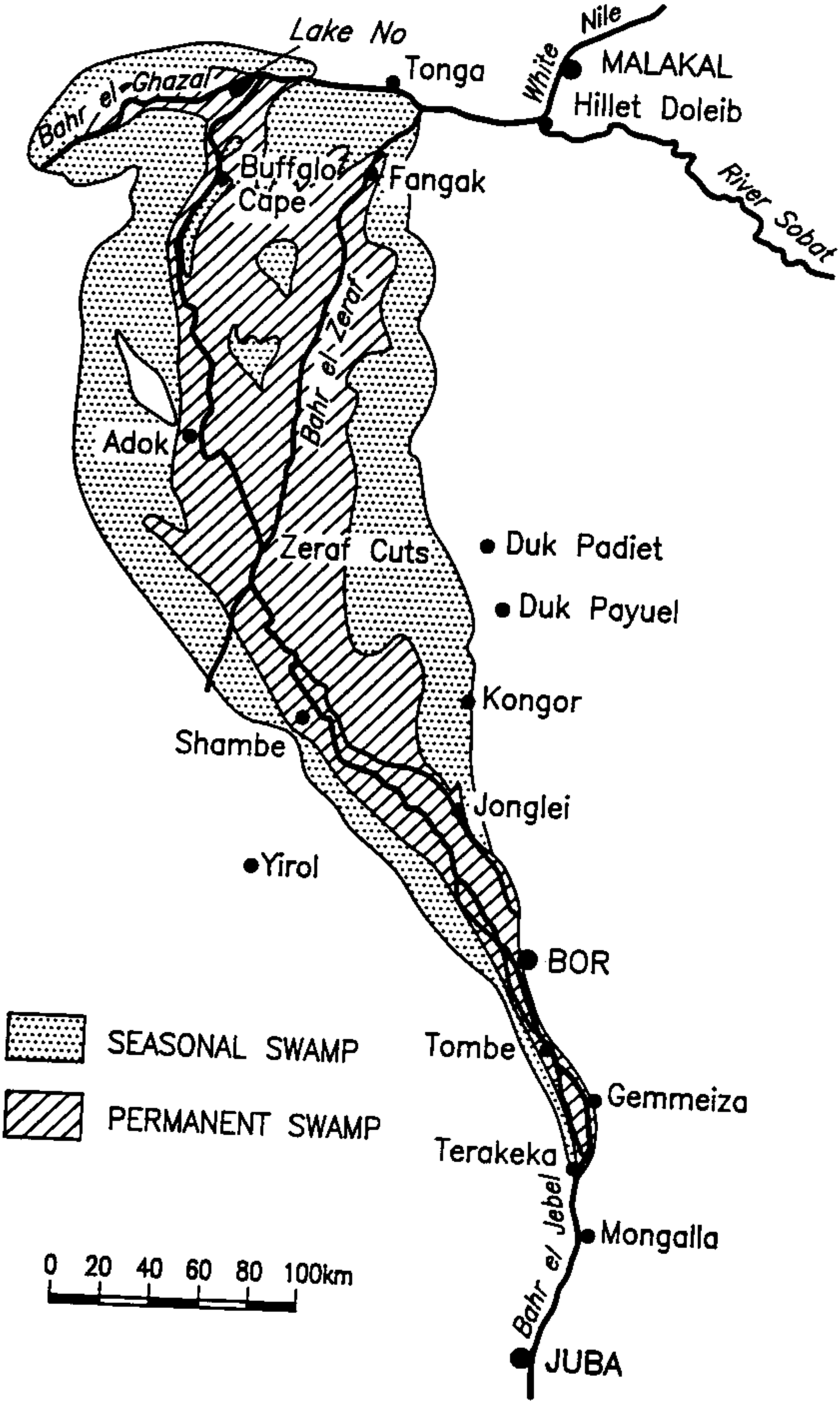

Fig. 2. Post 1961 map of the Sudd (Howel *et al.* 1988).

Outflow from the Sudd is augmented by the River Sobat which rises in the highlands of western Ethiopia and southern Sudan.

The permanent swamps are flanked by seasonally flooded areas. Topographic relief in the Sudd is minimal, but the seasonal swamps are characterized by a "microtopography", consisting of gentle swells and depressions with a relief of the order of a metre (Rzoska, 1976), locally accentuated by termitaria. The topographic highs often have a central depression and are frequently the sites of villages as they are less prone to flooding. The mean depth of flooding over the entire swamp is of the order of 1 m (Sutcliffe and Parks, 1987). According to Howell *et al.* (1988), the soils of the seasonal swamps consist of coarse sand and "clay" with little silt and fine sand.

Hydrology

The inflow to the Sudd represents a combination of outflows from Lakes Victoria, Kioga and Albert, augmented by seasonal discharge of torrents upstream of Mongalla. Most important, however, is Lake Victoria, a depression between the eastern and western branches of the Rift Valley (Fairhead, 1986; Frostick and Reid, 1989), which supplies 80 per cent of Sudd inflow. Lake Victoria receives most of its water by rainfall directly on the lake and hence outflow is critically dependent on fluctuations in rainfall (Piper *et al.*, 1986). In the period 1961 to 1964, Lake Victoria experienced a 20 per cent increase in rainfall, doubling the outflow to the Sudd (Piper *et al.*, 1986; Sutcliffe and Parks, 1987). Increased outflow has persisted because of the large storage capacity of lakes Victoria, Kioga and Albert. Average discharge in the Bahr el Jebel measured at Mongalla was 28.6×10^9 m^3/a for the period 1905-1960 but increased to 50.3×10^9 m^3/a for the period 1961-1980 (Sutcliffe and Parks, 1987). The swamp area doubled as a result.

Discharge from the lakes is seasonal and peaks at Mongalla between August and October (Fig. 3a). Water level in the Nile rises as the flood arrives, producing a seasonal stage variation of 0.67 m at Shambe. This fluctuation decreases to 0.37 m at Adok and 0.25 m at Buffalo Cape, because, in the absence of lateral confinement, excess water simply spills outward, increasing the area of inundation. Along the northern boundary of the Sudd, seasonal fluctuations in water level increase from 0.53 m at Lake No, to 1.39 m at Tonga and 1.63 m at the confluence of the Bahr el Zeraf (Sutcliffe, 1974). Movement of the flood wave is slow and peak discharge at the northern end of the Sudd occurs between December and January, some four months after peak discharge at the southern end, in spite of the fact that current velocities in the Bahr el Jebel range from 1.13 m/s at Bor to 0.6 m/s at Lake No (Rzoska, 1976). Only forty percent of inflow plus rainfall leaves as surface outflow (Sutcliff and Parks, 1989). Migahid (1947) suggested that transpiration is the major cause of this loss.

Climate

The Sudd lies perpendicular to the isohyets which define the Sahel (Fig. 1) and accordingly there is a decrease in rainfall from south to north;

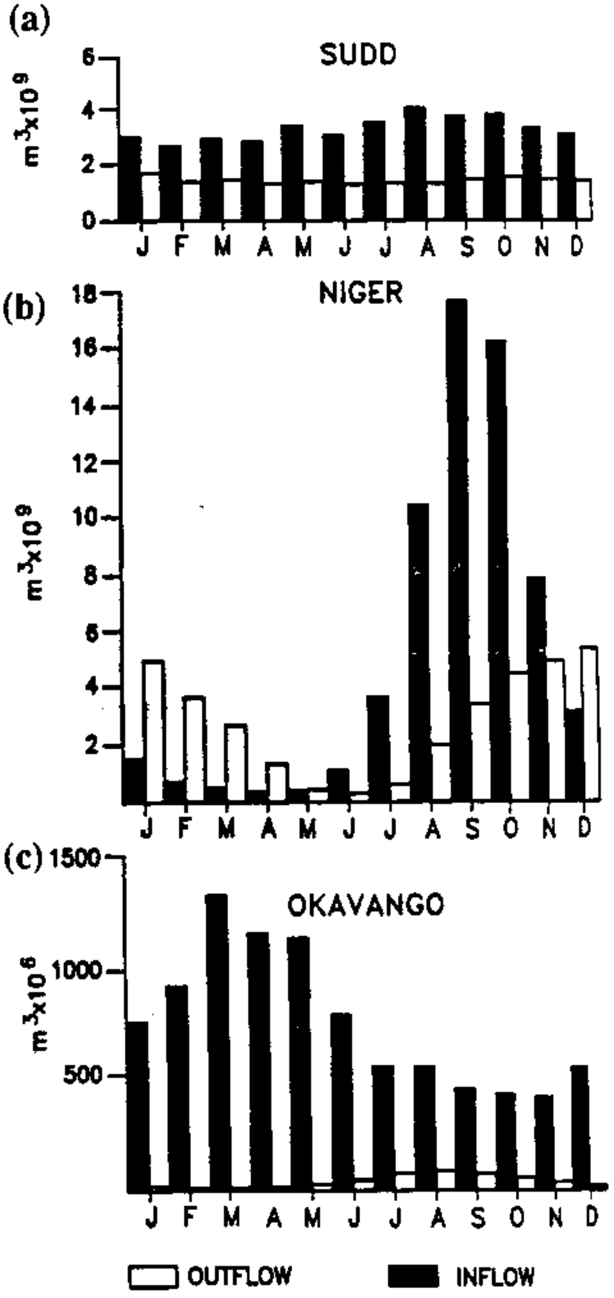

Fig. 3. (a) Discharge at inlet and outlet of the Sudd (Sutcliffe and Parks, 1987). (b) Discharge at inlet and outlet of the Niger Inland Delta (Sutcliffe and Parks, 1987). (c) Discharge at inlet and outlet of the Okavango Delta (UNDP, 1976).

at Bor mean annual rainfall is 904 mm, while at Malakal, 789 mm (Howell *et al.*, 1988). Average annual rainfall for the entire Sudd is 871 mm (Sutcliffe and Parks, 1989), and falls between May and October (Fig. 4). Mean daily temperature is 28°C (Howell *et al.*, 1988). Evaporation exceeds precipitation for all but two months of the year (Fig. 4) and also increases from south to north. Mean annual evapotranspiration is 2150 mm, some 2.5 times greater than precipitation, accounting for the large water loss from the Sudd (Sutcliffe and Parks, 1987).

Water chemistry

Two systematic studies of variations in water chemistry across the Sudd have been carried out (Tailling, 1957; Howell *et al.*, 1988). Neither published complete analyses, the emphasis being on nutrient species. The study by Tailling indicated that change in total dissolved solids across the swamp was of the order of 10%, most of which occurred in the upper reaches, in spite of the high evapotranspirational losses. Dissolved load tends to fluctuate seasonally because of quite large differences in the composition of water in Lakes Victoria and Albert (Rzoska, 1976). Typical water composition at Bor is shown in Table 1. The water is bicarbonate dominated. Sulphate content decreases across the Sudd from 3 mg/l to about 1 mg/l (Talling, 1957).

Table 1. Chemical compositions of water from the Inland Deltas

	1	2	3	4
Na mg/l	15	2.1	2.3	2.0
Ca mg/l	9	2.7	3.2	5.0
Mg mg/l	5	0.6	1.0	0.6
K mg/l	9	1.7	2.2	1.4
HCO_3 ..	110	18	21	22
Cl mg/l	14	0.0	0.0	<1
SO_4 mg/l	3	-	-	<1
SiO_2 mg/l	18	10	5	16

1 Bahr el Jebel river at Bor. (Ilaco, 1981; Talling, 1957; Rzoska, 1976).

2. Niger River at Segu. Average of four monthly samples collected between July and October 1969. SiO_2 from a single sample collected in October (Grove, 1972).

3. Bani River at Mopti. Samples collected over same period as in 2 (Grove, 1972).

. Okavango River, apex of Panhandle. (Hutton, 1976).

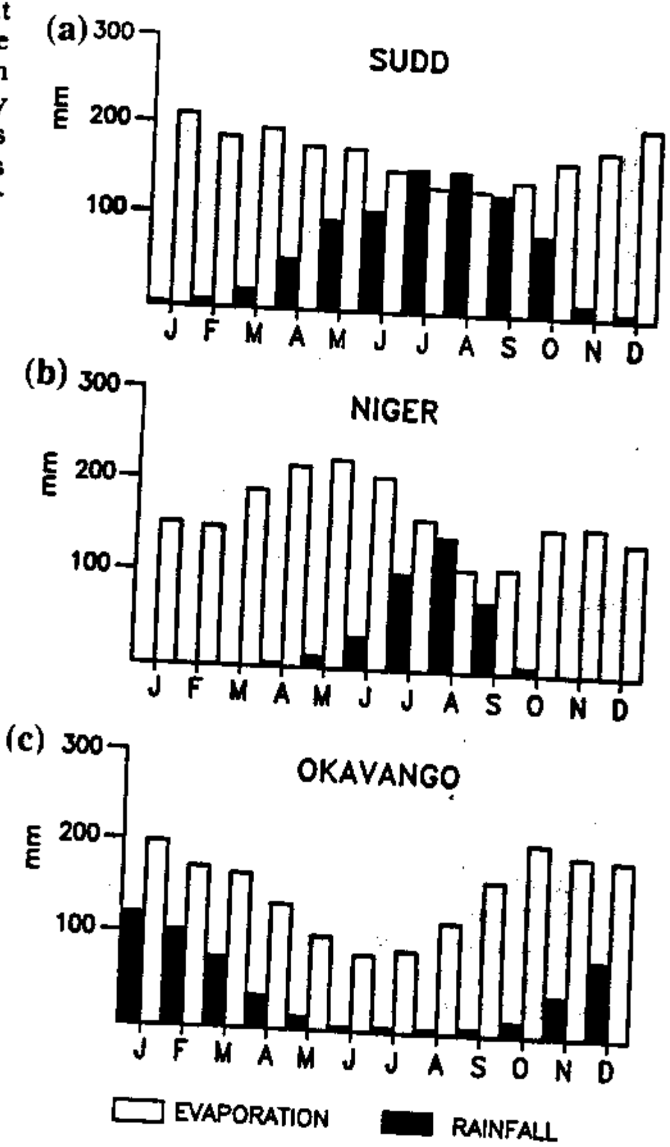

Fig. 4. (a) Monthly rainfall and evaporation in the Sudd (Sutcliffe and Parks, 1989). (b) Monthly rainfall and evaporation in the Niger Inland Delta (Sutcliffe and Parks, 1989). (c) Monthly rainfall and evaporation in the Okavango (Sutcliffe and Parks, 1989).

Sediment

No studies of sediment transport have been undertaken in the Sudd. Suspended sediment load is likely to be low, because the bulk of the water originates in lakes, although rain-fed torrents upstream of the Sudd increase the turbidity (Howell *et al.*, 1988). Turbidity measurements (Secchi disc) reported by Howell *et al.* (1988) showed a 50% decline across the Sudd, but as the swamps probably generate considerable organic particulates, the net loss of detrital particulates is likely to be greater than indicated by the turbidity. Williams and Williams (1980) note that the contribution of the White Nile to the total sediment load of the Nile is negligible.

Geological controls

Adamson and Williams (1980) noted the unusual convergence of drainage and deflection of the course of the Bahr el Jebel at the northern end of the Sudd (Fig. 2) and ascribed this and other features of the drainage to tectonic controls. Recent oil exploration activities in the area have shown that the Sudd is part of a northwesterly striking rift system (Southern Sudan Rift, Fairhead and Green, 1989) containing an excess of 13 km of non-marine sediment (Schull, 1988). The history of rifting is complex and began during the Cretaceous (Fairhead and Green, 1989) and involved at least three periods of extension. The terminal phase, which began in the mid Miocene, was characterized by gentle subsidence (Schull, 1988; Salama, 1987, 1990). The rift is formed by a series of linked half-grabens (Mann, 1989) each bounded by a master fault (Sander and Rosendahl, 1989) with smaller synthetic or antithetic normal faults. The presence of Precambrian rocks north of the Sudd along the Bahr el Gazal suggests that the master fault forms the northern boundary of the Sudd. Adamson and Williams (1980) suggested that the course of the Bahr el Jebel in the southern portion of the Sudd might also be subject to tectonic control by northwesterly striking faults. The area is seismically active, with most activity occurring in the south around Juba (Ambraseys and Adams, 1986) and a recent series of large earthquakes was associated with the northwesterly striking faults (Gaulon *et al.*, 1992).

Vegetation

Three species dominate the permanent swamps. *Vossia cuspidata* occurs primarily towards the southern end of the swamps close to flowing water. It forms floating mats over water up to 4 m deep. *Cyperus papyrus* forms a fringe to the major distributaries 30 km broad in the south, declining to 50 m in the north and disappearing completely in the far north. The plants also decrease in stature from south to north. *Typha domingensis* is most extensive in the north especially away from channels. *Phragmites karka* grows in shallow permanent swamps in the upper reaches (Perry, 1984; Migahid, 1947). Water hyacinth, *Eichhornia crassipes* was introduced in 1957 and has become an important component of channels and lakes. Common submerged species in lakes are *Ceratophyllum demersum*, *Otelli* spp and *Najas pectinata*. The seasonally flooded grasslands are dominated by three species: in the more deeply flooded areas, *Oryza longistaminata* predominates, while *Sporobolus pyramidalis* and *Hyparrhenia rufa* occur in shallow flooded areas. More distal areas, which are infrequently flooded are dominated by *Echinocloa pyramidalis*. The area beyond the flooded fringe is largely woodland, with *Acacia seyal* and *Balanites aegyptiaca* and a few *Combretum fagrans*. Towards the flooded fringe, distribution of trees is controlled by microtopography, with crests of mounds covered by woodland thicket (Howell *et al.*, 1988).

THE NIGER INLAND DELTA

Morphology

The Inland Delta of the Niger is located at the confluence of the Niger and Bani Rivers in Mali (Fig. 1). The total area of the wetland is about 30000 km² (McIntosh and McIntosh, 1980) of which some 4000 km² is permanently inundated (Grove, 1985). The Delta is flanked on its eastern side by the Bandiagara Plateau which has a prominent escarpment facing west, reaching an altitude of 700 m, some 400 m above the surface of the Delta (Gallais, 1967). To the west of the Delta lies an extensive area of fluvial deposits at about 10 m above the elevation of the present Delta, reffered to as the "Dead Delta" (Fig. 5) (Gallais, 1967) or Fala de Molodo system, which is covered by a thin veneer of aeolian sand (McIntosh and McIntosh, 1980). The northern boundary of the Delta is formed by prominent set of ENE trending linear dunes, the Erg de Niafounke (or Erg de Bara), against which two large lakes (Debo and Korientzé) are situated. Outflow from the lakes has broken through the Erg, which consists of about 20 dunes, in several places, causing the development of lakes and swamps in dune streets and in blow-outs in the lee of basement highs which project through the sand (Grove, 1985). These various outflow channels reunite in an intensely braided channel near Tombouctou (Fig. 5).

The Inland Delta consists of a cone with a northeasterly inclination. The area is very flat, with an average gradient of 0.05 m/km (Gallais, 1967). However, considerable local relief is developed. This relief is caused by sets of levees which lie parallel to active channels; by sinuous sandy ridges, probably representing former channel beds, now topographically inverted; by ENE trending dunes, now dormant, developed in the central and northwestern region of the Delta and by a gently undulating topography around the fringes of the Delta which gives rise to extensive archipelagos during the season flood, especially on the western margin.

Gallais (1967) considered the Delta to comprise several "sub-deltas" each supplied by an arterial channel. The incised tunk channels are 400 to 600 m wide and typically braided with prominent sand bars several hundreds of metres long. These be-

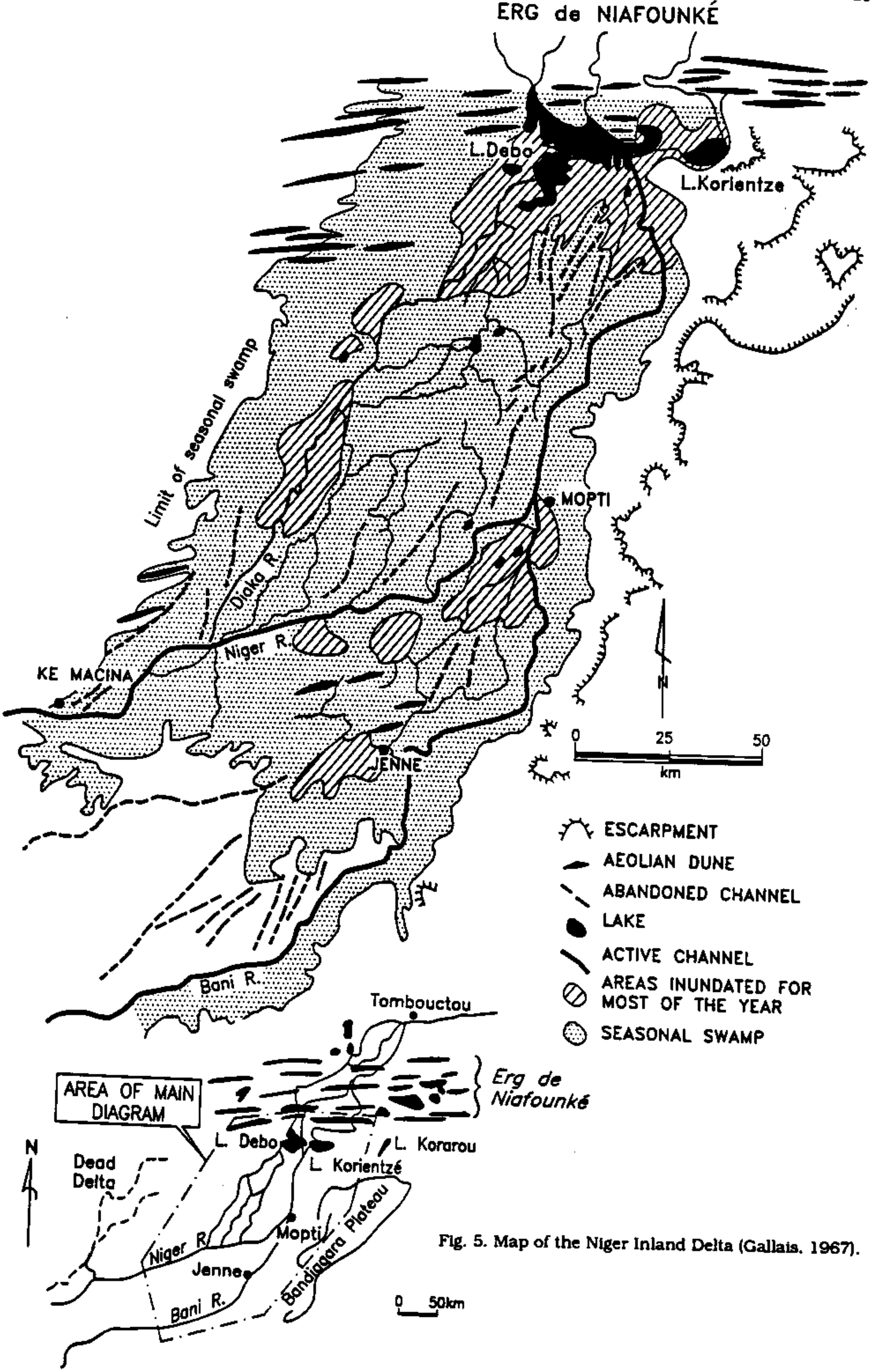

Fig. 5. Map of the Niger Inland Delta (Gallais. 1967).

come submerged and migrate downstream during the flood season. Levees, consisting of silt sized material (Jacobberger, 1987, 1988) flank the channel and are paralleled on either side by older levee systems. Lateral distributaries cut across the levee systems (Tricart, 1965). These consist of coarse sand, in contrast to the silty levee material, but there appears to be a general lack of crevassing (Jacobberger, 1988). Downstream, the confining levees become less prominent and more lateral branches occur, although each is braided. Beyond the levees are gently undulating plains or "flood basins" (Gallais, 1967) which are seasonally inundated, covered by a carpet of dense grass. In the distal reaches, braiding ceases, the channels take on a U-form and levees are very subdued. These areas remain flooded for most of the year and are characterized by floating grass and by small lakes. The beds of the flood basins are formed of clay (kaolinite) and fine quartz (McIntosh, 1980), with evidence of siliceous duricrust development (Jacobberger, 1987). Distal areas around the fringes of the Delta are underlain by sandy soils, which frequently contain carbonate nodules (McIntosh and McIntosh, 1980). The general absence of meander related features led Jacobberger (1987, 1988) to suggest that sedimentation is predominantly by vertical accretion, with frequent avulsion and channel abandonment.

Hydrology

The Niger and Bani Rivers rise in the rainfall belt along the West African coast. The catchment areas are 120 000 km^2 and 101 600 km^2, with average annual rainfall of 1600 mm and 1264 mm respectively (Gallais, 1967). Rainfall is strongly seasonal, peaking in September. There is a two to three week delay in arrival of peak flood of the Bani relative to the Niger, the Niger flood generally occurring at the end of September. The Niger contributes about 50 x 10^9 m^3 and the Bani about 20 x 10^3 m^3/a to the Delta.

The flood wave is considerably slowed by its passage through the Delta. Thus, the Niger flood takes 5 days to travel 300 km upstream of Ke-Macina; the 160 km between Ke-Macina and Mopti takes one month; and the 135 km between Mopti and Lake Debo takes a further month. Maximum outflow occurs in December, three months later than maximum inflow (Fig. 3b). Only one half of inflow plus rainfall leaves as surface outflow (Sutcliffe and Parks, 1989) most of the rest being lost to the atmosphere.

Climate

The Niger Inland Delta straddles the marked climatic gradient of the Sahel (Fig. 1). Rainfall decreases from 680 mm in the south to 330 mm in the north (Gallais, 1967). Sutcliffe and Parks (1989) estimated an average annual rainfall of 425 mm for the Delta. Rainfall is very seasonal, falling between April and October (Fig. 4b). The area is subject to pronounced variations in rainfall and frequent droughts (Jacobberger, 1988). Annual evapotranspiration varies from 2200 mm in the north to 2100 mm in the south (McIntosh and McIntosh, 1980) and exceeds rainfall in all months of the year except August (Fig. 4b). Mean daily temperature at Mopti is 27.7°C (McIntosh and McIntosh, 1980).

Water chemistry

Studies of the seasonal variability in dissolved solids in the Niger River upstream of the Inland Delta indicate a maximum of about 60 ppm in April-May declining to a minimum of about 20 ppm in September (Grove, 1972). The Bani River probably shows a similar pattern. Dissolved solid concentrations in the outflow varies from a low of about 20 ppm in October to a maximum of about 40 ppm in June. The chemical compositions of Niger and Bani River waters is shown in Table 1. The water is bicarbonate dominated and chloride and sulphate contents are below 1 ppm (Martins, 1982). Mass balance calculations based on inflow and outflow led Grove (1972) to conclude that "a volume of water about equal to the annual discharge of the Bani plus its dissolved solids are 'lost' from the Niger each year in its passage through the Inland Delta" (p. 288).

Sediment

Gallais (1967) reported suspended sediment loads in the Niger River. These show a maximum of 107 mg/l in the dry season. McIntosh and McIntosh (1980) reported an average sediment load in the inflowing water of 75 mg/l and an average in outflow of 8.15 mg/l. No studies of bedload transport have been carried out. There is currently some active aeolian transport in the Delta (Jacobberger, 1987, 1988).

Geological controls

It is widely accepted that tectonic movements have played a role in regional drainage patterns in the area (Petit-Maire and Riser, 1987, Blanck and Tricart, 1990), but the mechanisms are as yet unclear. Gallais (1967) and Grove (1985) cited the progressive easterly movement of the Delta as indicating subsidence, possibly accompanied by faulting along the Bandiagara escarpment (Grove, 1985). Gallais (1987) suggested that the Erg de Niafounke might overlie an upfaulted block of underlying Palaeozoic sandstones. The barrier thus created has facilitated preservation of the dunary relief. McIntosh and McIntosh (1980) and McIntosh (1983) further suggested that the relic dunes in the central Delta may also be anchored on an ENE trending upfaulted basement block or scarp. Blanck and Tricart (1990) refer to the existence of an ENE trending upfaulted block bounding the northern end of the "Dead Delta" and suggested that the Delta as a whole may be influenced by several large fault blocks.

Vegetation

The vegetation in the areas flanking the Inland Delta is strongly influenced by the climatic gradient of the Sahel. *Acacia albida* occurs throughout, but is stunted in the north. *Guira senegalensis* occurs on the shores upstream, but is replaced by *Boscia senegalensis* to the south. In the southern region, the palm *Borassus aethiopum* predominates, but in the north it is replaced by *Hyphaenae thebaica*. Palms colonize the numerous islands along the edge of the swamp. On the fringes of the swamps, *Acacia regal* grows in heavier soils, while *Acacia senegal* prefers more sandy soil. Along channel banks, *Diospyros mespiliformus*, *Acacia ataxacantha* and *Moerua senegalensis* occur, together with the grass *Cynodon dactylon*. *Sporobolus spicatus* occurs where saline conditions exist in the soils.

Grasses generally occur in areas which are prone to flooding, species being determined by depth and duration of flooding. The "shore" zones are characterized by *Andropogon gayanus*; areas flooded for less than three months are dominated by *Vetiveria nigritana*, especially in clayey soils, while *Cynodon dactylon* occurs on the sandier soils. Areas flooded between three and six months are characterized by *Oryza barthii*. Areas flooded for more than six months are dominated by "bourgou", an association of *Echinochloa pyramidalis*, *E. stagnina and Panicum stagnum*. All possess long, fleshy stems and rise and fall with the changing water level. Ponds may also contain *Nymphaea* spp. (Gallais, 1967).

THE OKAVANGO DELTA

Morphology

The Okavango Delta is situated on the Okavango River in northern Botswana (Fig. 1). It consists of about 6000 km² of permanent swamps flanked by a further 7 000 to 12 000 km² of seasonally inundated swampland. In the upper "Panhandle" region of the Delta (Fig. 6) the flood plain of the Okavango River is confined by 4 to 5 m high shoulders of Quaternary aeolian (Kalahari) sediment. At the southern end of the Panhandle, the lateral confinement ceases and the Okavango River branches into three distributary channel systems, the Thaoge to the west, the Jao/Boro to the centre and Nqoga/Maunachira to the east. The last mentioned is the major distributary at present, but in the last century, the Thaoge was the major distributary (Wilson, 1973). The region below the Panhandle is a broad, gentle conical surface or fan (Fig. 1), with an average gradient of 0.28 m/km (Wilson and Dince, 1976). The permanent swamps are confined to the Panhandle and to an area around the apex of the fan, extending along the distributaries. Average water depth in the swamps is about 1.6 m (UNDP, 1976). Lakes, representing ancient oxbows, are locally developed in the permanent swamps (McCarthy *et al.*, 1993a).

The distal limit of the Delta is defined by NE striking fault scarps, against which the fan abuts. Two depressions are developed on either side of the fan, the Mababe Depression in the east and Lake Ngami (currently dry) in the west. These depressions contained lakes at various times in the past (Shaw, 1984, 1988). Overflow from the fan crosses the scarp via the Boteti River (Fig. 6). Currently dormant fans of comparable size to the Okavango Delta occur to the east and west (Hutchins *et al.*, 1976; Thomas and Shaw, 1991), and the overall fan complex exceeds 65 000 km² in area. Extensive linear dune fields are developed to the east and west of the Panhandle (Thomas and Shaw, 1991) while smaller dunes also occur along the southern extremily of the Delta. Most of the Delta is covered by a mantle of aeolian sand and as a result the soils are generally very sandy.

In the Panhandle and upper fan, the Okavango River is meandering, although the channel is largely vegetatively confined (McCarthy *et al.*, 1991a). In the lower permanent swamps, the channels are sinuous but not meandering and are also vegetatively confined. Levees consist mainly of swamp vegetation (McCarthy *et al.*, 1991a, 1992). These channels are subject to periodic avulsion which results in major shifts in water distribution on the fan (McCarthy *et al.*, 1988, 1992). Channels in the upper seasonal swamps are somewhat incised with minor levees locally developed, but both levees and incision become less prominent downstream, where the channels consist of shallow sinuous depressions.

Topographic relief within the Delta is confined to gentle swells, producing islands, which are particularly abundant around the fringes of the Delta in the seasonal swamps. Occasionally, these islands are arranged in sinuous chains (Wilson and Dincer, 1976). The islands often have a raised margin with a slight interior depression and are characterized by subsurface carbonate and amorphous silica accumulations under the raised rim (McCarthy *et al.*, 1991b; McCarthy *et al.*, 1993a). The local relief is generally less than two metres, but is often accentuated by termitaria.

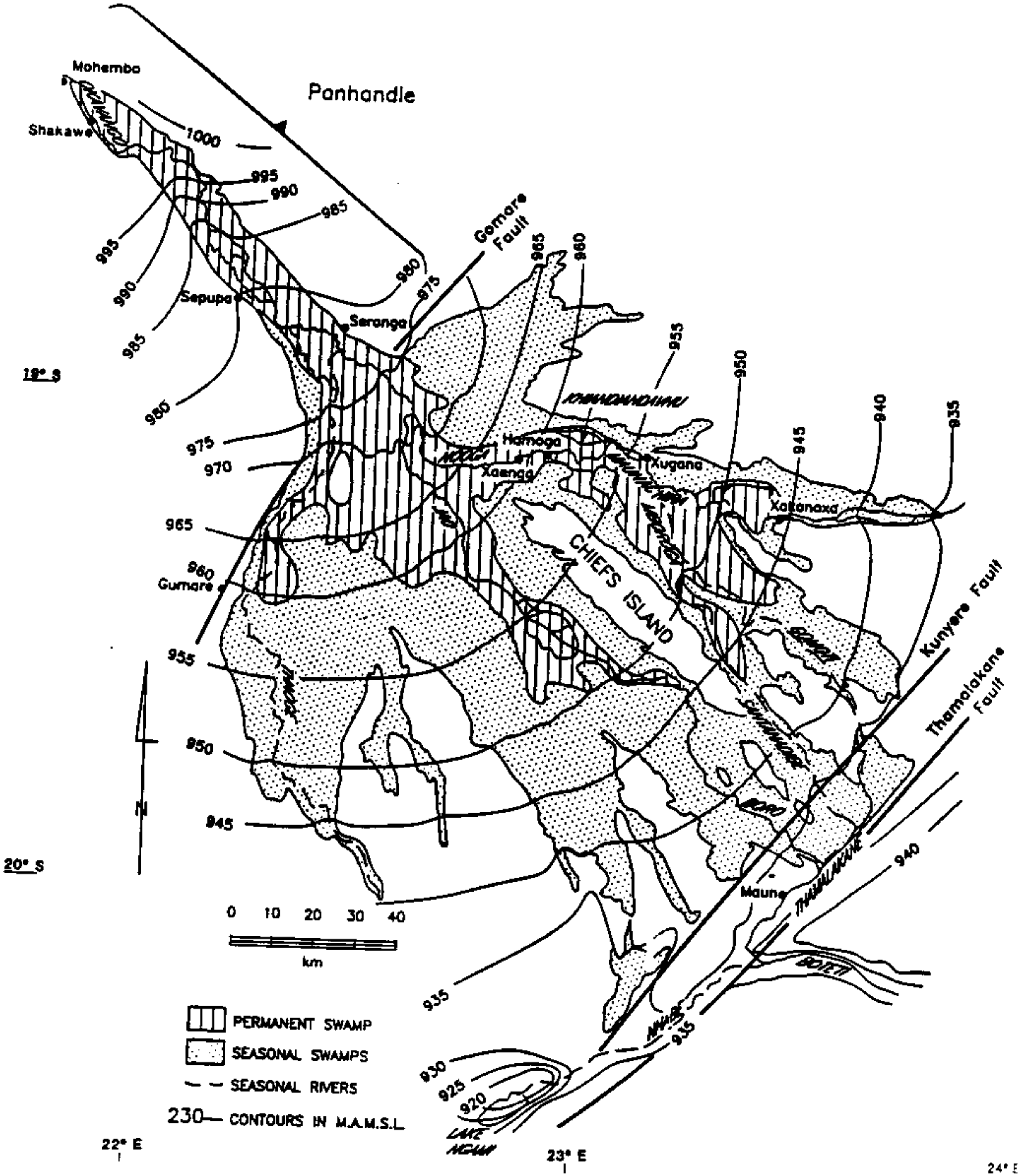

Fig. 6. Map of the Okavango Delta (McCarthy *et al.*, 1991a).

Hydrology

The major tributaries of the Okavango River are the Cubango (catchment area 115 000 km²) and Cuito (catchment area 65 000 km²) Rivers which rise in subtropical central Angola. Average rainfall in the two catchment areas is 983 mm and 876 mm respectively (Wilson and Dincer, 1976). These rivers combine in southern Angola to form the Okavango River. Peak discharge at the apex of the Panhandle occurs in March or April. Total discharge is 10.6×10^9 m^3/a. The flood wave is slowed considerably in its passage across the Delta, and peak discharge at the lower extremity occurs in July or August (Fig. 3c). Only two percent of total inflow plus rainfall leaves the Delta as surface outflow (Dincer *et al.*, 1982). It is estimated that only two percent leaves via groundwater flow (Dincer *et al.*, 1982), the rest being lost by evapotranspiration.

The passing of the flood wave results in a seasonal change in water level of 1.7 m in the upper reaches of the Panhandle (UNDP, 1976), but this decreases to 0.15 m in the upper reaches of the fan, increasing again as much as 2.7 m in the channels of the lower seasonal swamps (Wilson and Dincer, 1976).

Climate

The Okavango Delta is situated on the northern fringe of the Kalahari Desert. Average rainfall for the entire Delta is 500 mm/a (Wilson and Dincer, 1976), falling from November to March. Annual evaporation is about 1800 mm, and evaporation exceeds rainfall in all months of the year (Fig. 4c) (Sutcliffe and Parks, 1989). Mean daily temperature is 30.4°C (Wilson and Dincer, 1976).

Water chemistry

The Okavango River water in the Panhandle (Table 1) is bicarbonate dominated and silica is a major component. Total dissolved solid content approximately trebles between inlet and outlet (Sawula and Martins, 1991), northwithstanding the large evapotranspirational losses within the Delta. Saline pans are very rare in the Delta and are confined to the interior depressions of a few islands (McCarthy *et al.*, 1991b).

Sediment

Suspended sediment load in the Okavango River in the Panhandle is very low (*ca* 8 to 9 mg/l, McCarthy *et al.*, 1991a) and declines downstream. Although no measurements have been made in the outflow, water clarity suggests that very little sediment leaves the Delta in suspension. Total sediment load is dominated by bedload, which consists of reworked aeolian sand which underlies most of the catchment area of the Okavango River (Thomas and Shaw, 1991). Total annual bedload influx into the Delta has been estimated to be 170 000 t, 95% of which is currently being deposited in the Panhandle (McCarthy *et al.*, 1991a).

Geological controls

The Okavango Delta lies in a seismically active area which is believed to represent an extension of the East African Rift System (Scholz *et al.*, 1976). Two major faults striking NE-SW and downthrowing to the northwest (Thamalakane and Kunyere faults) define the south eastern limit of the Delta. Displacement on these faults is of the order of 200 to 300 m (Reeves, 1978). The parallel Gomare fault appears to transect the Delta at the southern end of the Panhandle with downthrow to the south east. Lineament analysis based on satellite imagery has revealed a second, less prominent set of faults orientated NW-SE, parallel to the Panhandle (Hutchins *et al.*, 1976; McCarthy *et al.*, 1993b). A structural analysis carried out by McCarthy *et al.* (1993b) suggests that east-west crustal extension is occurring, reactivating NE-SW orientated basement structures, producing an oblique slip half-graben structure in which the Thamalakane and Kunyere faults represent the principal detachments. Antithetic faults have developed at a high angle to this direction, producing more localized graben structures, of which the Panhandle is the largest. Local horsts form large land masses within the Delta (e.g., Chief's Island, Fig. 6). NE and NW striking faults have produced a system of interconnected grabens which in part control water dispersal in the Delta.

Vegetation

The upper, deeper reaches of the permanent swamps are dominated by *Cyperus papyrus* and *Thelypteris confluens*, with *Vossia cuspidata* along channel margins. In shallower swamp, *Typha latifolia* and *Phragmites australis* are common. Downstream, the papyrus becomes stunted and gives way to *Miscanthus junceus*. *Ficus verruculosa* also becomes common in the distal swamps. In distal backswamp areas, *Pycreus nitidus* is most common, along with *Scirpus cubensis*. *Nymphaea* spp are common in slow flowing, open water, along with a variety of other emergent and submerged plants, notably *Eichhornia natans*, *Najas pectinata*, *Trapa natans* and *Typha capensis*. Islands in the permanent swamp support large trees, including *Diospyros mespiliformis*, *Ficus sycomorus*, *Acacia* *nigrescens*, *Garcinia livingstonei*, *Combretum imberbe* and the palms *Pheonix reclinata* and *Hyphaene ventricosa*. Grasses are *Cynodon dactylon*, with *Imperata cylindrica* on the damp margins and *Sporobolus spicatus* towards island centres where soils are more saline (McCarthy *et al.*, 1993a). Seasonal swamps are dominated by *Panicum ripens*, *Oryza longistamina*, *Scipus inclinatus* and *Cyperus articulatis*. The palm *Hyphaene ventricosa* is very common on islands in the distal seasonal swamps. Woodland areas surrounding and on large land masses within the Delta are dominated by *Acaccia* spp, *Combretum imberbe*, *Colophospermum mopane* and *Zizyphus mucronata* (Smith, 1976).

DISCUSSION

Unifying factors

The Inland Deltas described here differ in detail, but there are several remarkable similarities which suggest common underlying conditions and processes. The conditions which give rise to these features have occurred at least three times on the African continent. The Chari-Logone river system south of Lake Chad, where 90 000 km² are annually flooded (Lowe-McConnell, 1985), could constitute a fourth example as this area has many features in common with the Inland Deltas described here (Grove, 1985). Unfortunately, detailed information is not available. The frequency of occurrence of Inland Deltas on the African continent is of the same order as marine deltas and the resulting sedimentary sequences must therefore be at least as important in the geological record as are marine deltaic sequences.

The use of the term "Delta" to describe these features is, as pointed out earlier, a misnomer. Although they have all, at some time, discharged into lakes, the "Delta" was invariably larger than the lake and quite different from lake deltas described elsewhere, such as at Lake Maracaibo (Hyne *et al.*, 1979) or Lake Turkana (Frostick and Reid, 1986). These Inland Deltas are more correctly described as large alluvial fans, but of a type only recently recognized (Stanistreet and McCarthy, 1993).

The common environmental factors which unite these fans are:

i) their association with active faulting;

ii) evapotranspiration significantly exceeds inflow, yet saline lakes are not developed;

iii) suspended load is generally low (compare with Milliman and Mead, 1983);

iv) they have bicarbonate dominated water, with low chloride and high silica content;

v) they are subject to seasonally variable but not flashy discharge;

vi) they experience periodic desiccation.

The role of tectonism

All of the fans have upfaulted blocks at their distal ends. There is more to this than simple obstruction to flow as is indicated by the case of the White Nile between the Sudd and the Blue Nile confluence. Here, the sediment-laden Blue Nile has constructed a large alluvial fan which has obstructed the course of the White Nile and reduced its gradient to 0.015 m/km (Berry and Whiteman, 1968), one third that in the Sudd. No inland deltas has developed and the White Nile follows a straight course with minor anastomosis (Williams *et al.*, 1982).

Rather than simple uplift, what appears to be important in each of the fans is the development of a half graben, with the river approaching from the hanging wall side. This relationship was recognized by Frostick and Reid (1987) as being generally important in rift settings. Active subsidence in the more distal reaches appears to be an important process in sustaining the fan. It must be emphasized that flooding of the fan is not caused by ponding against the terminal scarp, but arises from overbank flooding over the entire length of the fan. As a result, the fans tend to aggrade vertically, especially in the distal reaches, rather than prograde as with normal deltas.

Sediment load

In such a setting, sediment load is evidently important in fan development. Too high a sediment load would result in filling of the graben and extension of the fluvial system across the graben, as for example, in the case of the Euphrates River (Hempton and Dunne, 1984). In effect, sediment volume must be equal to or less than the volume created by subsidence for a fan to form. Arid source areas with intermittent, sediment-laden discharge could not produce fans of the type described here.

Differences in sediment load may account for the difference between the three fans described here. Thus Niger River has far higher suspended sediment load than the Okavango River and its fan has well developed levees and a smaller proportion of permanent swamp compared to the Okavango, because levees tend to cannalize low discharge flow. The Bahr el Jebel appears to have a suspended sediment load between these two and hence levee systems are only developed in the southern end of the Sudd.

Climate

An arid or semi-arid environment in which evapotranspiration exceeds rainfall appears to be important in fan formation. Such an environment enhances chemical sedimentation and reduces the importance of organic sediment accumulation. In a more humid environment, permanent swamps and lakes would become important and organic sediment would be a major component in the sedimentary succession.

Lakes have intermittently developed adjacent to and beyond the terminal uplifts in each of the fans as a result of global climatic oscillation (Lake Sudd, Salama, 1987; an enlarged Lake Debo or Lake Arawan, McIntosh, 1980; Beadle, 1974; Petit-Marie and Riser, 1987; Lake Thamalakane; Shaw, 1988). Lake sedimentation is generally very slow, because of the lack of clastic sediment, and diatomites and various diagenetic minerals generally make up much of the lake sediment, as can be found in Lake Chad at the present time (see review by Grove, 1985b). During more arid periods, aeolian sand incursions occurred, remnants of which are evident in and around the fans described in the form of dunes and sandy soils. Both lacustrine and aeolian sediments are likely to be substantially modified by processes operative on distal reaches of the fans, as discussed below.

Water chemistry

The high evapotranspiration loss, coupled with high silica and bicarbonate and low chloride content of water appears to be important in fan development. The almost total absence of saline lakes associated with the fans indicates that open water evaporation is subordinate to transpiration and capillary evaporation (McCarthy and Metcalfe, 1991). Increased salinity arising from the latter processes occurs in ground water rather than surface water so that the salinity of outflowing water does not reflect the high evapotranspirational loss. Moreover, increased salinity in ground water is offset by precipitation of silica and magnesian calcite and the formation of the diagenetic minerals such potassium feldspar (McCarthy *et al.*, 1991b; Eugster and Jones, 1979) and a variety f other minerals (Gac *et al.*, 1977; Grove, 1985b). his would not be possible if the proportion of chloride was high; solute species would not precipitate as diagenetic minerals and evapotranspiration would produce brines rich in highly soluble lkali and alkaline earth chlorides. These would ll vegetation and result in saline surface brines. ocally, soils do, however, become alkaline as a sult of the accumulation of sodium bicarbonate n the ground water. This manifests as extensive occurrence of salt tolerant plants such as palms (*Hyphaene* spp) and the grass *Sporobolus spicatus* (Ellery *et al.*, 1993). Tree covered islands are particularly important on these fans, and appear to act as transpirational pumps. Carbonate and silica precipitation occurs preferentially beneath the islands and is an important aggradational process on the fans (McCarthy and Metcalfe, 1991; McCarthy *et al.*, 1993a), and is the cause, at least in the Okavango, of the characteristic undulating topography, especially in the more distal areas of the seasonal swamps (McCarthy *et al.*, 1993a).

Islands appear to nucleate on any topographically elevated feature such as termitaria, topographically inverted channel beds, (McCarthy *et al.*, 1988) levees or aeolian features. These become accentuated over time due to displacive subsurface precipitation of carbonate and silica. The relative importance of this chemical sedimentation compared to clastic sedimentation seems to vary in the different fans. In the case of the Okavango fan, chemical exceeds clastic sedimentation by a factor of two (McCarthy and Metcalfe, 1991) while clastic sedimentation exceeds chemical sedimentation by at least a factor of three in the Niger fan. While clastic sedimentation predominates in the proximal areas of the fans, chemical sedimentation occurs primarily in the distal areas and contributes towards maintaining the low gradients on the fans.

Vegetation

Dense aquatic vegetation flanking channels serves to trap suspended sediment and to confine bedload channels. Channel aggradation leads to avulsion, increasing the area of sediment dispersal over the fan (McCarthy *et al.*, 1992; Jacobberger, 1988). In spite of prolific plant growth, however, the preservation potential of organic material is low because of fires which burn off accumulated organics either seasonally (Gallais, 1967) or following an avulsion (Ellery *et al.*, 1990). Swamp environments therefore will appear in the sedimentary record as layers of shaly sediment, rich in detrital quartz and kaolinite and in phytolitic silica (McCarthy *et al.*, 1989). Bioturbation of such material by termites and burrowing animals is likely to be intense and the material is also likely to show varying degrees of pedogenesis. Swamp vegetation also serves to retard the passage of the seasonal flood, increasing lateral dispersal and enhancing evapotranspirational loss.

Variability of discharge

Marked seasonality in discharge is also important. Levees are poorly developed because of the low sediment load. As the trunk river emerges from its confined erosional upper reach into the graben structure, the flood plain widens and in the absence of well developed levees, it will seasonally overtop its banks and disperse water widely across the flood plain. In this way evapotranspirational loss and the consequent chemical aggradation processes are enhanced. This would not occur if discharge were uniform throughout the year.

Coincidence of environmental variables

The important variables, which are common to the fans and are considered to be fundamental to their formation, are apparently unconnected; yet the coincidence of these variables has occurred on three and possibly four occasions on the African continent. The question as to why such a coincidence of apparently random variables is so common needs to be addressed.

Continental break-up frequently creates marginal uplifts (Summerfield, 1984) which divert drainage into the interior, as has been documented in the case of southern Africa (Thomas and Shaw, 1988). These interior drainages are in time captured by coastal rivers which have cut through to the interior by headward erosion: by the Tilemsi in the case of the Niger (Grove and Warren, 1968) and by the Lower Nile, in the case of the Bahr el Jebel (Williams and Williams, 1980). The capture process has not yet occurred in the case of the Okavango River, although adjacent rivers (Kwando and Zambezi) have been captured (Thomas and Shaw, 1988). The Chari also remains an interior drainage.

While rainfall along coastal uplifts may be high, the interior of continents in mid-latitudes is invariably arid so that rivers flowing inland may encounter arid conditions. Runoff from high rainfall areas is usually of low suspended load because of vegetation cover in the catchment. Moreover, such runoff is low in dissolved solids and is usually bicarbonate dominated (Nkounkou and Probst, 1987) because of intense leaching of weathering profiles in the catchment, and especially if granitic rocks are abundant in the catchment (Garrels and McKenzie, 1967).

Rifting within a continent has a profound effect on drainage and while major rivers will be deviated away from uplifts, they readily flow into half graben sub-basins across the hanging wall (Frostick and Reid, 1989). Such rifts may actually entrain an entire drainage system, as in the case of the Benue River (Frostick and Reid, 1989). It is for these reasons, therefore, that the coincidence of apparently randon variables is not an uncommon occurrence.

Fan classification

Stanistreet and McCarthy (1993) discussed the classification of alluvial fans and recognized three end member types. There are: debris flow dominated fans (e.g., the fans of Death Valley, California); braid dominated fans (e.g., the Kosi fan); and what they termed losimean (an acronyn for "low siniousity, meandering") fans (e.g., the Okavango fan). The Sudd is very similar to the Okavango fan and is therefore of the losimean type, thereby extending the size of known examples of this type of fan. The Niger Inland Delta appears to be intermediate in character between losimean and braid dominated fans, as it shows well developed clastic levees and channels are braided in its upper reaches.

The environmental variables in the three fans are similar, the main difference between the Niger and the other fans detailed being the sediment load, which is higher in the case of the Niger. Consequently, it appears that this factor may be particularly important in determining fan character on the spectrum between braid dominated and losimean types. In contrast, climate in catchment area, which determines the nature of discharge, appears to control the character of fans between braided and debris flow type. It is evident from the examples considered here that aridity in the area of the fan itself is of little consequence in influencing the braid or debris flow character.

CONCLUSIONS

Three large, low gradient alluvial fans, termed "Inland Deltas" by early travellers, have been recognized on the African continent. Analysis of their environmental setting has indicated that they have several features in common, and appear to form when low suspended load rivers, with bicarbonate dominated water, discharge across the hanging wall of a rift half graben situated in a semi-arid environment. The frequent coincidence of these apparently unconnected variables is a consequence of plate tectonic processes and global climatic structure.

Sedimentation on these fans is mainly of two types. The proximal areas are dominated by clastic sedimentation, in which channel deposits, produced by bedload deposition, form a major component. Although channel systems are usually associated with densely vegetated swamps, preservation potential of organic material is low because of destruction by fire. Swamp terrain will therefore be represented in the sedimentary record by shales or silts. The distal reaches of these fans are dominated by diagenetic carbonate and silica precipitation, resulting from transpiration by plants. This occurs in the subsurface within some previously deposited substrate, frequently an aeolianite, and leads to the formation of massive calcrete and silcrete. The relative proportions of clastic and chemical sedimentation will depend on the sediment load of the river system feeding the fan.

These fans are subject to periodic desiccation and invasion by aeolianite, which will result in interbedding of aeolian and fluvial sediment. Much of the fluvial sediment may in fact be reworked aeolian sand. Lakes may also develop from time to time in the distal reaches of such fans. Lake sediments will be dominated by carbonate and silica precipitates, various diagenetic minerals and by diatomite, because of the low suspended load.

Vegetation, especially grasses and sedges, plays an important role in fan sedimentation. These plants confine the channels, localizing bedload, and limit the spread of suspended sediment but at the same time allow widespread distribution of water, thereby promoting chemical sedimentation in the distal areas. This type of fan is therefore only likely to have developed in post-Cretaceous times. However, it is possible that in earlier times, other plant species may have occupied the ecological niche of grasses, contributing to similar types of fans in pre-Cretaceous times. These fans can develop at any stage during rifting: early, as in the case of the Okavango, or at a very late as in the Sudd. It appears from this analysis that sediment-ry sequences arising from these fans are likely to orm an important component of continental rift equences.

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