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The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango swamps, Botswana

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Abstract - The Okavango alluvial fan occurs in an extension of the East African Rift system. Changes in water dispersal patterns on the fan have been attributed both to neo-tectonic activity and to sedimentation. Analysis of SPOT satellite imagery in an area where major changes in water distribution are currently taking place indicates that these changes are initiated by neo-tectonic activity, which creates interconnected graben systems which divert water flow. The process of redistribution is accentuated by sedimentation in distributary channels. The graben systems arise due to East-West extension which has produced intersecting, conjugate fault sets. Analysis of associated seismic activity indicates that seasonal flooding has no influence on seismicity, which is due entirely to crustal extension.

INTRODUCTION

The Okavango Delta of northern Botswana (Fig. 1) is one of the largest alluvial fans on earth. It is flanked by currently dormant fan systems (Hutchins *et al.*, 1976; Shaw and Thomas, 1992) which, together with the Okavango, cover an area of 65000 km². The fan complex is situated in a graben structure which is believed to represent a southerly extension of the East African Rift System (Du Toit, 1925; Fairhead and Girdler, 1971; Scholz *et al.* 1976). The area is seismically active (Reeves, 1972; Scholz *et al.*, 1976) and evidence of neo-tectonic influence on drainage and geomorphology abounds in the general area (Cooke, 1980; Thomas and Shaw, 1991).

Water distribution in the Okavango swamps is prone to change (Shaw, 1984) and it has been suggested that these changes are due to tectonic activity (Wilson, 1973). Such tectonic influences have been recorded in major alluvial systems elsewhere, such as the Mississippi (Russ, 1982) and the Brahmaputra (Coleman, 1969). In the case of the Mississippi, it has moreover been shown that seismicity is influenced by loading due to annual flooding (McGinnis, 1963). In contrast, McCarthy *et al* (1986, 1988a, 1992) have suggested that sedimentation is the primary cause of changes in water distribution in the Okavango swamps.

In an attempt to reconcile these conflicting views, a detailed review was undertaken of the seismic activity in the Okavango region. In addition, high resolution SPOT satellite imagery covering an area where channel abandonment is currently occurring was examined in order to obtain data on water dispersal patterns.

METHODS

Seismic data

Reliable seismic data are available from 1951 from the South African and Zimbabwe Geological Surveys. The early period of instrumentation (pre 1960) was such that only events greater than magnitude (M_L) 4 were reported. Post 1960, event as small as 2.7 were located. Error estimates of epicentral determination were quoted at approximately half a degree (Reeves, 1972), based on comparisons of international and local network determinations. Magnitude estimates were converted to energy using the standard Richter-Gutenberg magnitude energy relationship ($\log E = 1.5\ M + 4.8$) in order to determine release rates. Only data between 22°E and 24°E and 18°S and 20.5°S were selected.

SPOT imagery

Data for the study were collected by the SPOT 2 satellite on the 8th October, 1991. This period was chosen as it coincides with the end of the long dry season as well as the waning of the seasonal flood, thereby ensuring maximum contrast between flooded and non-flooded terrain. Image processing of the data was carried out on a 486 PC using the Map and Image Processing System package. A colour image of the Transformed Vegetation Index (McCarthy *et al.*, 1993) (100* sqr.rt ((NIR - red)/ (NIR + red))) (Jensen, 1986) was produced from the SPOT data for use in this study. This parameter was chosen so as to obtain maximum enhancement of the vegetation, thereby emphasizing flooded areas. The location of the image is shown in Fig. 1.

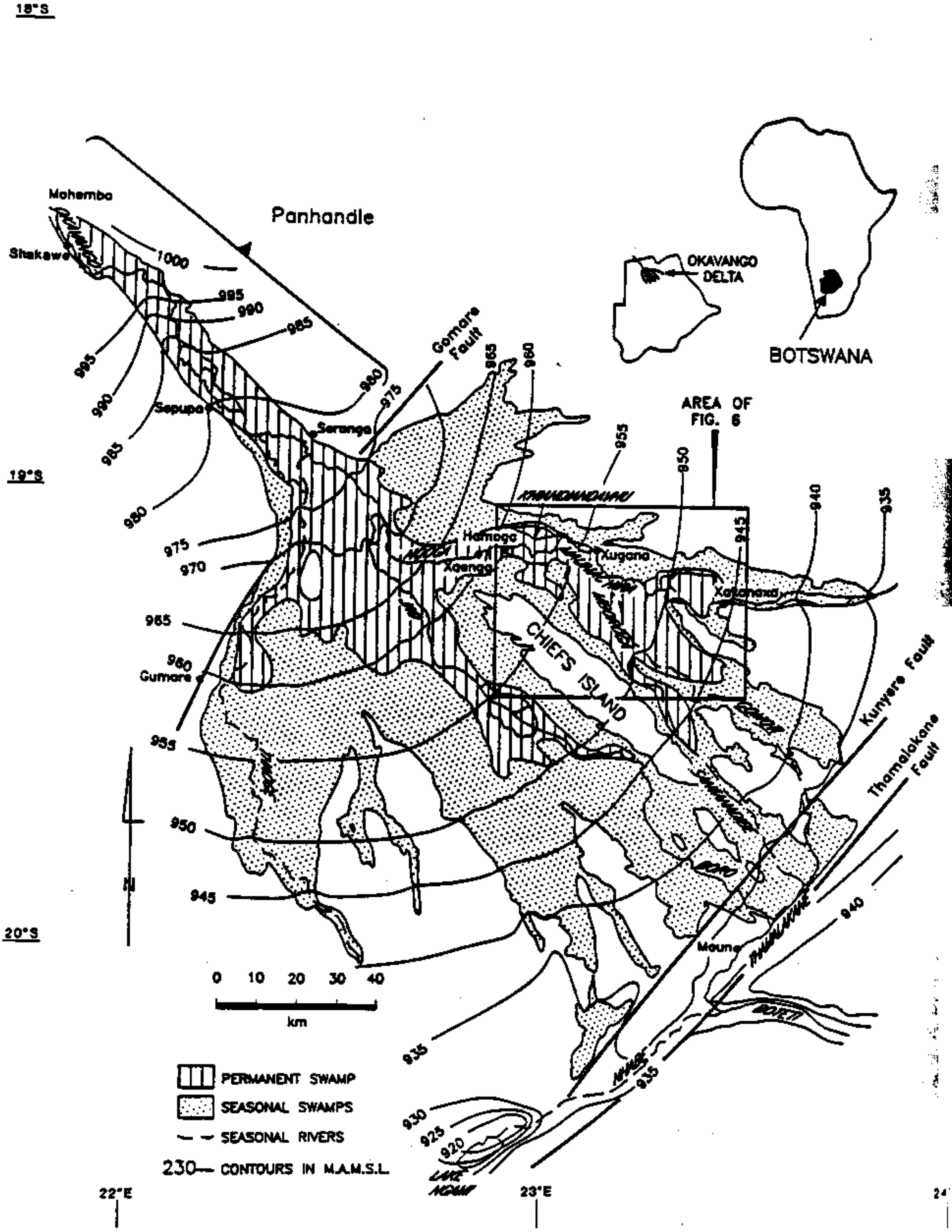

Fig. 1. The Okavango Delta.

RESULTS AND DISCUSSION

Geomorphology, hydrology and sedimentology of the Okavango

The Okavango Delta is traditionally divided into three geomorphic regions (Wilson, 1973): the Panhandle, the upper permanent swamps (*ca.* 6000 km²) and the lower seasonal swamps (*ca* 6000-12000 km²) (Fig. 1). Topographic gradient across the entire Delta is 1:3600, and the Delta has an overall conical form (UNDP, 1976; Fig. 1) typical of alluvial fans. The southern boundary of the Delta is formed by fault scarps associated with the northeasterly striking Thamalakane and Kunyere faults (Fig. 1) (Mallick *et al.*, 1981). Two depressions, Lake Ngami and the Mababe Depression, lie adjacent to the fault scarps on either side of the fan and have contained lakes at various times in the past (Shaw, 1988).

The area surrounding the Delta complex is characterized by aeolian features, notably by a longitudinal dune system striking 105°. A less prominent dune system is also developed between the Thamalakane and Kunyere faults. These dune systems are probably dormant at present. Within the area of the Delta, few aeolian features are evident although the soils consist mainly of aeolian sand (Cooke, 1975). The topography is gently undulating with a relief of the order of 1 to 2 metres. The thickness of fill beneath the Delta is of the order of 300 m (Reeves, 1978; Meixner and Peart, 1984).

Water is supplied to the Delta by the Okavango River, which rises in central Angola (catchment area 180000 km²; Wilson and Dincer, 1976). Annual discharge is about 10.6 x 10^9 m³/a which is augmented by 5 x 10^9 m³/a of rain. Peak seasonal flood (*ca* 1600 m³/s) occurs at the apex of the Panhandle in February (Fig. 2), but dissipates slowly through the swamps, taking four months to traverse the 250 km length of the Delta (Wilson and Dincer, 1976; McCarthy *et al.*, 1991). Only 2 percent of inflow exits as surface outflow and it is estimated that a further 2 per cent leaves via ground water flow, the remainder being lost to the atmosphere by evapotranspiration (Dincer *et al.*, 1982). Water is conveyed onto the Delta by a istributary channel system, but channel margins re permeable (McCarthy *et al* 1988b) and leak ater to the surrounding swamps (McCarthy *et al.*, 991). Sediment load is dominated by bedload McCarthy *et al.*, 1991) and in the permanent wamps loss of water from the channels induces edload deposition and hence vertical aggradation the channels (McCarthy *et al.*, 1986, 1988a). cCarthy *et al.* (1992) cited this process as the imary cause of channel avulsion.

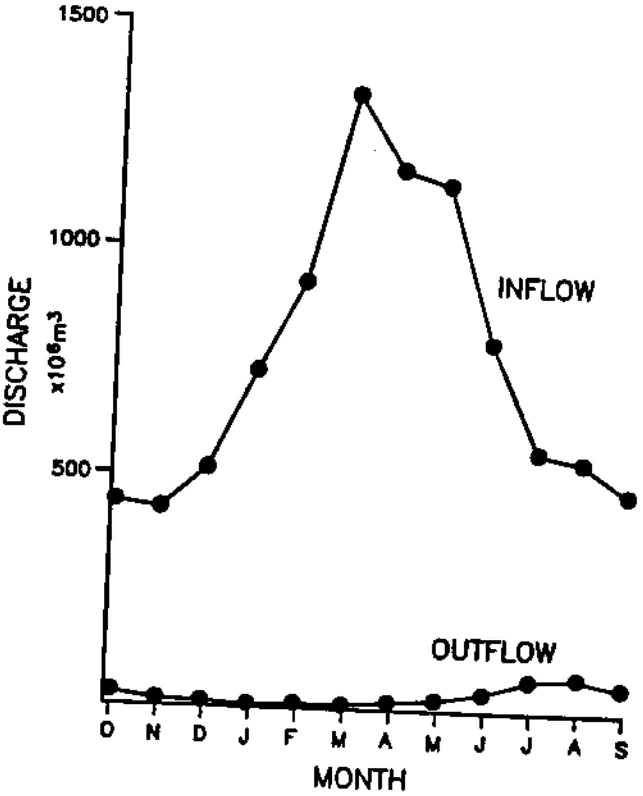

Fig. 2. Typical inflow and outflow patterns for the Okavango (UNDP, 1976)

Water distribution over the Delta has changed dramatically in historic times (Shaw, 1984; Wilson, 1973; McCarthy *et al.*, 1986). In the mid 1800's, the main distributary system (Thaoge, Fig. 1) discharged down the western flank of the Delta, sustaining a permanent water body in Lake Ngami. This channel began to fail in the late 1800's and water diverted to the east. By the early 1900's the Nqoga-Mboroga-Santantidibe system was the main distributary (Stigand, 1923). This channel system was severed by the failure of the lower Nqoga and water began to divert northwards to the Maunachira channel. In the 1950's, water also began to enter the Jao-Boro system, a diversion possibly linked to a major earthquake (6.7 on the Richter Scale) in 1952 (Wilson, 1973). The Nqoga Channel has continued to fail progressively upstream and has been the subject of intensive study (McCarthy et al., 1986,1988a, 1992; Ellery *et al.*, 1989). The SPOT image used in the present study included this area of current channel failure.

Basement Geology

Most of Botswana is covered by Kalahari sediments (Thomas and Shaw, 1991) and outcrops are confined to the southeastern region of the country. The geology of the greater part of Botswana is therefore only known through geophysical evidence and limited drilling. The southeastern portion of the country is underlain by Archaean granite-greenstones of Zimbabwe and Kaapvaal cratons with local cover of Proterozoic rocks (Fig. 3). These are flanked to the west and northwest by a series of orogenic belts. The oldest of these is defined by the early Proterozoic Kheis and Okwa sequences which were deformed in the *ca* 2-1.8 Ga Ubendian orogeny. These are flanked to the north and west by the more extensive Kgwebe and Ghanzi sequences of middle Proterozoic age which were deformed during the Irumide Orogeny (*ca* 1.0 Ga). Finally, the northwestern region is underlain by late Proterozoic Damaran sequence rocks, which were deformed during the Pan-African orogeny (*ca* 0.5 Ga). Rocks of the orogenic belts have a strong northeasterly grain. Palaeozoic to Mesozoic Karoo rocks cover most of the basement. Reactivation of older structures in the orogenic belts has led to the local development of thick Karoo sequences in the northwest (Orpen *et al.*, 1989). The Karoo strata are intruded by northwesterly striking dykes, the most prominent of which is a swarm which passes through the Okavango area (Reeves, 1978b).

Seismicity in the Okavango Delta

A total of 109 events exceeding magnitude 2.7 (which was the cut-off limit of the intrumentation) over the period 1951 to 1992 were extracted. The frequency of events as a function of time is shown in Fig. 4. The activity peaked in 1952 and it was

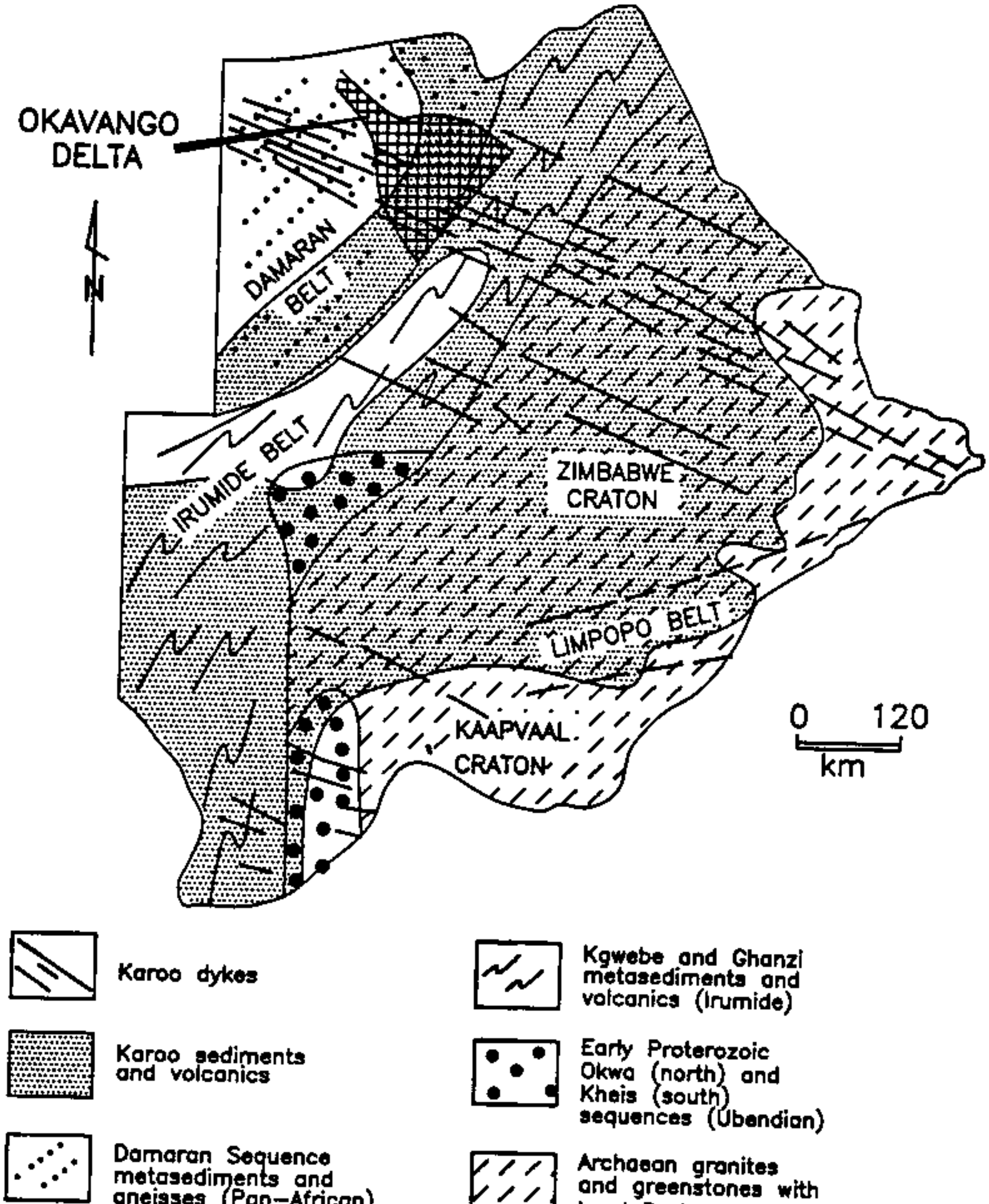

Fig. 3. Generalized map showing the sub-Kalahari and sub-Karoo geology of Botswana. (Based on Thomas and Shaw, 1991; Master, 1991; Fairhead and Stuart, 1982 and other sources).

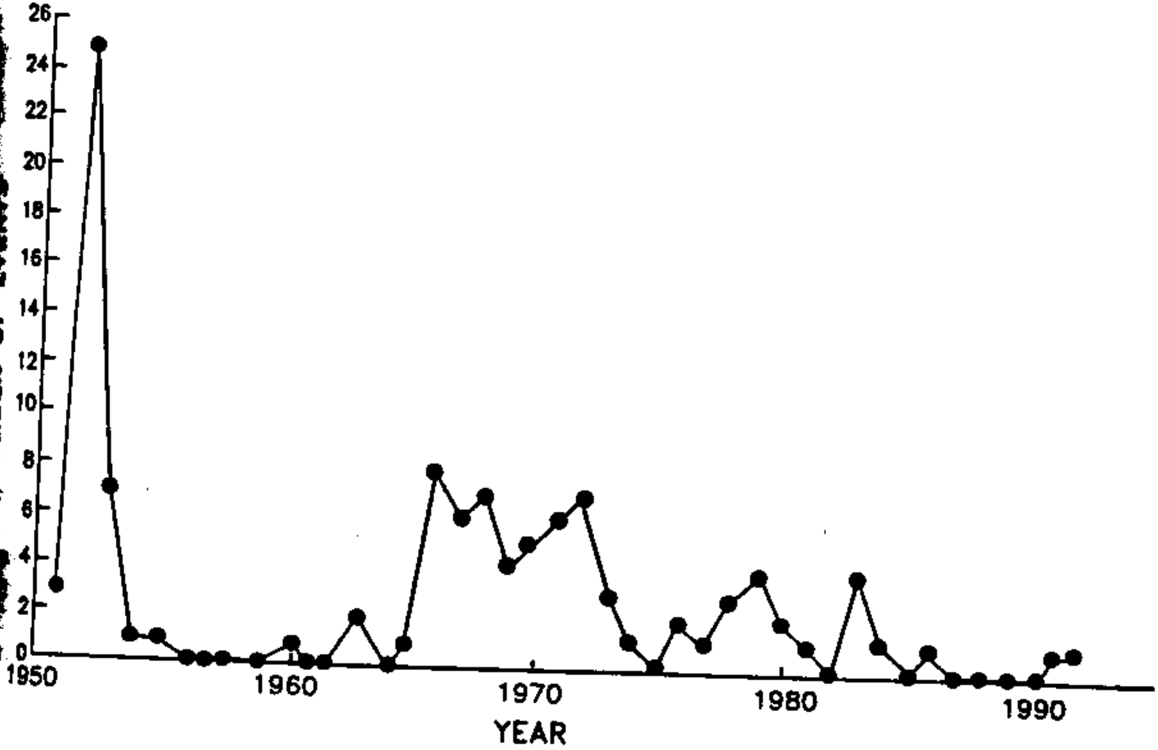

Fig. 4. Frequency of seismic events in the Okavango Delta as a function of time.

uring this period that a sequence of seismic ents exceeding magnitude 5, and including an ent of magnitude 6.7, was recorded. The late 50s and early 1960s were seismically quiet but tivity recommenced during 1966. Since then tivity has diclined. Energy release per year is own in Fig. 5. The early 1950s are dominant and count for more than 95 per cent of the total ergy released over the last forty years. There pears to be a significant decrease in activity nce the high of 1952.

neaments in the study area

Lineaments in the study area are defined by gned swamp margins, linear arrays of islands d straight segments of channel. The distribution lineaments in the study area is shown in the notated SPOT image in Fig. 6. It is evident from s figure that the Maunachira channel system d its associated swamps are confined on either e by numerous lineaments. The gently undula- topography causes the swamp water to over- these features periodically, producing an inter- tent trace on the image. Nevertheless some of features can be traced over tens of kilometres. ee distinct sets of lineaments are developed, ding northeast and west-northwest. These form connected systems which bound large areas wamp. It is significant that the section of the ga channel which has been abandoned is ounded by lineaments.

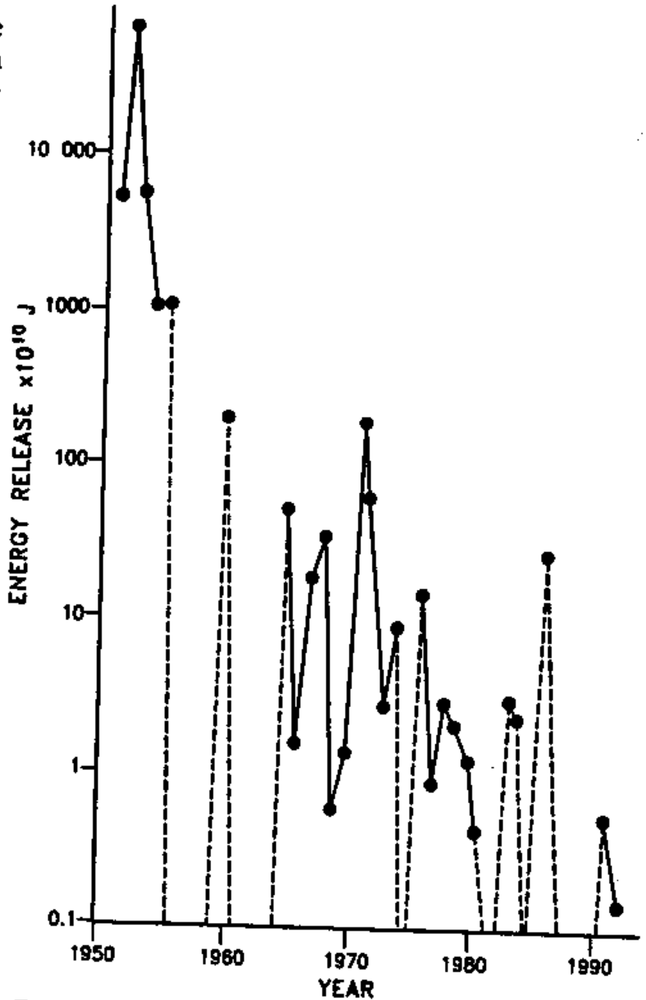

Fig. 5. Seismic energy release as a function of time.

Fig. 6. Annotated SPOT image of the study area. Inundated areas are darker in hue. The width of the scene is 50 km.

A frequency distribution diagram of the lineaments in the study area is shown in Fig. 7a. The most prominent set is that striking in a west northwesterly direction, followed by the northwesterly set. Hutchins *et al* (1976) prepared a lineament map for the entire Delta area using LANDSAT imagery. A frequency diagram based on their map is shown in Fig. 7b. The west north-

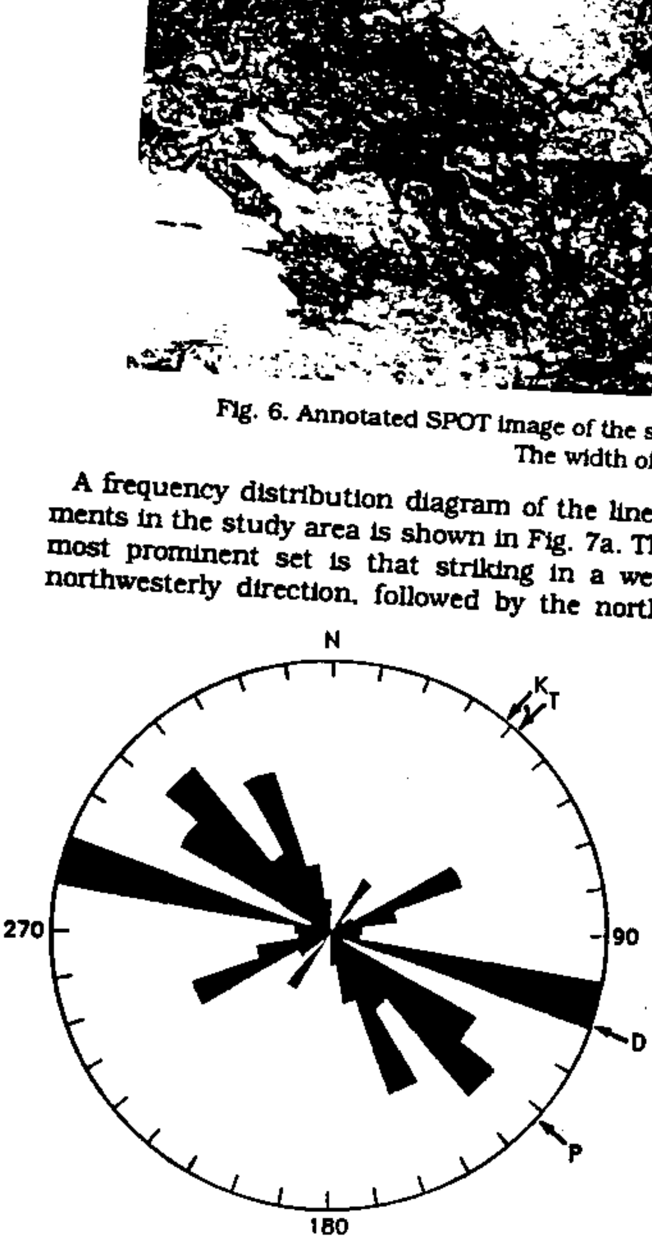

Fig. 7a. Frequency distribution of lineaments in the area. K = Kunyere fault, T = Thamalakane fault, D = Dyke swarm, P = Panhandle

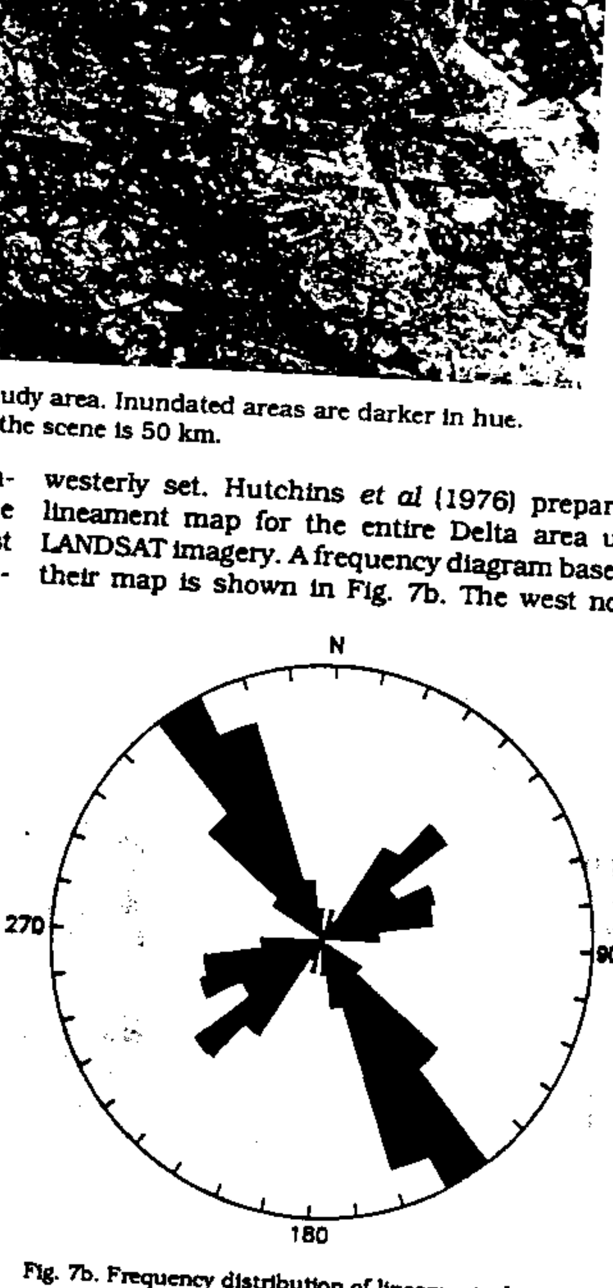

Fig. 7b. Frequency distribution of lineaments determined from LANDSAT imagery by Hutchins *et al.*, 1976.

westerly striking lineament set is not in evidence in their analysis, which is dominated by the northwesterly set.

Origin of the lineaments

Northeasterly trending lineaments of tectonic origin have long been recognized in northern Botswana (Du Toit, 1925; Reeves, 1978a) and include the Thamalakane and Kunyere faults. The prominent northeasterly set of lineaments within the Delta area are therefore concluded to be of tectonic origin. The more prominent northwesterly set include the Panhandle (Fig. 1), an apparent graben structure. There are no known basement structures of this orientation, but the widespread development of this set both within the Delta and beyond (Sinding-Larsen *et al.*, 1991), suggests that it too is of tectonic origin. The west nothwesterly set is more enigmatic. The only basement structures of this general trend are Karoo dykes (Fig. 3) which strike 110°, but the lineaments strike mainly between 100° and 105°. This is parallel to the strike of a major longitudinal dune field which lies to the west of the Okavango and upon which the fluvial deposits of the Delta have been superimposed (Cooke, 1975). It is possible that this orientation is a relic of this dune system, although reactivation of the fracture system associated with the Karoo dyke swarm cannot be ruled out. It is evident from Fig. 6 that the northeasterly and northwesterly lineaments from sets of interconnected grabens which control water distribution in the swamps.

Tectonic analysis

Fairhead and Stuart (1982) have demonstrated that the localization and orientation of much of the East African Rift system is controlled by basement structure, especially by the location and structural grain of metamorphic belts which separate the cratonic massifs of continent. The incipient rifting in northern Botswana is no exception (Fig. 3): the northeasterly trending Pan-African and Irumide belts are clearly serving as a line of weakness in the current rifting.

Focal mechanism solutions for seismic events in e Okavango led Scholz et al. (1976) to propose p-slip movement on the northeasterly trending ults, implying northwest extension. However, irhead and Stuart (1982), in a regional study of e seismicity of the East Africa Rift, proposed west rthwesterly extension along the entire southern rtion of the rift. In contrast, Sander and sendahl (1989) proposed east-west extension, ile Bosworth (1989) suggested east-west to st-southwesterly extension.

he northwesterly extension proposed by Scholz l (1976) is inconsistent with the widespread elopment of northwesterly striking lineaments in the Okavango, which are more compatible with east-west extension proposed by later workers. This extension direction implies a component of strike-slip movement on the northwesterly striking faults. The fact that the magnetic anomalies associated w: the west northwesterly striking dykes show no offset along the northeasterly striking Thamalakane and Kunyere faults is not inconsistent with this view as the total movement on these faults is probably only of the order of a few hundred metres (Reeves, 1978a). Indeed, the absence of offset attests to the very recent onset of fault movement.

The orientation of tectonic lineament directions in the Okavango can be understood in the context of east-west crustal extension in northern Botswana. This extension has reactivated the northeasterly structural trend of the basement to form oblique-slip faults, producing, in essence, a divergent strike-slip system. It has been shown experimentally that in such systems antithetic faults are prominently developed (Wilcox *et al.*, 1973) which correspond to the northwesterly striking faults in the Okavango. Moreover, Wilcox *et al.* (1973) showed that the antithetic faults are dominated by graben development, because of the overall extensional nature of the system.

Although the northwesterly striking faults are more numerous, the most prominent faults in terms of strike length and displacement strike northeast, notably the Thamalakane and Kunyere faults. Moreover, sediment thickness appears to increase southeastwards towards these faults (Reeves, 1978a). This implies that the overall structure is one of a half-graben (an interpretation in keeping with current views on the East African Rift) transected by northwesterly striking antithetic faults, as shown in Fig. 8.

The contribution of tectonism and sedimentation in controlling water distribution in the Delta

It appears from the lineament pattern on the annotated SPOT image shown in Fig. 6, that the abandoned reach of the Nqoga channel lies across a horst block, flanked by graben systems, which are particularly well developed towards the north where the Maunachira channel flows. This suggests that rise of the horst block may have been responsible for channel abandonment. However, several lines of evidence indicate that this is an oversimplification.

Abandonment of the lower Nqoga was progressive from the distal end. Abandonment commenced in the early 1920s and today continues well upstream of the horst block. Aggradation rates of the channel bed are rising along a considerable length of the Nqoga channel, reaching values in

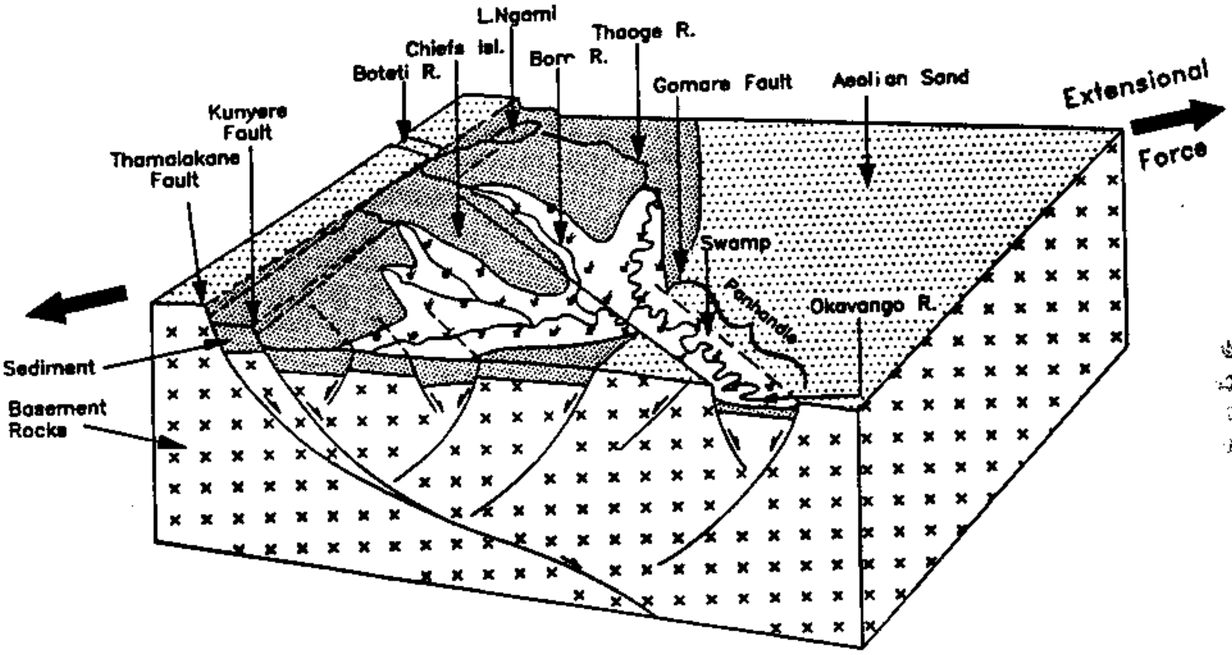

Fig. 8. Schematic block diagram of the Delta illustrating the inferred relationship of the major fault sets to the regional stress field.

excess of 5 cm/a near its distal end (McCarthy *et al.*, 1992). This has been confirmed by measurements of bedload along the Nqoga channel, which have shown that bedload deposition is taking place over a long reach of the channel well upstream of the horst (McCarthy *et al.*, 1991). The topographic gradient along the abandoned reach of the Nqoga channel is 1:2250, steeper than the gradient in the Delta as a whole (1:3600) and there is no indication of a flattening of gradient onto the horst (McCarthy *et al.*, 1988a). These observations suggest that simple rise of the horst is not the sole cause of channel failure.

Divergent wrenching of the type inferred to be operative in the Okavango results in a net lowering of the surface, manifest by the dominance of grabens, in the experiments of Wilcox *et al.* (1973). Horsts may develop in a relative sense, but they are not necessarily uplifts in an absolute sense, i.e. with respect to a datum outside of the affected area. In effect, the entire area of oblique extension is one of subsidence, but some regions will subside faster than others, producing relative graben structures. Water will flow preferentially into such developing grabens.

In this context, the processes of sedimentation and neo-tectonics may act in a complementary manner. Grabening adjacent to the Nqoga channel may have locally enhanced water loss, causing more rapid aggradation of the channel, thereby initiating channel failure. Once started, the region of channel blockage would tend to migrate upstream in the manner described by McCarthy *et al.* (1992) as bedload accumulates in the channel.

As the Nqoga channel progressively failed, water has been diverted towards the north where new channel systems have developed, evidently controlled by a developing system of inter-connected grabens. Channel failure is therefore not due to a rise of a horst, but the subsidence of an adjacent area.

Relationship between seismicity and hydrology

Several authors have noted a relationship between seasonal water loads and seismicity (e.g. McGinnis, 1967; Simpson *et al.*, 1988). In the case of the Okavango Delta, there is a very marked seasonal flooding (Fig. 2) with maximum loading occurring between April and August. Given that the area is seismically active, a correlation may exist between water loading and seismicity. In order to investigate this, the monthly seismicity trends for the entire period were plotted, but it was found that the swarm of the early 1950s completely dominates the trends. Accordingly, these data were removed and only post 1960 data were utilized. These are shown in Fig. 9.

In terms of the frequency of events (Fig. 9a), there does not appear to be any correlation with water dynamics. In terms of energy release (Fig. 9b), the data are erratic but a major peak occurs in July, which is within the period of peak loading. This peak is almost entirely accounted for by two events in 1963 and 1971. We note that the 1952 swarm occurred over several months, commencing in September. We therefore conclude that there is no obvious systematic relationship between water

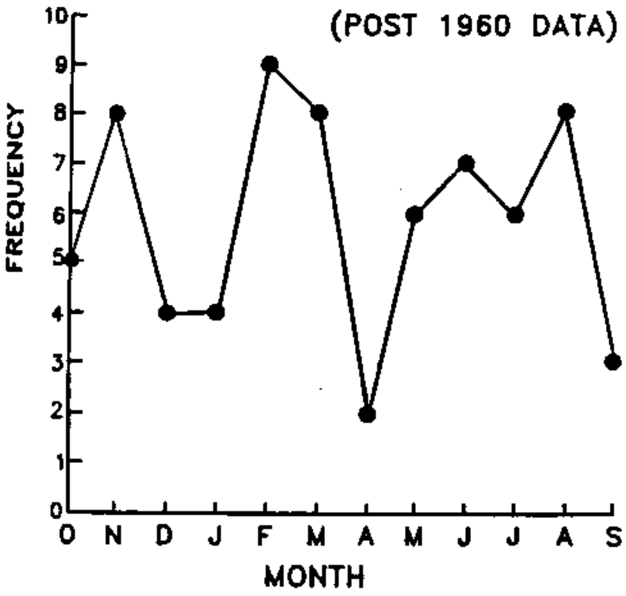

Fig. 9a. Frequency of seismic events by month.

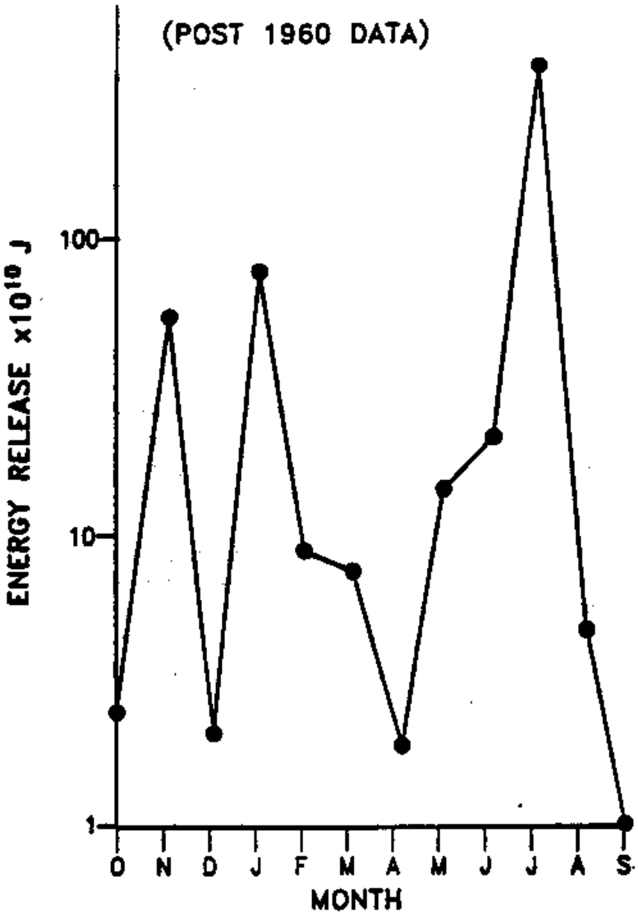

Fig. 9b. Seismic release by month.

load and seismic energy release.

Studies of dam induced seismicity suggest that the important variable in water loading is water depth. In the case of the Okavango, seasonal changes in water depth are small, generally less than a metre (Wilson and Dincer, 1976). Moreover, the seasonal flood dissipates over a large area, limiting point load effects. It is therefore not surprising that there is no relationship between seasonal flooding and seismicity and it must be concluded that the measured seismic activity is due to regional tectonics.

CONCLUSIONS

The Okavango graben has developed in response to east-west extension of the African continent, which has reactivated ancient northeasterly trending basement structures. This has resulted in oblique slip, normal faulting, creating a large half-graben structure. The oblique slip nature of the movement has resulted in the strong development of northwesterly striking antithetic faults. The two complimentary fault sets have resulted in the development of interconnected graben structures which control water distribution in the swamps. Further influence may be provided by relic west northwesterly striking dune structures or the reactivation of Karoo-age fractures. While the area is probably subsiding as a whole, regions of more rapid subsidence cause water diversion on a local scale. Such local subsidence results in rapid draw-off of water from the channels, initiating channel bed deposition and hence channel failure. This results in swamp abandonment and ultimately channel avulsion. It appears therefore that water dispersal patterns are related to both neo-tectonics and sedimentation in channels. The absence of seasonal patterns in the seismicity indicates that seasonal water loading does not have any influence on graben development.

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