Sedimentology (1993) **40**, 979–1017

Sedimentation in a river dominated estuary

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ABSTRACT

The Mgeni Estuary on the wave dominated east coast of South Africa occupies a narrow, bedrock confined, alluvial valley and is partially blocked at the coast by an elongate sandy barrier. Fluvial sediment extends to the barrier and marine deposition is restricted to a small flood tidal delta.

Sequential aerial photography, sediment sampling and topographical surveys reveal a cyclical pattern of sedimentation that is mediated by severe fluvial floods which exceed normal energy thresholds. During severe floods (up to 10×10^3 m^3 s^{-1}), lateral channel confinement promotes vertical erosion of bed material. Eroded material is deposited as an ephemeral delta in the sea. After floods the river gradient is restored within a few months through rapid fluvial deposition and formation of a shallow, braided channel. Over an extended period (approximately 70 years) the estuary banks and bars are stabilised by vegetation and mud deposition. Subsequent downcutting in marginal areas transforms the channel to an anastomosing pattern which represents a stable morphology which adjusts to the normal range of hydrodynamic conditions. This cyclical pattern of deposition produces multiple fill sequences in such estuaries under conditions of stable sea level.

The barrier and adjacent coastline prograde temporarily after major floods as the eroded barrier is reformed by wave action, but excess sediment is ultimately eroded as waves adjust the barrier to an equilibrium plan form morphology. Deltaic progradation is prevented by a steep nearshore slope, and rapid sediment dispersal by wave action and shelf currents.

During transgression, estuarine sedimentation patterns are controlled by the balance between sedimentation rates and receiving basin volume. If fluvial sedimentation keeps pace with the volume increase of a basin an estuary may remain shallow and river dominated throughout its evolution and excess fluvial sediments pass through the estuary into the sea. Only if the rate of volume increase of the drowned river valley exceeds the volume of sediment supply are deep water environments formed. Under such conditions an estuary becomes a sediment sink and infills by deltaic progradation and lateral accretion as predicted by evolutionary models for microtidal estuaries. Bedrock valley geometry may exert an important control on this rate of volume increase independently of variations in the rate of relative sea level change.

If estuarine morphology is viewed as a function of the balance of wave, tidal and fluvial processes, the Mgeni Estuary may be defined as a river dominated estuary in which deltaic progradation at the coast is limited by high wave energy. It is broadly representative of other river dominated estuaries along the Natal coast and a conceptual regional depositional model is proposed. Refinement of a globally applicable model will require further comparative studies of river dominated estuaries in this and other settings, but it is proposed that river dominated estuaries represent a distinct type of estuarine morphology.

INTRODUCTION

Sedimentary models of transitional fluvio-marine environments, other than deltas, are poorly developed (Nichols & Biggs, 1985). This is especially true of estuaries, where slow progress in the synthesis of sedimentary models stems largely from the limited number of descriptions of estuarine sedimentation from a restricted number of environmental settings (King, 1980). Present sedimentary models of estuaries are commonly subdivided on tidal range (Hayes, 1979) and are frequently biased toward barrier environments in meso- and microtidal areas (Hayes, 1975, 1979; Boothroyd, 1978; Nichols & Briggs, 1985). Zaitlin & Shultz (1990) recently proposed a division of estuarine sedimentary models based on the relative importance of tides, rivers and waves.

A general model for macrotidal estuaries was proposed by Dalrymple *et al.* (1990), based on comprehensive studies in the Bay of Fundy. These estuaries are generally funnel shaped and exhibit high current velocities. Three up-estuary zones exist: elongate tidal sandbars; sandflats with braided channels; and single channel tidal–fluvial transition.

Boothroyd (1978) summarized information on mesotidal estuaries (tidal range of 2–4 m), suggesting that they are characterized by large tidal deltas on either side of a barrier inlet. Back barrier environments include subtidal channels, intertidal flats, large tidal creeks and small tidal creeks. He stressed the importance of the tidal deltas in the facies architecture, a common thread in many studies of mesotidal estuaries which focus on the barrier environments to the detriment of back barrier facies (see for example Hayes, 1975).

Roy *et al.* (1980), Roy (1984) and Nichols (1990) have presented sedimentary models for wave dominated microtidal estuaries in eastern Australia and the eastern USA, respectively. Zaitlin & Shultz (1990) constructed a generalized sedimentary model for wave dominated estuaries, based on the work of Roy (1984) and Boyd *et al.* (1987). This model identifies three depositional zones which run parallel with the estuary axis. These are:

(a) a wave dominated 'sand plug' which constricts the mouth and dissipates wave energy;
(b) a low energy back barrier 'lagoonal' zone;
(c) tidal–fluvial channels and overbank (delta plain) deposits (bayhead delta).

Although these models of estuarine sedimentation have only recently been formulated, they generally represent well documented regional syntheses rather than a unique model (Frey & Howard, 1986; Zaitlin & Shultz, 1990). The problems of formulation of such a model are complicated by the wide definition of estuaries and the overlap which exists between estuaries and other depositional environments such as deltas, lagoons, river mouths, embayments, etc. Dalrymple *et al.* (1992) provided a conceptual framework for transitional fluvio-marine environments including estuaries. In this scheme estuarine morphology varied between two end-members, tide- and wave dominated estuaries. Deviation from these end-members could be viewed as a result of variation in the relative importance of wave and tidal energy, as well as local variability. Dalrymple *et al.* (1992) argued that the addition of a fluvially dominated category of estuary is unnecessary because 'the relative influence of the river primarily determines the rate at which the estuary fills and does not alter the fundamental morphology of the system'.

This paper details the geomorphology and sedimentation patterns in a river dominated estuary, which appears broadly representative of many estuaries in the same environmental setting in South Africa. This mode of estuarine sedimentation has not previously been documented in detail and the information is intended to add to the available body of knowledge. River dominated estuaries from other areas are briefly discussed, and the position of the river dominated estuary as a distinct end-member in a conceptual framework for transitional fluvio-marine environments is discussed.

THE STUDY AREA

General setting

The Natal coast on the eastern margin of South Africa is characterized by a steep hinterland, lack of a coastal plain, an abundance of rivers, high sediment yields and perennial, though seasonally variable, discharge (Orme, 1974). One of the largest of these rivers is the Mgeni which enters the sea through the northern suburbs of Durban (Fig. 1). The lowest 2·5 km of its course experiences tidal water level and salinity fluctuations through a semi-permanent outlet. Some aspects of its sedimentation have previously been documented (Cooper, 1986a, b, 1988; Cooper & Mason, 1987; Cooper & McMillan, 1987) and these observations, coupled with the fortuitous occurrence in September 1987, of a high magnitude flood, enabled assessment of the effects of such events on sedimentology of the estuary (Cooper *et al.*, 1990; Cooper, 1991a). The results of the flood impact study, together with intensive pre-flood studies and interpretation of a set of vertical aerial photographs spanning a 60 year period, permitted both long and short term analysis of estuarine geomorphology.

Coastal hydrodynamics

Tides on the Natal coast are semi-diurnal. At Durban mean spring tidal range is 1·72 m and mean neap tidal

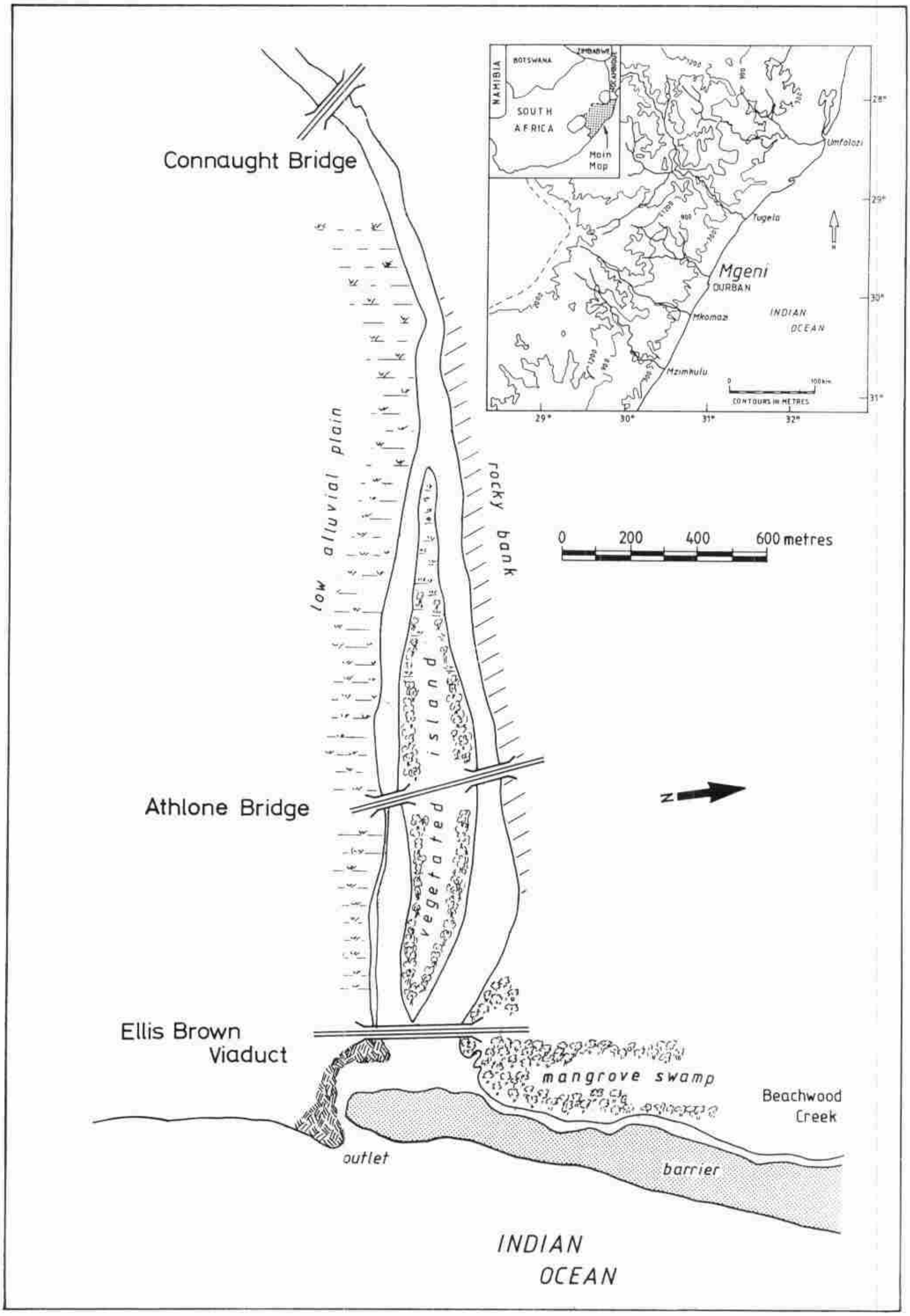

Fig. 1. Morphology of the Mgeni River estuary (1986). Location and topography of the Natal hinterland is shown in the inset.

range is 0·5 m. The Natal coast is therefore microtidal in the classification of Davies (1964) or low mesotidal in the sense of Hayes (1979). The coastal sedimentary regime is wave dominated. Recorded wave heights over a 2 year period ranged from 0·3 to 7·6 m (Hydraulics Research Unit, HRU, 1968) with a median wave height of 1·49 m. The dominant direction of wave approach at Durban is ESE to SE. The greatest significant wave heights were recorded from SSE to SW directions and the lowest from E to ESE directions. Maximum wave periods (> 17 s) occurred from SE to SSE, while the shortest wave periods (5–7 s) came from E to NE. The median wave period is 10·7 s.

Climate

The climate of the Natal hinterland is dominated by the subtropical high pressure belt (Tyson, 1987). The mean annual rainfall of 900–1000 mm is largely restricted to the summer months when 80% of the rain falls (Tyson, 1987); rapid altitudinal rise inland produces orographic forcing of rainfall. Winter rainfall is typically associated with coastal low pressure systems moving northwards and produces only a minor proportion of the annual total. Associated variable stream discharges impact on sediment transport in rivers.

Periodically, intense rainfall during a few days causes widespread floods. This was the case in September 1987 when a strong Atlantic high pressure system began to advect cold, moist air over the southern part of South Africa. Over the interior of the country, moist, warm air flowed in from the north along the eastern side of a surface low pressure system combined with an upper air cut-off low (Kovacs, 1988). Cut-off lows are associated with strong convergence and are responsible for many of the flood-producing rains over South Africa (Taljaard, 1982).

Catchment characteristics

The Mgeni River catchment covers 4400 km^2 (Fig. 2). The river rises 250 km from the Indian Ocean, at an altitude of 1889 m. Its overall gradient is 1:132 (0·0075) but in its lower 10 km the gradient is reduced to 1:550 (0·0018). Mean annual runoff is 323×10^6 m^3 (National Research Institute for Oceanology, NRIO, 1986) and mean discharge varies from 18·4 m^3 s^{-1} in summer to 6·5 m^3 s^{-1} in winter (Orme, 1974). Four major dams are present on the river (Fig. 2) and the catchment area below Inanda Dam is only 395 km^2.

Most of the catchment is subtropical and this has produced deep weathering profiles on the underlying lithologies. The upper catchment consists of fine grained sedimentary rocks, intruded by dolerite. They are underlain by a series of diamictites and glaciolacustrine rocks. In the central part of its catchment, the river traverses a deeply weathered, Proterozoic granite–gneiss complex. Alluvium fills the lower river valley and Tertiary and Pleistocene sediments crop out at the coast.

The annual sediment yield from the Mgeni River was estimated at $1{\cdot}6 \times 10^6$ tonnes (NRIO, 1986) using a sediment yield map compiled by Rooseboom (1975). However, the five dams in the catchment reduce contemporary sediment (particularly bedload) yield to the coast. The catchment area below the four dams completed in 1987 is approximately 1700 km^2 and the sediment yield from this area was calculated at $0{\cdot}5 \times 10^6$ tonnes per year from Rooseboom's (1975) map of sediment production in South Africa (NRIO, 1986). Inanda Dam further reduces sediment supply from the catchment but, most importantly, cuts off the main source of gravel to the estuary. As it was only closed in 1988, the effects of this have not yet been assessed.

Given a mean annual runoff of 323×10^6 m^3 and an average suspended sediment concentration of 165 mg/l^{-1} in the Mgeni River (Brand *et al.*, 1967), the average total suspended load is about 53×10^3 tonnes per year. Estimates of the proportion of bedload in Natal rivers range from 12% (Swart, 1987) to 50% (Alexander, 1976). Calculated total sediment load using each of these figures is 59 000 or 106 000 tonnes, only 12–20% of the figure derived by NRIO. The large discrepancies underline the need for further research on this phenomenon. Nonetheless, during the Holocene, sediment yield has been comparatively high in relation to the volume of the estuary and its bedrock valley.

HOLOCENE EVOLUTION OF THE MGENI RIVER ESTUARY

Sea level in South Africa rose from a maximum low of −130 m about 17 000 year BP (Vogel & Marais, 1971) to its present elevation about 7000 years BP (Deacon & Lancaster, 1988). Since that time it has fluctuated through about 3 m above or below its present level (Cooper, 1991a). No detailed regional investigation of this late Holocene sea level fluctuation has yet been undertaken.

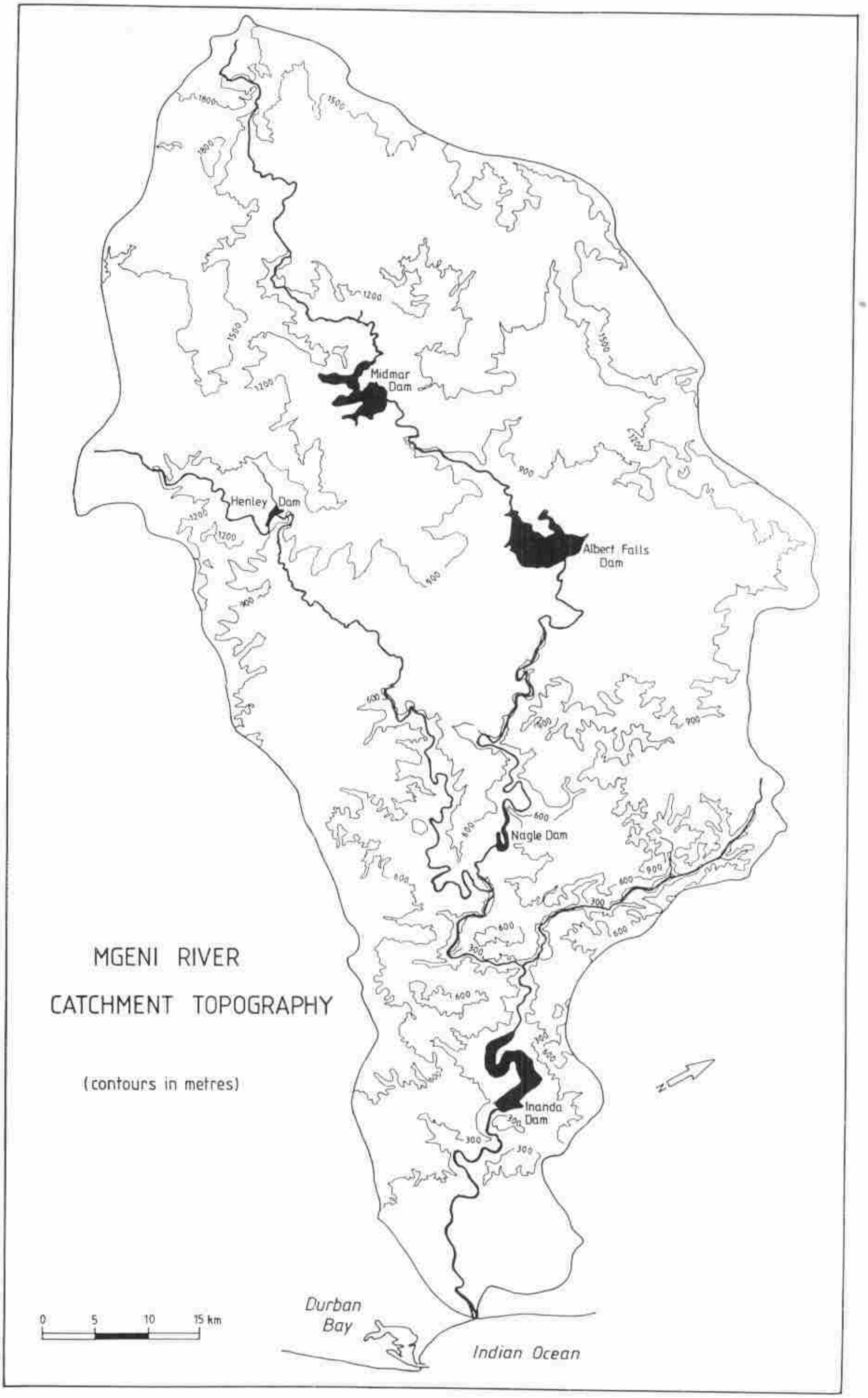

Fig. 2. Topography of the Mgeni River catchment showing major dams. See inset to Fig. 1 for location.

The Holocene evolution of the Mgeni River estuary may be assessed by reference to several lines of evidence. These include borehole cores from foundation investigations below Durban, fossil seacliffs and beachridges north of the present mouth, a change in barrier and dune orientation near the present outlet, the surrounding geomorphology, the incised estuarine channel and comparison with other rivers.

Several cores have been drilled in the Mgeni River during foundation investigations (Kantey & Templar, 1964; Orme, 1974, 1975; Francis, 1983). These reveal a narrow bedrock channel extending to 56 m below sea level under the modern estuary, filled entirely with Holocene sediments. Investigations in the adjacent area under the City of Durban (Fig. 3) show that the sub-Quaternary surface occurs at depths between 25 and 40 m (Maud, 1978). The overlying material accumulated in a lagoonal setting, marginal to the main estuary channel. This former lagoon is infilled by silts and clays in its lowest part but passes upwards into more frequent horizons of coarse grained sand and gravel (King, 1962; King & Maud, 1964). Some of the lagoonal fill under Durban is pre-Holocene while that under the modern estuary is entirely

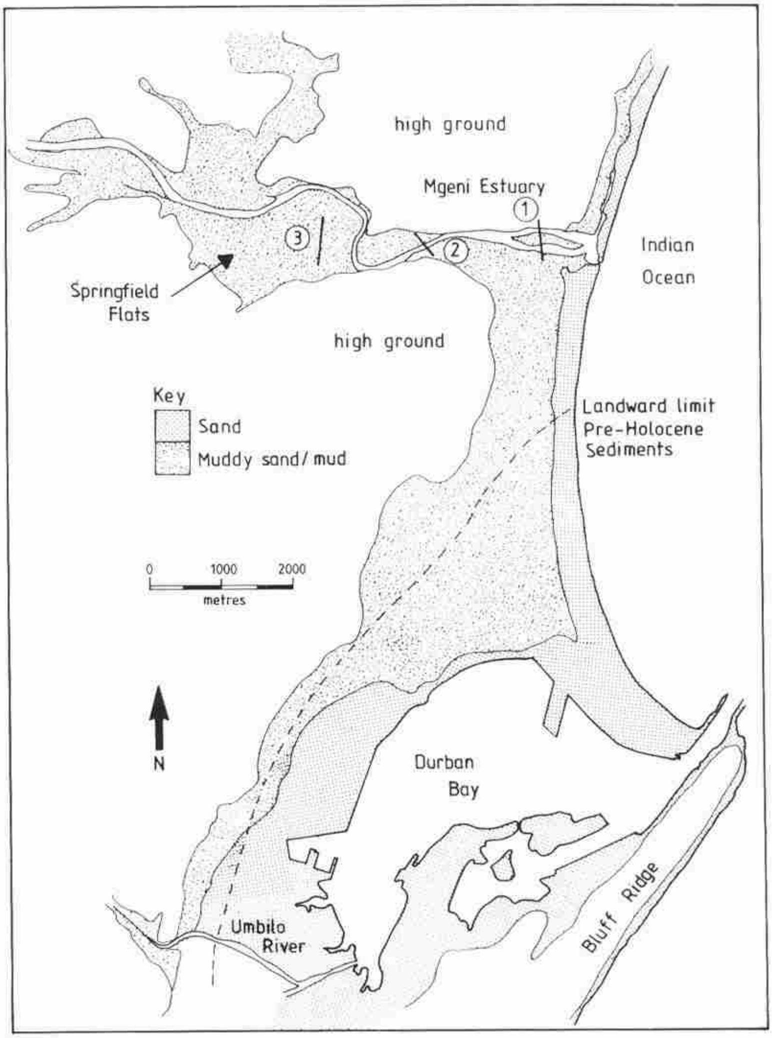

Fig. 3. Distribution of alluvium around the Mgeni River estuary. Locations of cross-sections 1, 2 and 3 in Fig. 4 are shown. The suboutcrop of the 'Black Mud Stratum' (dashed line) marks the landward limit of the area in which pre-Holocene deposits are preserved in the valley fill.

Holocene, earlier deposits having been scoured from the narrow bedrock channel.

The vertical sequence revealed beneath the Mgeni River estuary channel (Fig. 4) indicates that in the middle stages of its Holocene inundation it was characterized by relatively deep water in which suspension settling was the dominant depositional mechanism. This is well illustrated in Sections 2 and 3 where muddy deposits extend from about 19 to 7 m below present sea level. Under shallow water conditions fine grained sediment would not be retained in the laterally restricted channel. Comparison with a sea level curve for the area (Cooper, 1991a) suggests that this period lasted from approximately 8200 to 7600 years BP. At 12–8 m below sea level near the modern estuary mouth (Section 1), sands containing marine molluscs indicate a period in which barrier related sediment extended into the lower reaches of the estuary. They are overlain by fluvial sediment.

Coarse grained fluvial sediments in the low lying area between the modern estuary and Durban Bay (Fig. 3) show that the late Holocene Mgeni River flowed south behind a transgressive coastal barrier (King, 1962) into Durban Bay. In the early nineteenth century the Mgeni River followed the same path only during floods (Barnes, 1984). The modern outlet position has been assumed by the mid-nineteenth century and was stabilized in the early 1930s.

The rear of the lagoonal area at Beachwood Creek (Fig. 1) is backed by a cliff cut into reddened dune sands. This Holocene cliff is aligned with a forested dune which extends both north and south of the modern outlet. The present barrier is offset from this earlier shoreline and its orientation indicates a change in plan morphology in the Durban Bight which may be tentatively correlated with a regression from a late Holocene sea level 1·5 m above present (Cooper, 1991a). During this drop in sea level the coast-parallel lagoon at Beachwood Creek was formed. North of the lagoon is a series of low dune ridges which indicate coastal progradation during the regression.

HISTORICAL DEVELOPMENT OF THE ESTUARY 1931–1991

Historical changes in morphology of the Mgeni River estuary were studied using aerial photographs taken between 1931 and 1985. All photographs were reduced to the same scale (initially 1:10 000) for comparison. Tidal range in the estuary is small and therefore sub-, inter- and supratidal areas could generally be differentiated, irrespective of the state of the tide at the time of photography.

Morphological changes

Changes in morphology discussed below are illustrated in Figs 5 and 6. For ease of reference the changes in the estuarine channel and coast-parallel lagoon are depicted separately.

In December 1931 (Fig. 5A) the estuary had a wide, shallow channel, filled with sandy braid bars. Bridges crossed the middle reaches and the head of the estuary. At the coast, a broad, coast-parallel, back barrier lagoon extended north of the constricted outlet (Fig. 6A). The course of a narrow tidal channel was visible in the lagoon, surrounded by unvegetated, shallow subtidal or intertidal mudflats. Mangroves were present in the upper reaches of the lagoon. A salt marsh extended through most of the lower reaches. The outlet was prevented from migrating southward by a groyne, south of which was a small lagoon remnant. No dunes were present on the barrier.

In 1937 a prominent supratidally exposed central bar was present (Fig. 5B). It was sparsely vegetated, as were some side-attached bars in the upper reaches. Intertidal braid bars filled most of the channel. Photographs taken on 30 April and 16 July 1937 record a change in outlet position; the earlier position is marked by a dashed line in Fig. 5(B). The preservation of intervening barrier features indicates that this change occurred through outlet closure and reopening. The lagoonal area showed little change since 1931 (Fig. 6B).

In 1959 (Fig. 5C) side-attached bars in the estuary were incorporated into the floodplain, causing the channel to narrow. Many braid bars had coalesced, forming a large, elevated central island with scattered trees on it. The river formed two distinct channels around this island. The isolated pond south of the groyne was reduced in size and the coast-parallel lagoon was reduced to a narrow channel, surrounded by supratidal mudflats and mangroves. Mangroves had extended through the lagoon since 1937 (Fig. 6C). The coastline had retreated and an aeolian dune was formed on the barrier.

In 1967 (Fig. 5D) the central island was enlarged by downstream and vertical accretion. Channels between braid bars were shallow and intertidally exposed and many side-attached bars were incorporated into the floodplain (Fig. 5D). The central island was densely vegetated and mangroves had extended

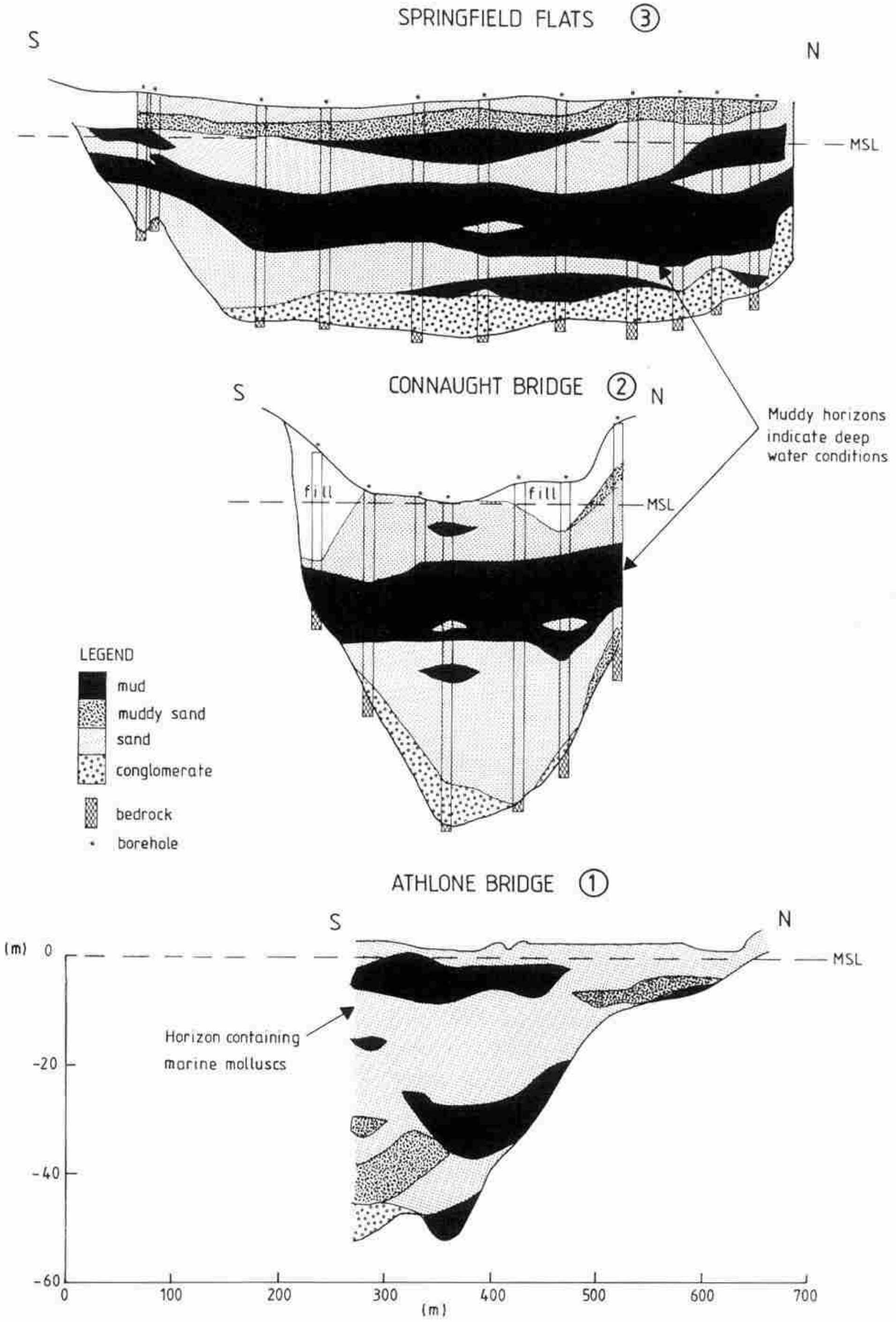

Fig. 4. Simplified cross-sections of the bedrock valley fill in the Mgeni River estuary (locations in Fig. 3). Note the pronounced muddy horizon between the upper and lower sand dominated horizons in Sections 2 and 3 (compiled from engineers logs). Section 1 is based on Orme (1974) who did not illustrate borehole positions.

their distribution into the lower estuary. The coastline had retreated further (Fig. 6D).

The 1973 vegetation covered the central island and mangroves were colonizing its margins (Fig. 5E). Small washover fans had flattened the barrier, causing an increase in its width. A small flood tidal delta was present in the estuary opposite the outlet. The coast-parallel lagoon was reduced to a narrow tidal channel surrounded by a mangrove swamp and salt marsh (Fig. 6E).

By 1983 the remaining braid bars in the estuary had all become side- or island-attached. The island vegetation included large trees (Fig. 5F). In the lower reaches mangroves formed a fringe around the margin and had colonized former channels. Mangroves were also present along the lower margins of the tidal creek (Fig. 6F) and had spread through the lower reaches of the estuary. A well defined flood tidal delta was present in the estuary. The barrier had retreated further landward and small washover fans were present on the barrier.

In July 1985 (Fig. 6G) the barrier had retreated further landward and a large washover fan had infilled part of the mangrove swamp channel system (Cooper & Mason, 1986). The flood tidal delta was smaller than in 1983 but was still distinct, despite floods associated with tropical cyclone Demoina in February 1984.

The long term changes up to 1986 led to the geomorphological conditions under which previous work on the estuary was undertaken (Cooper 1986a, 1988; Cooper & Mason, 1987; Cooper & McMillan, 1987). It had changed little in the preceding 10 years and was apparently dynamically stable and in a mature stage of development. Under such conditions the estuary comprised, in its upper 700 m, a narrow, laterally restricted channel (average width 60 m) confined between prominent bedrock outcrops (Fig. 1) in the lower 1·8 km the right bank was bounded by a broad alluvial plain into which a 400 m wide channel was incised. A central vegetated island, with a mean elevation of 2 m above mean sea level, caused the channel to bifurcate. The channels recombined in the back barrier area before reaching a narrow outlet, typically located against the artificial rocky groyne. Beachwood Creek drained a low lying mangrove swamp which occupied a coast-parallel area behind the beach barrier.

Tidal attenuation by the constricted outlet, produced a mean tidal range of 1·4 m in the estuary. Tidal salinity changes extended 2·5 km upstream from the mouth and a salt wedge developed in the channel at high tide. Ocean waves were prevented from entering the estuary by the river mouth barrier.

Estuarine sediments consisted mainly of fluvially derived gravel and compacted mud. Gravel, sourced from deeply weathered granite gneiss upstream, comprised over 30% of the bottom sediment through most of the estuary. This precluded formation of small scale bedforms but side-attached bars were present.

The channel sediments generally contained less than 10% mud. Higher concentrations occurred on small sections of the channel margins, where low flow velocities and algal coated pencil roots of mangroves assisted in its deposition. Even a low mud content adds cohesion to estuarine sediments (Terwindt *et al.*, 1968) and thus much of the bed was erosion resistant. Mud was mixed with other sediments by the burrowing infauna (Cooper, 1986a). In the lower 200 m, bottom sediment consisted of more than 80% poorly cohesive, marine sand. Variations in the volume of the flood tidal delta indicate that this sediment is susceptible to erosion by seasonal, increased discharge events.

Discussion: long term geomorphological changes in the Mgeni River estuary

The changes in estuary morphology documented above may be divided into three categories: estuarine channel changes, barrier/lagoon changes and groyne induced beach erosion.

Channel changes

Between 1931 and 1986 the estuary changed from a wide, braided channel to two relatively deep channels with a vegetated central island (Fig. 5A–F). This occurred through coalescence and emergence of braid bars and incorporation of side-attached bars into the bank. Essential conditions for braiding are a high sediment transport and a low threshold of bank erosion (Reineck & Singh, 1973). The Mgeni River estuary banks are typically vegetated or muddy and thus generally unsuitable for braiding. Erodible sandy banks are, however, produced after major floods which erode the channel margins and deposit sandy overbank sediments. These are reworked by waves and produce sandy margins. Such channel margins have little chance of stabilizing due to continual slumping and thus a braided channel forms (Leopold & Wolman, 1957).

After floods, vegetation is rapidly re-established on the banks as a result of the subtropical climate of Natal. This, combined with mud deposition, stabilizes

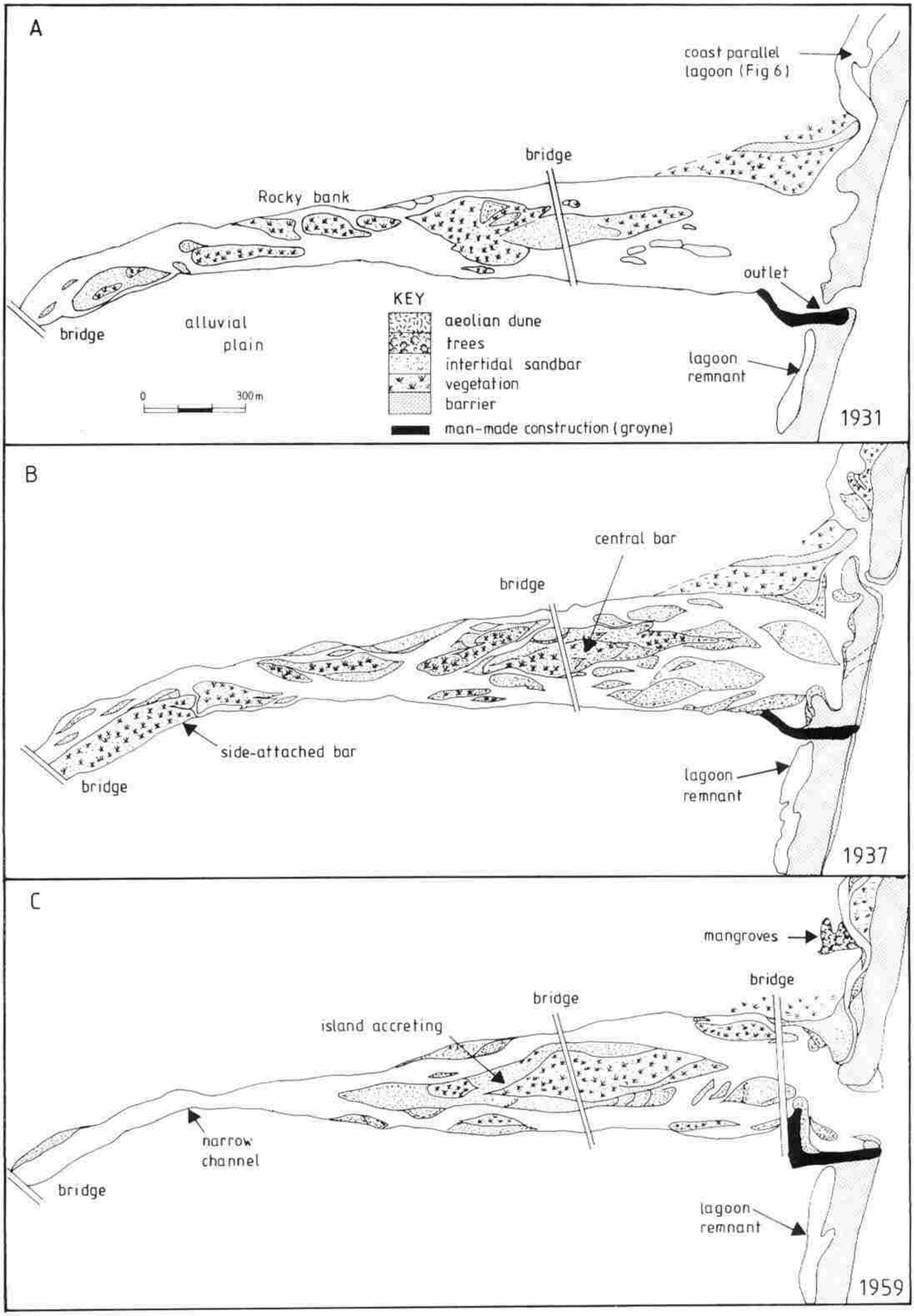

Fig. 5. Aerial photograph interpretations showing historical development of the coast-normal estuarine channel of the Mgeni River between 1931 and 1983.

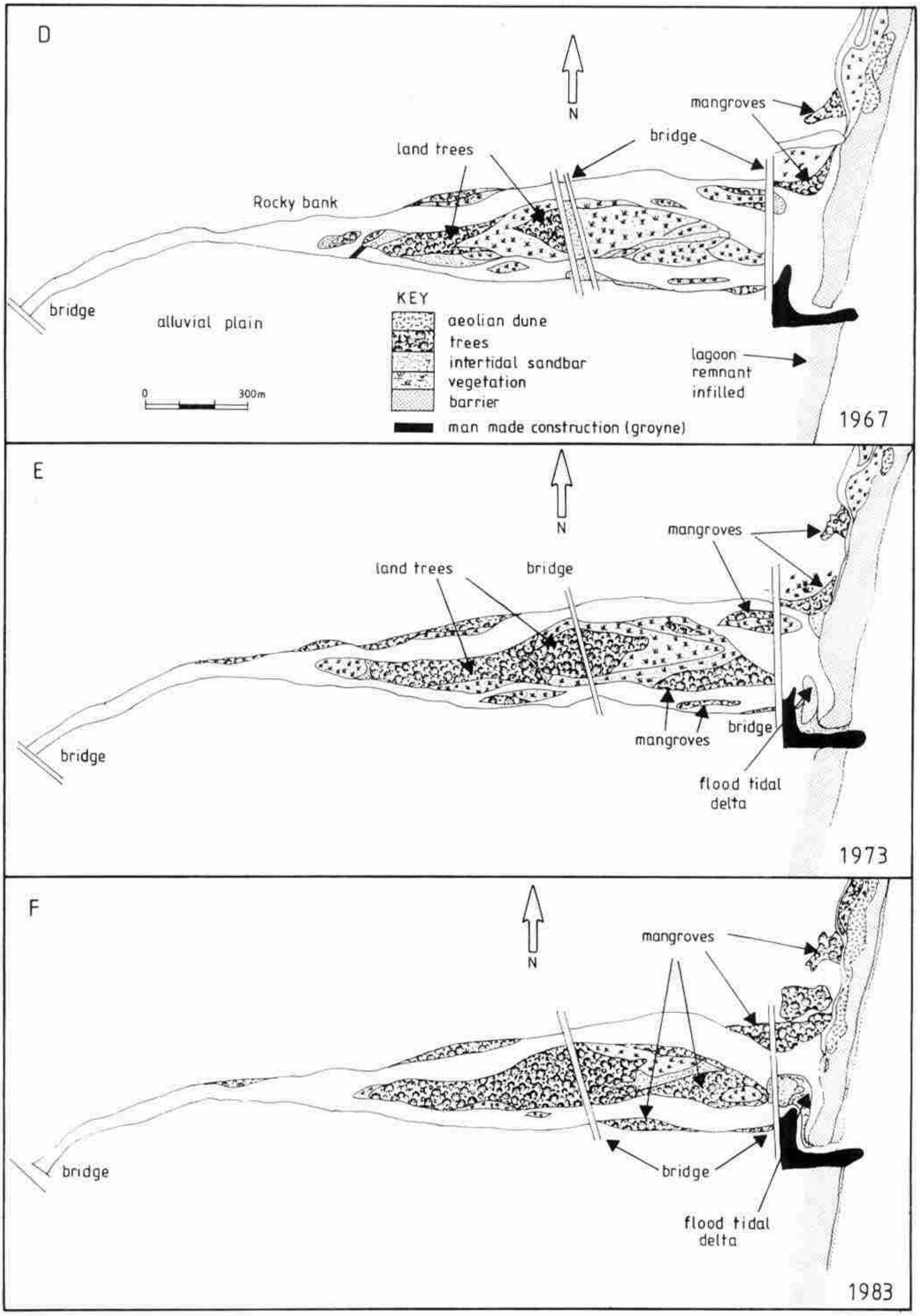

Fig. 5. *continued.*

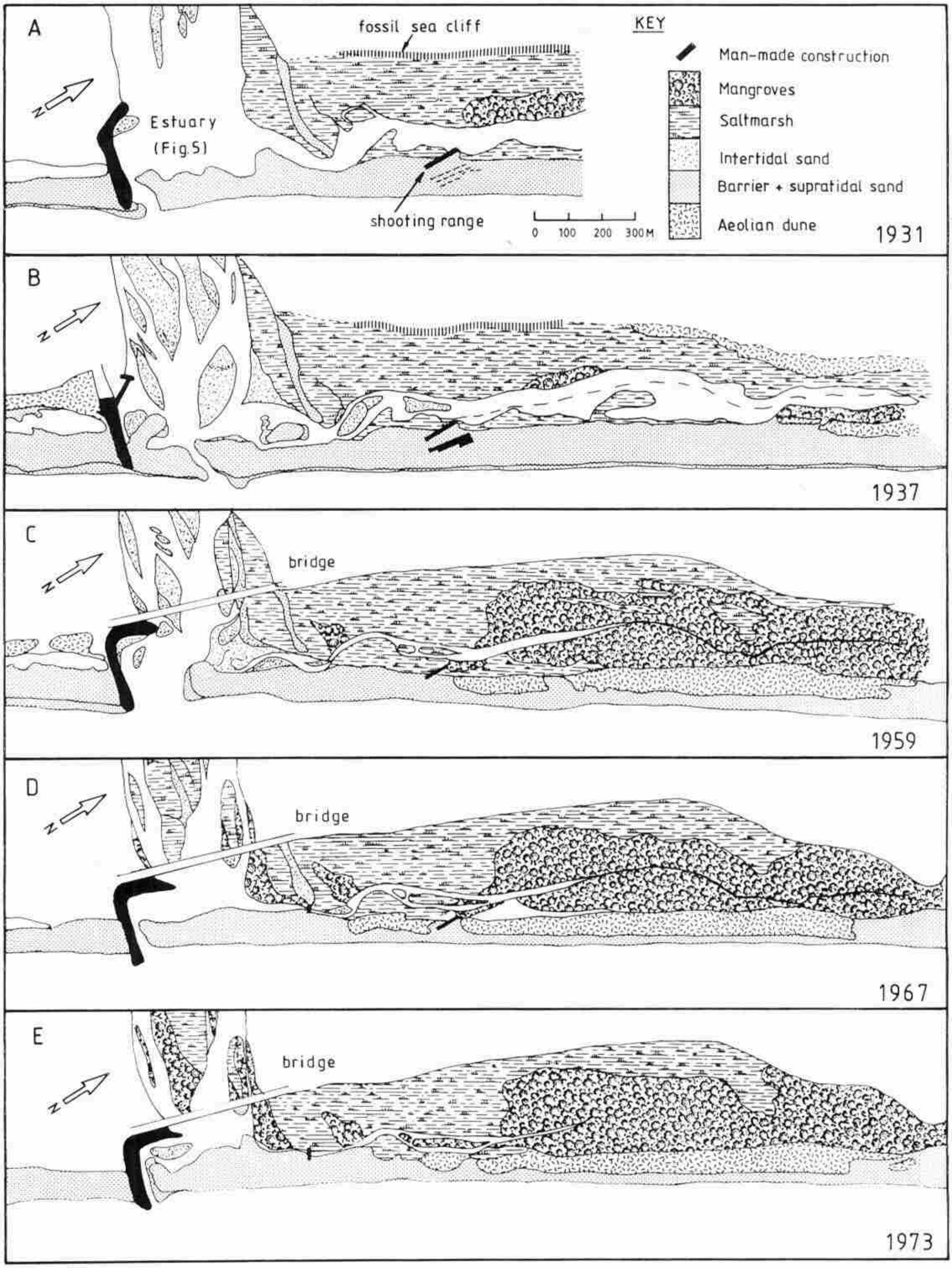

Fig. 6. Aerial photograph interpretations showing development of the coast-parallel lagoon between 1931 and 1985. In (H) successive shoreline positions are compared.

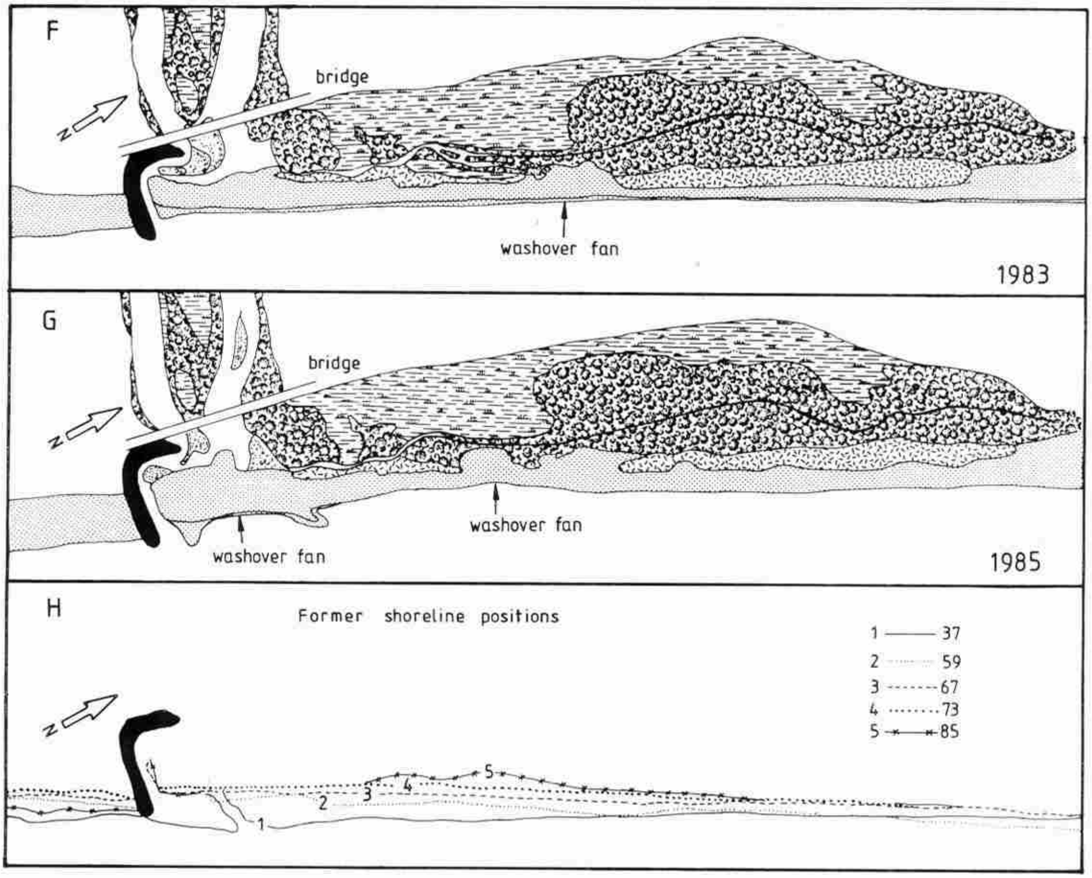

Fig. 6. *continued.*

the banks, thus removing one of the essential conditions for braiding. Tidal rise and fall promotes slack tide deposition of mud on the braid bars as noted on intertidal flats (Klein, 1977) and the braid bars are thus rendered more cohesive. Deposition continues until the bars become emergent at high tide and are then colonized by terrestrial vegetation. Thereafter they are inundated only during high river stages and overbank deposition further elevates the bars. As the bars accrete the cross-sectional area of the channel is reduced and so, to accommodate river discharge, downcutting of the flanking channels occurs. This reduces flow through the remaining braid channels which become hydraulically incompetent and ultimately shallow to become part of the central island. Downcutting in the flanking channels is promoted by the cohesive banks of the estuary and central island.

Rivers and estuaries with cohesive muddy or vegetated banks tend to have laterally restricted channels in which flow is confined to a narrow cross-section: consequently channels are comparatively deep (Reddering, 1988).

Flume studies of the formation of a central island in a braided channel (Leopold *et al.*, 1964) followed a similar pattern to channel evolution in the Mgeni River estuary between 1931 and 1986, although in the flume study only coarse grain sizes were used. Additional stabilization of banks by muddy sediment enhanced the formation of the island in the Mgeni River.

The channels were dominated by gravels in 1985/86 (Cooper 1986a, 1988), which suggests that this was an erosion base. Under these conditions, variations in river discharge are accommodated by a tendency to meander within the confines of the two anastomosing channels, thus producing side-attached bars in the two channels.

At the same time as island formation enabled downcutting of the flanking channels and maintenance of relatively deep channels, so the subtidal volume increased. This permitted deposition of a flood tidal delta which had previously been impossible due to the elevated bed levels in the estuary. Planktonic foraminifera carried into the estuary (Cooper & McMillan, 1987) indicated that marine sediment was entering in suspension on the flood tide. Flood tidal delta sediment was largely derived from the seaward margin of the barrier and transported through the outlet as the barrier progressively retreated.

Lagoon evolution

Between 1931 and 1985 the back barrier lagoon changed from a shallow, muddy lagoon with unvegetated intertidal mudflats to a mangrove swamp and salt marsh drained by a narrow channel (Fig. 6A–G). Much of this infilling occured between 1937 and 1959. Mud deposition occurs in the lagoon when river floods bypass the lagoon and mud laden water ponds there. Suspended sediment then settles and raises the bed level in the lagoon. As the lagoon was already shallow in 1937, only a small amount of deposition was required to raise it to a supratidal level. After 1959, mangroves colonized the now elevated muddy areas and eventually extended into the lower reaches of the estuary. A sparsely vegetated salt marsh forms at higher elevations and possibly replaces the mangroves as vertical accretion continues.

Barrier retreat

A major feature of the long term development of the Mgeni River estuary is the progressive erosion of the barrier north of the outlet (Fig. 6H). Erosion was concentrated in the 1200 m north of the groyne and led to the formation of a concavity there. Comparison of shoreline positions indicated that most erosion occurred up to 1973 after which the coast stabilized. Beach erosion was not matched by landward migration of the barrier, which consequently narrowed. This was accompanied by deposition of an aeolian dune at the rear of the barrier. In 1983 and 1985 erosion culminated in severe overwash into the mangrove swamp (Cooper & Mason, 1986). This overwash was generated by extreme wave action. Forebeach erosion exposed lagoonal muds on the foreshore at that time.

The fact that erosion is restricted mainly to the 1200 m north of the groyne suggests that the groyne is responsible. The changes therefore reflect an adjustment of the plan form to a new swash-aligned equilibrium. Minor changes after 1973 suggest that the beach had reached a new equilibrium by that time. The progressive dune growth which accompanied erosion indicated that some excess sediment was transferred onshore. The fact that erosion was comparatively slow in relation to the high littoral drift rates ($1{\cdot}6 \times 10^6$ m^3 per year) calculated by Swart (1987) suggests that either the calculated littoral drift rates are too large or that sediment was added at a rate lower than that at which longshore drift and wind action could remove it. However, lack of erosion north of this point (Cooper, 1991b) suggests that the beach was adjusted to an equilibrium and that groyne construction caused only a minor local change in shape.

This coastal retreat also affected the outlet stability by inducing a change in the nature of the beach plan form from an essentially drift equilibrium to swash equilibrium (Carter, 1988). As this happens the outlet position is altered. When the beach was wide, littoral drift bypassed the end of the groyne and the position of the outlet was variable, as illustrated by the photographs of 1931 and 1937. However, as the coast retreated, the groyne began to affect the incident wave field and the outlet stabilized against the groyne, as reported in other areas by Bascom (1954).

THE EFFECT OF FLUVIAL FLOODS

The morphology of an alluvial channel and floodplain is greatly affected by high discharge (Leopold *et al.*, 1964). Floods might therefore be expected to produce marked geomorphological changes in a small laterally restricted estuary fed by a large river. Due to their infrequent occurrence, the impacts of major floods on rivers and estuaries are poorly documented and the role of such floods in long term sedimentation and stratigraphical record is poorly understood. In September 1987 a high magnitude flood, with a calculated 120 year recurrence interval, occurred in the Mgeni River estuary. In this section the impacts of the flood are assessed and in the following section the post-flood recovery is documented. An attempt is then made to place flood associated changes in evolutionary perspective.

During the 5 days beginning on 26 September 1987 up to 800 mm of rain fell over Natal. During the associated floods, water level in the Mgeni River estuary rose to 5 m above normal high tide level, inundating the surrounding low lying land to the south and the mangrove swamp to the north (Cooper *et al.*, 1990). Sea water was flushed from the estuary and a plume of highly turbid river water extended over 2 km into the Indian Ocean. Suspended sediment concentrations measured 3 km upstream from the mouth reached 5698 mg l^{-1}, compared with a mean concentration of 165 mg l^{-1} under average flow conditions. The flood peak occurred at about midnight on the 28 September (Kovacs, 1988).

The steep river gradient caused the surface runoff to be transported rapidly to the sea. Surface current velocities of 6–7 m s^{-1} were recorded about 4 h before the estimated peak by timing floating objects over a fixed distance at the Ellis Brown Bridge. There are no accurate records of the flood peak as all gauging stations were destroyed, but Cooper *et al.* (1990) calculated a peak discharge of about 10 000 m^3 s^{-1}. The previous highest recorded peak discharge (5700 m^3 s^{-1}) was in October 1917. A. M. Smith (personal communication, 1990) calculated an ancient floodpeak of 28 000 m^3 s^{-1} using palaeoflood hydrology in the Mgeni River. This pre-dated the earlier documented flood of 1856 (Barnes, 1984), but such a discharge may relate to different climatic conditions.

Flood controlled morphological changes

During the 1987 flood the outlet was enlarged by erosion of the barrier. A plume of turbid water entered the sea and hundreds of tonnes of plant debris, including large trees, were thrown onto the adjacent beaches by wave action. The vegetated island in midstream and sections of the southern bank were eroded from the estuary. A survey of several channel cross-sections, carried out 20 days after the flood peak, revealed that sediment was also scoured from the bed (Fig. 7). Some fine grained sand had been deposited in the upper reaches, but coring revealed a maximum thickness of 0·04–0·05 m. Thus, the surveyed sections give an indication of the post-flood erosion base of the estuary. The post-flood channel cross-sections are superimposed on the pre-flood sections in Fig. 7. Volume changes were calculated using channel dimensions calculated from these cross-sections (Cooper *et al.*, 1990).

A total of $1{\cdot}8 \times 10^6$ m^3 of sediment was eroded from the estuary. Of this 17% was from supratidal areas. The remaining $1{\cdot}5 \times 10^6$ m^3 represented the increase in volume of the estuary due to the erosion of sediment from below high tide level. The increase in subtidal volume was $1{\cdot}28 \times 10^6$ m^3. An increase of approximately 271×10^3 m^3 (15% of the total volume increase) in intertidal volume (tidal prism), established a post-flood tidal prism of 425×10^3 m^3.

Channel sediments were sampled by diving 8 days after the flood peak. The channel base comprised poorly sorted, gravelly sand and bedrock outcrops. All mud had been eroded from the estuary and the carbonate and organic content of the sediment was reduced to zero. Fine sand was deposited in the deeper sections in the upper reaches. At the time of sampling flow velocities were still high (1–2 m s^{-1}) and fresh water extended to the outlet.

The gravel content of the channel sediments was lower than under pre-flood conditions. Examination of the grain size characteristics of the sand fraction showed that the lower reaches were dominated by coarse grained sand, the middle reaches by medium grained sand and the upper reaches by fine grained sand (Fig. 8). In general, the sediments were only moderately to moderately well sorted (Fig. 8). In the upper reaches the fine sand was well sorted and sand of various grain sizes were well sorted at Athlone Bridge.

Overbank deposits (Fig. 9A) consisted of either well sorted fine grained sand or mud. Mud was deposited from suspension in water-filled depressions and a layer up to 1 m thick was deposited supratidally in Beachwood mangrove swamp. Thinner mud deposits (<0·1 m thick) filled depressions to the south of the estuary. Overbank deposits of fine, angular, well sorted sand (mean grain size 0·12 mm) deposited on the south bank often preserved small antidunes (50 cm wavelength). Local flow reversal produced by eddy currents on the overbank areas resulted in some upstream dipping planar cross bedded units up to 2 m thick in the overbank sands.

Discussion: flood impacts

Flood impacts were controlled by the geomorphology of the estuary. Rock outcrops prevented erosion of the northern bank and enhanced downward scouring of the bed at cross-sections 9–12 (Fig. 7). The gently dipping bedrock surface is close to surface in this area and consequently the alluvium of the south bank was preferentially eroded. Downstream, at sections 7 and 8, bedrock occurs at greater depth and downcutting occurred while the banks were little eroded in that area. Downcutting was enhanced by high gravel concentrations in that area which were associated

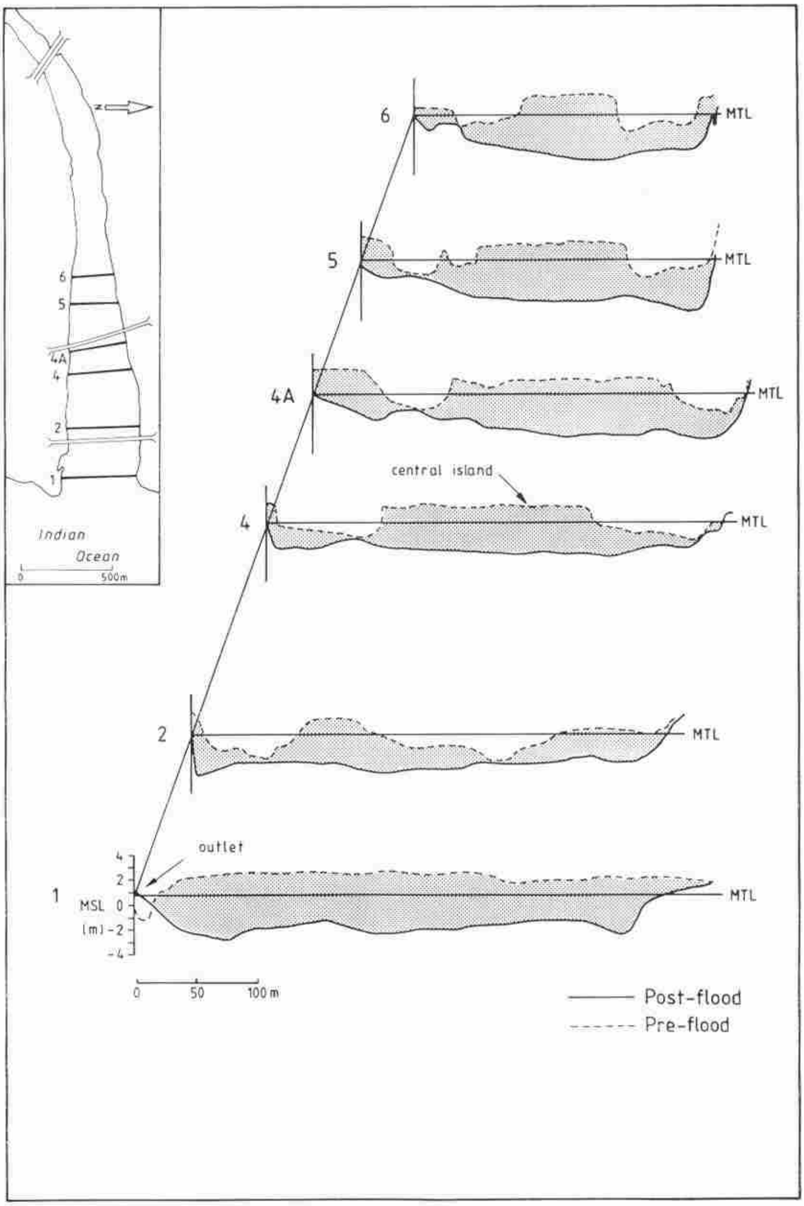

Fig. 7. Cross-sections of the estuarine channel in July 1984 (pre-flood) and October 1987 (immediately post-flood) showing changes in volume. Positions of transects shown on inset (after Cooper *et al.*, 1990). MTL, mid-tide level.

with flow separation around the central island. This selective deposition of gravel upstream of the island locally decreased the channel depth before the flood. Thus, maximum depth increase in this area was partly due to erosion of a topographical high in the channel bed. The high porosity and lack of cohesion of the gravelly sediment enhanced its erosion potential. Erosion of sands from the lower estuary was facilitated by the non-cohesive nature of the barrier and flood tidal delta.

Post-flood sediment distributions revealed areas of coarse sediment which may have indicated the main

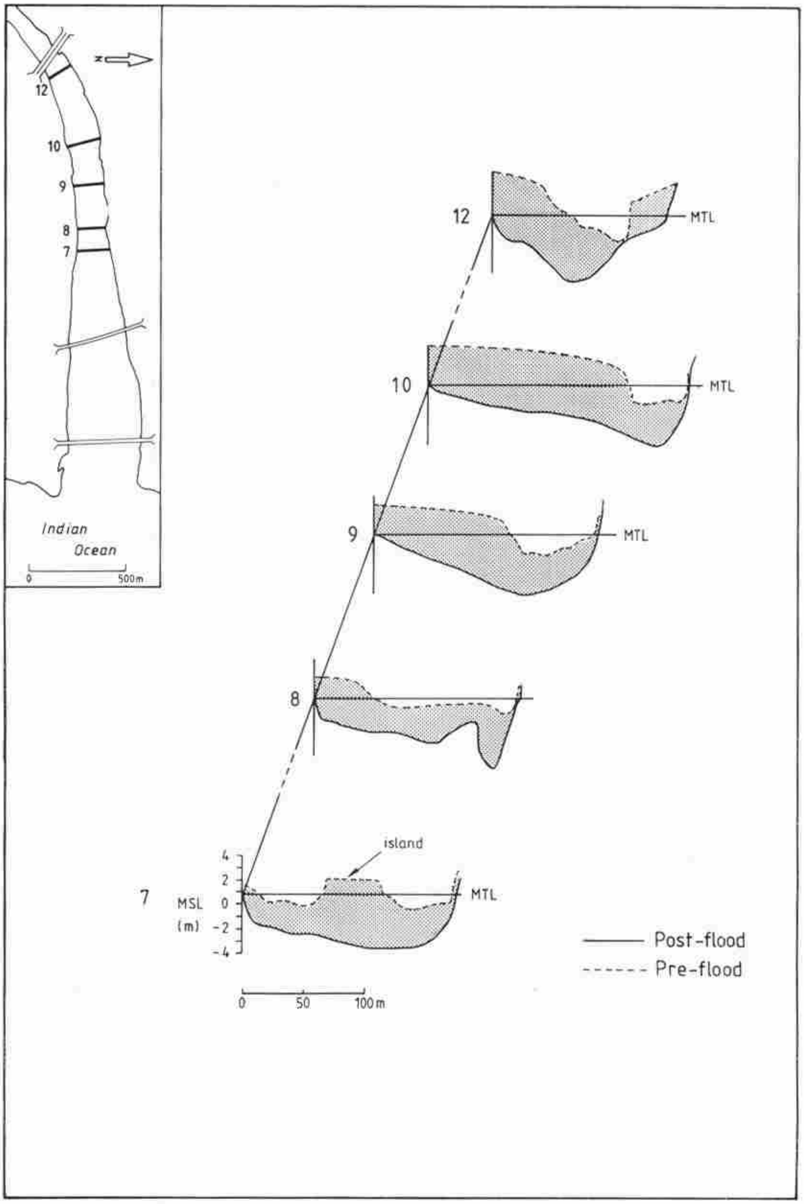

Fig. 7. *continued.*

flow directions during the flood peak. All the grain sizes (excluding bedrock) were within the range of grain sizes transportable during the flood and their distribution may therefore be indicative of both scour and waning stage deposition. This is evidenced particularly by the presence of fine grained sand in the upper reaches. As erosion is controlled by both current velocity and the sediment carrying capacity of the water, bottom sediments need not be at the threshold of motion for a given flow and thus are not necessarily indicative of current velocity distribution during the flood. The complete erosion of organic detritus, fine grained sediments and marine sand from the estuary was evident in post-flood sediment samples.

POST-FLOOD RECOVERY

In order to assess the relative importance of the flood event, the estuary was visited on several subsequent occasions and post-flood vertical aerial photographs were also examined. The condition of the estuary on each occasion is described below.

10/10/87. No barrier was present but shoaling was noted at the north side of the outlet and sand was accumulating adjacent to the groyne. South-easterly waves were entering the estuary, eroding the northern bank. The mouth of Beachwood Creek was closed by sand deposition. Water in the estuary was fresh.

21/10/87. A new barrier was partly emergent as a small sand body (150 × 30 m) with its long axis nearly parallel to the coast. Wave approach was from the south-east. A second small sand body was attached to the groyne. The larger of the two sand bodies was

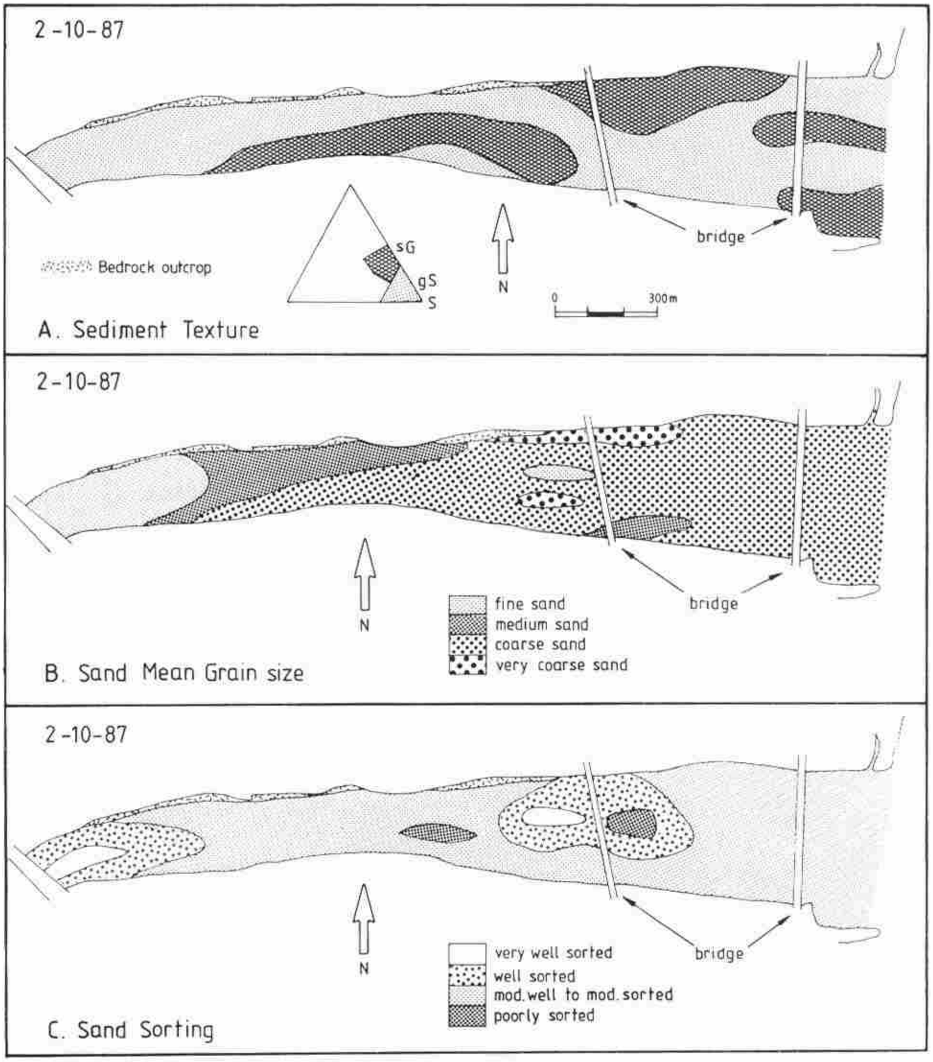

Fig. 8. Post-flood sediment distribution (2/10/87) showing (A) sediment texture, (B) mean grain size of the sand fraction and (C) sorting of the sand fraction. sG, sandy gravel; gS, gravelly sand; S, sand.

welded to the northern margin of the flood breach by the end of October. Small, upstream directed current ripples were present in the estuary opposite the outlet and most of the estuary bed was covered in a layer of soft, organic-rich mud, except in the lower reaches where it was sandy (Fig. 10A). Mud thicknesses were measured by pushing a rod through it until resistance was encountered from the underlying gravelly sand. Mud averaged 0·4 m in thickness, with a maximum of 2·5 m in the upper reaches (Fig. 10B) and thinned seaward. The mud had a near constant organic content of about 20%. Post-flood topographical variation in the channel was subdued by mud deposition in the deeper parts. Salinity was becoming re-established in the estuary.

19/11/87. The barrier was accreting seaward by beach ridge accretion. A subtidal sand body extended almost from the northern to the southern barrier segment. Aeolian sand was accumulating on the elevated ridge while the seaward ridge was composed of a lag of coarse grained sand, gravel and mollusc shells. The shells were all typically shallow nearshore species and indicated landward transport of sediment from the shoreface. Ripples produced by flood tidal currents were extended from the outlet to 250 m upstream. On the spring high tide the estuary was stratified and bottom salinities exceeded 30‰. The thickness of the mud layer in the estuary had increased slightly and extended further downstream.

28/1/88. Barrier accretion had continued until the outlet was virtually closed and only a small channel was maintained. Water levels in the estuary were high and most of the Beachwood area was inundated. Mud deposition had extended downstream to the barrier (Fig. 10C) but in the upper reaches the mud thickness was reduced compared to November (Fig. 10D). Increased resistance to pushing the stick through the mud layer suggests that this was due to compaction. Salinity was low (0·7‰) due to the nearly closed mouth.

28/3/88. In March 1988 the barrier had been re-established in a position seaward of that in 1985. Beaches to the north had accreted seaward by over 100 m. The estuary was shallow throughout its length (typically <0·5 m) and the bed was composed of micaceous, fine grained sand (Fig. 11). The similarity of the deposited sand to overbank deposits suggests that it represents the coarsest fraction of the fine suspended load which was deposited in the channel further upstream during waning flows and, with the return of normal flow conditions, migrated downstream as bedload. Very fine grained sand was more common in the lower reaches, particularly on the intertidal areas (Fig. 11B), suggesting less active currents in those areas. Sorting (Fig. 11C) followed a reverse trend, due also to stronger current action and selective winnowing of very fine grained sand. Very well sorted sands occurred in the upper reaches and in the outlet.

The bed was intertidally exposed between the Ellis Brown and Athlone Bridges and the channel thalweg ran obliquely across the estuary (see 8/5/88 aerial photographic interpretation, Fig. 9B). In the upper reaches a large unvegetated sand bar was exposed at all tides on the right bank. Bedforms in the channel comprised straight crested sand waves (20–30 m wavelength; 0·7 m amplitude) with small, superimposed linguiod, current ripples. The outlet was located adjacent to the groyne.

30/5/89. The sandy surface of intertidal flats began to be exposed above high tide as a result of swash action. Mud deposition on the intertidal flats had occurred during low tide exposure and surfaces comprised laminated and thinly interbedded sand and mud. The intertidal areas seaward of the Athlone Bridge were colonized by marine algae which helped bind the sediment. The more elevated parts of the sand bars were vegetated with *Scirpus* reeds. Adjacent to the barrier, a few mangrove seedlings had taken root in the shallow channel. In the channel sections where no vegetation had taken root, small flood-directed current ripples were produced by the rising tide. In the upper reaches the channel had narrowed through the growth of dense vegetation (reeds and grasses) and consequent stabilization of the right bank.

June/July 1989. A survey of several cross-sections was carried out in June 1989 for calculation of estuary dimensions and sediment deposition since September 1987. These cross-sections were compared with those measured immediately after the flood (Fig. 12). Comparison of the pre-flood, flood and post-flood channel dimensions shows that during the 21 months since the flood, a total of $1{\cdot}36\times10^6\ \mathrm{m}^3$ of sediment was deposited in the estuary. Of this, 93% was deposited subtidally while only 7% ($0{\cdot}95\times10^6\ \mathrm{m}^3$) represented intertidal deposition. The tidal prism was $333\times10^3\ \mathrm{m}^3$, almost twice that which existed before the flood. Aerial photography in July 1989 (Fig. 9C) depicts the estuary morphology close to the time of

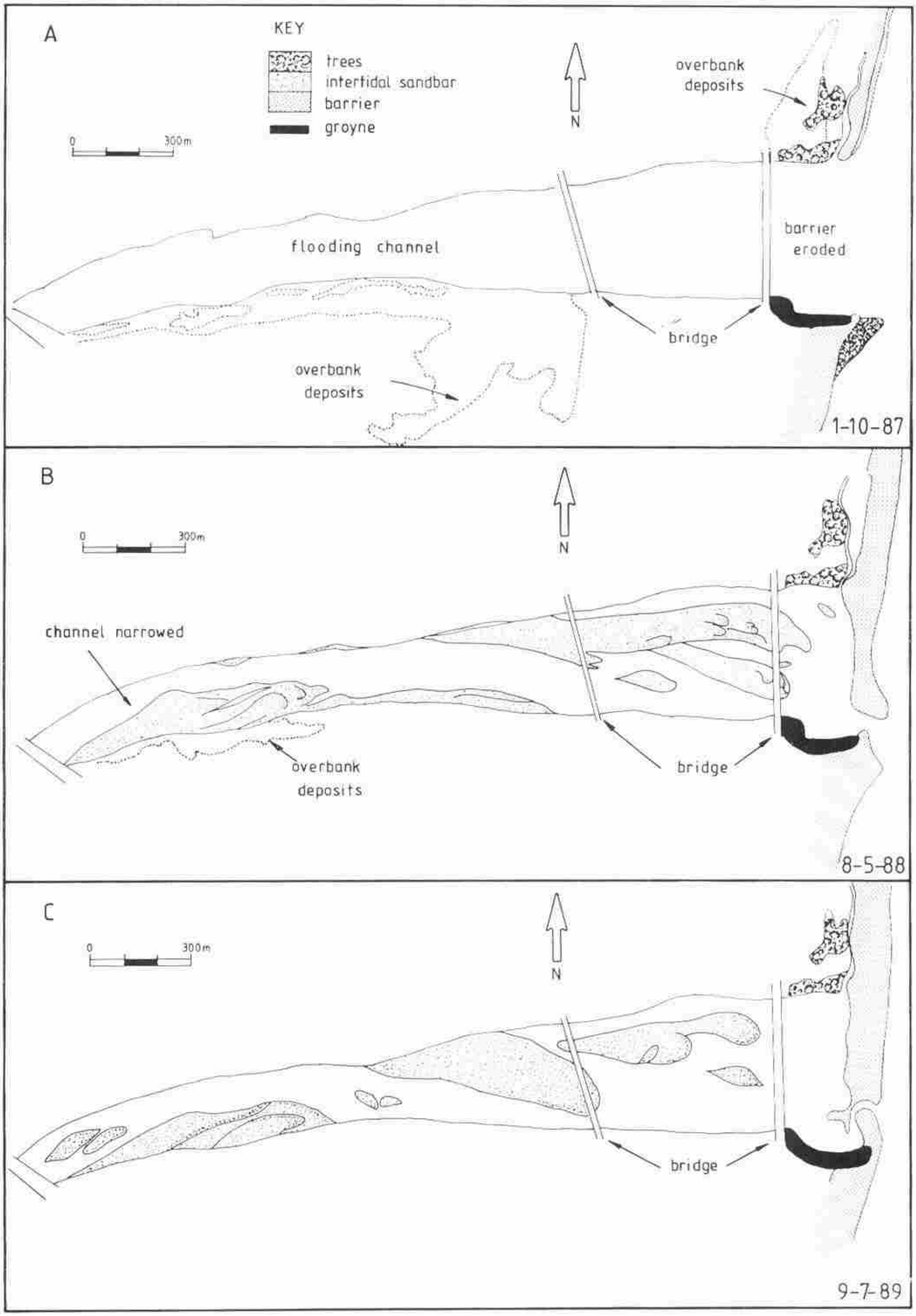

Fig. 9. Post-flood changes in the estuarine channel (October 1987 to April 1990) illustrating post-flood recovery.

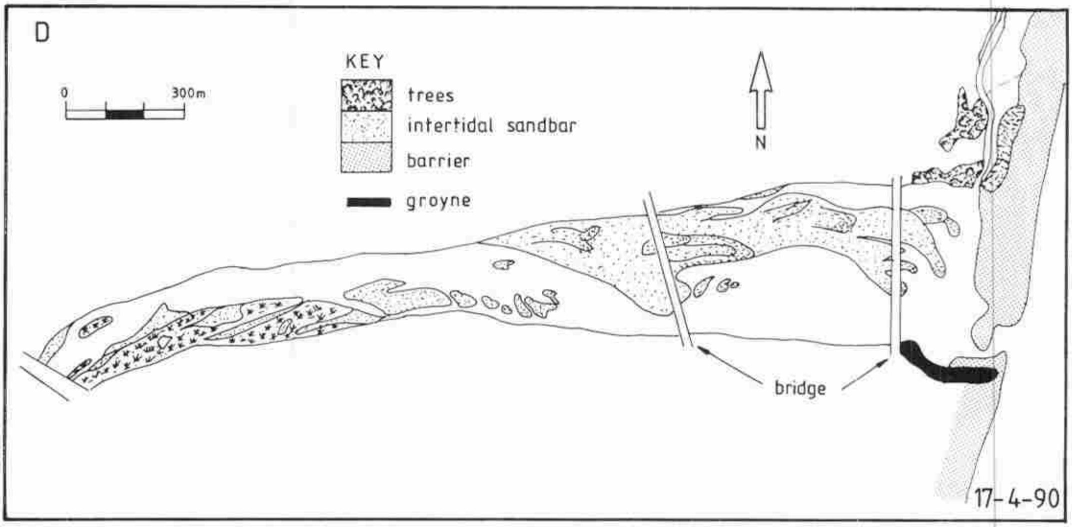

Fig. 9. *continued.*

the survey. The channel contained a large volume of intertidally exposed sand. The apparent reduction in downstream extent of the sand bars is due to a higher tidal level than the 8/5/88 photograph and turbidity which obscured the bedforms.

17/4/90. Aerial photography from almost 1 year later (Fig. 9D) showed that little morphological change had occurred. Vegetation was established on the elevated parts of the intertidal flats. A former intertidal bar in the upper reaches was thickly vegetated and incorporated into the floodplain. Two channels were present, one on either side of the elevated central area, although the southern channel was better defined.

Discussion: post-flood recovery

The recovery of the estuary after the flood may be divided into barrier and back barrier channel sections.

Barrier recovery

Coarse sediment deposited offshore as a subaqueous stream mouth bar was rapidly reworked by wave action and transported landward to reconstruct the barrier. The mechanism of mouth bar modification and barrier reconstruction was described by Cooper (1990). When the flood waned, wave action transported sand and gravel landward, forming a submarine bar which, through swash action and tidal rise and fall, gradually emerged above water level. The importance of swash action in supratidal growth of barriers was stressed by Reddering (1983).

Within 3 weeks of the flood peak, stream mouth bar sands had become emergent, through wave action and landward transport of formerly submerged sands. Through November and December 1987 wave action continued to transport sand landward against this northern emergent stream mouth bar fragment so that it appeared to grow southward and ultimately closed the mouth in the centre of the barrier in January 1988. Eventually, with increased river flows, a new outlet formed in its former position. The large quantity of sand in the littoral zone caused progressive accretion of beaches north of the estuary (Fig. 13), restoring the shoreline position to near that of the 1930s (compare with Fig. 6).

Estuarine channel recovery

In the 8 months following the flood, the river channel underwent rapid accretion. Four periods of post-flood recovery may be recognized in the 3 years after the flood: waning flood deposition, suspension settling of mud, downstream sand wave migration, and braid bar coalescence and emergence.

Waning flood deposition lasted only a few days and left the bed covered in a modertely sorted, unbedded

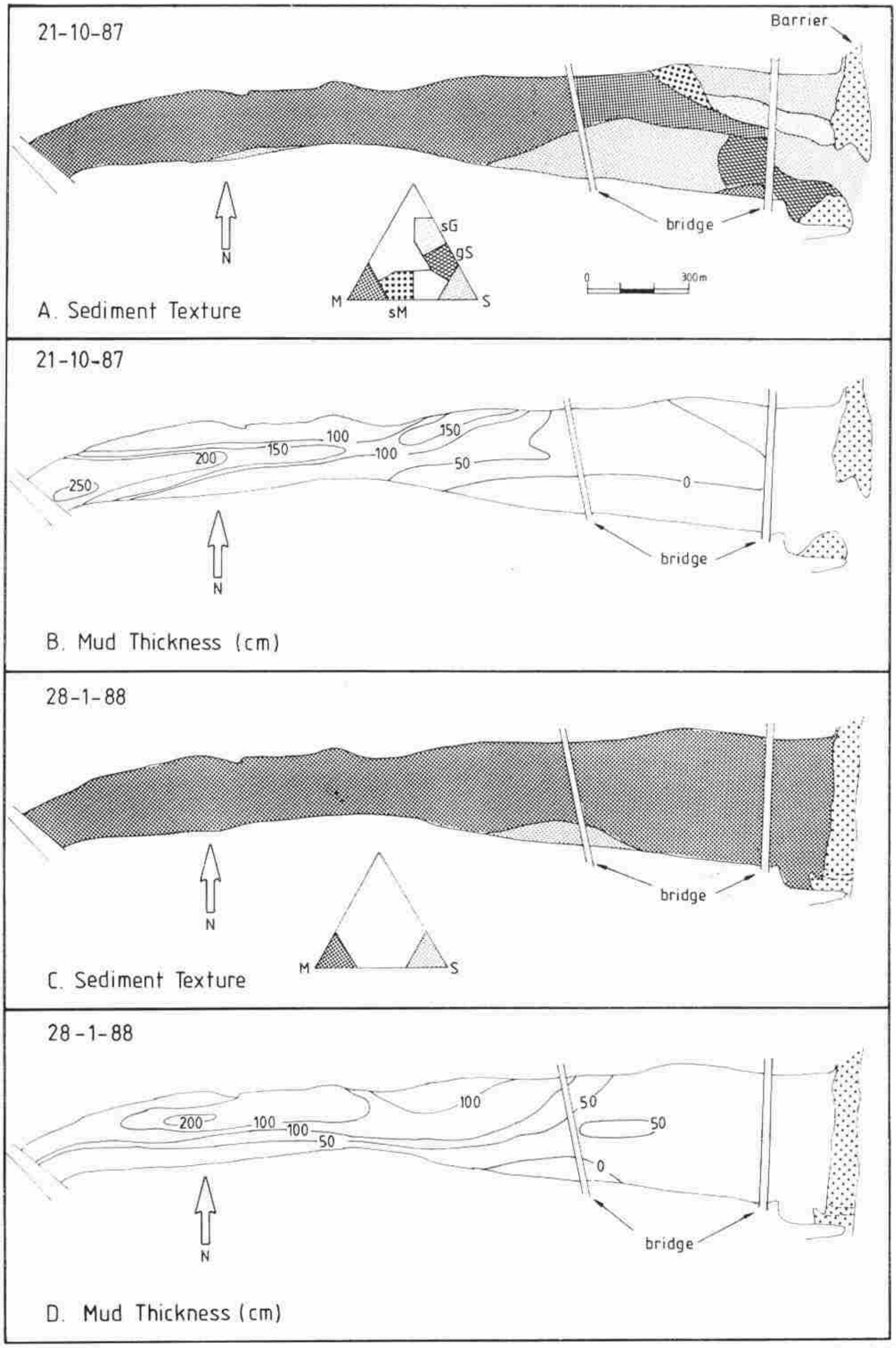

Fig. 10. Grain size distribution (A) and mud thickness (B) on 21 October 1987 and grain size distribution (C) and mud thickness (D) on 28 January 1988. Note the downstream extent of the muddy sediment and its apparent decrease in thickness in the interval between sampling. This is attributed to compaction. sG, sandy gravel; gS, gravelly sand; M, mud; sM, sandy mud; S, sand.

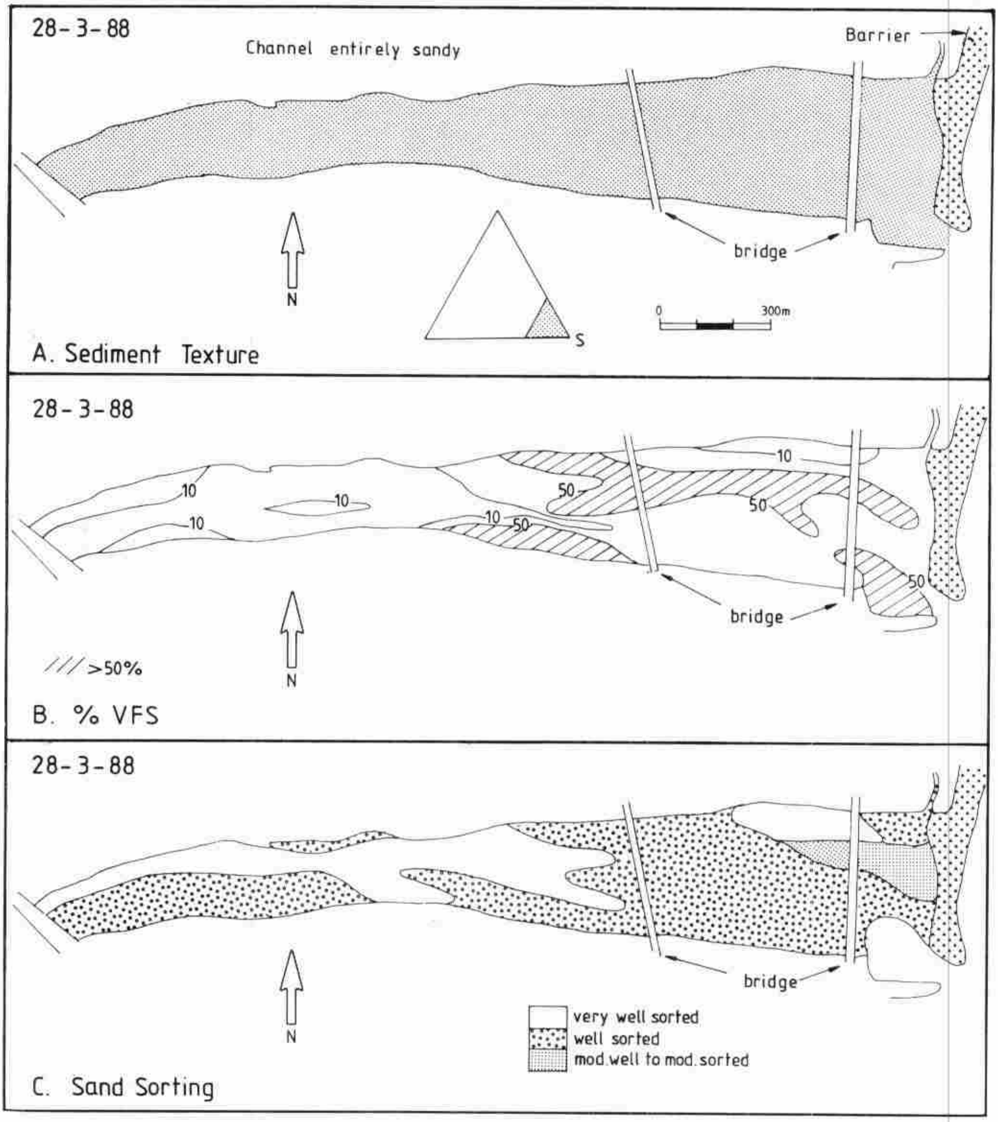

Fig. 11. Sediment grain size distribution in the estuary on 28 March 1988. The estuary is completely sandy (A) and grain size distribution is best illustrated by variations in the proportion of the very fine sand (VFS) fraction (B). Sorting of the sand fraction (C) is also shown.

mixture of sand and gravel. Fine grained sand deposition in the scoured upper reaches was associated with the falling stage and did not persist. Suspension settling of muddy sediments began after 10 October and by 26 October (30 days after the flood) had extended seaward of Athlone Bridge. Up to November (60 days after the flood) mud deposition extended beyond the Ellis Brown Bridge and had become consolidated. Mud deposition continued until the end of January as the barrier was reconstructed and eventually closed. By then, 120 days after the peak, mud extended to the barrier.

By the end of March 1988, however (180 days after the flood), the estuary bed was covered with fine grained fluvial sand. This is interpreted as formerly suspended sediment deposited upstream as the flood

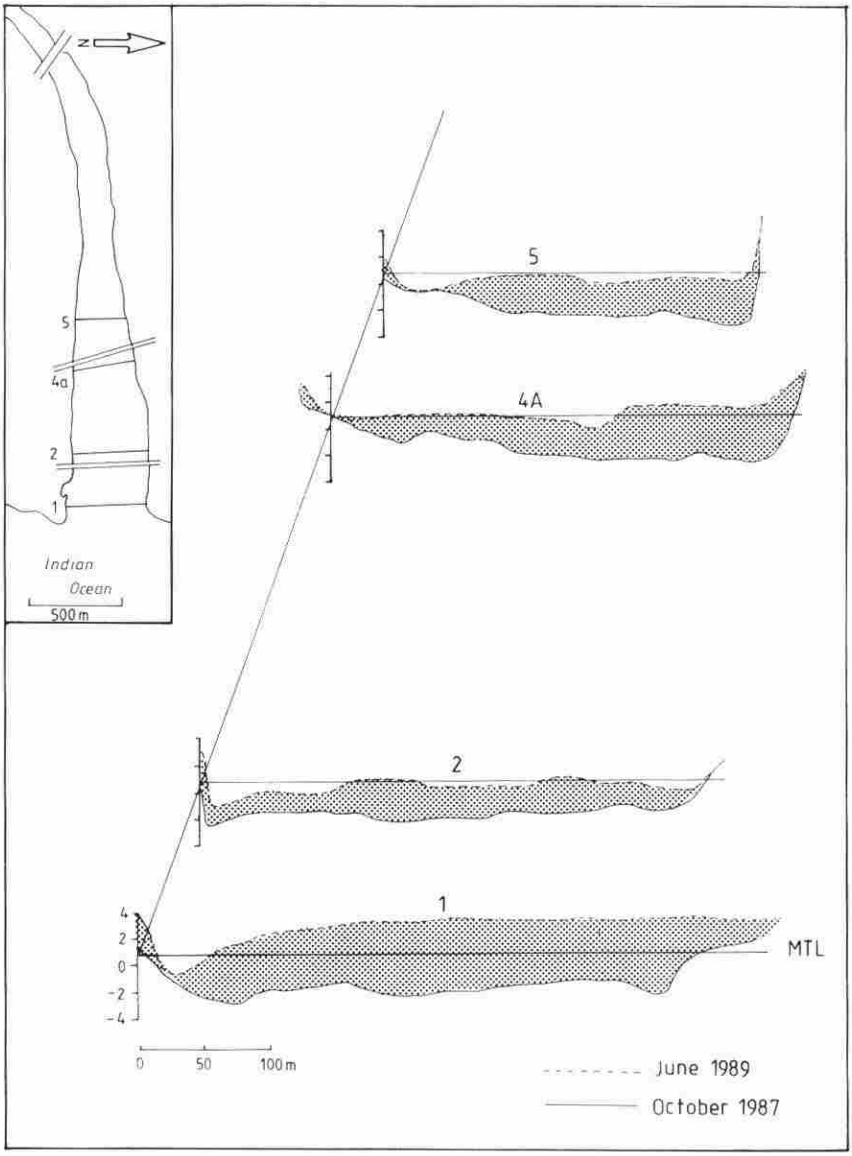

Fig. 12. Comparison of post-flood scoured channel (October 1987) and cross-sections surveyed in June 1989. Not all of the cross-sections were surveyed and only those which coincide with the earlier cross-sections are illustrated. Note the volume of sediment deposited since the flood (shaded area). MTL, mid-tide level.

waned. Subsequently it moved downstream as bedload and rapidly filled the estuary. Fine grained sand is the most easily transported bedload fraction (Blatt *et al.*, 1980). By the end of May 1988 (240 days after the flood) the fine grained sand deposited during the previous 2 months was thickly vegetated, a fact ascribed to rapid vegetation growth in the subtropical climate. Within the next year little sedimentation occurred in the estuary and the major changes which occurred involved vegetal stabilization of the intertidal bars and the initiation of mud deposition at low and high tide slack periods. The estuary now has essentially the same morphology to that of 1931, which by implication therefore can be assumed to have followed a major flood. Historical records (Begg, 1978, 1984a) indicate that the last major flood in the Mgeni

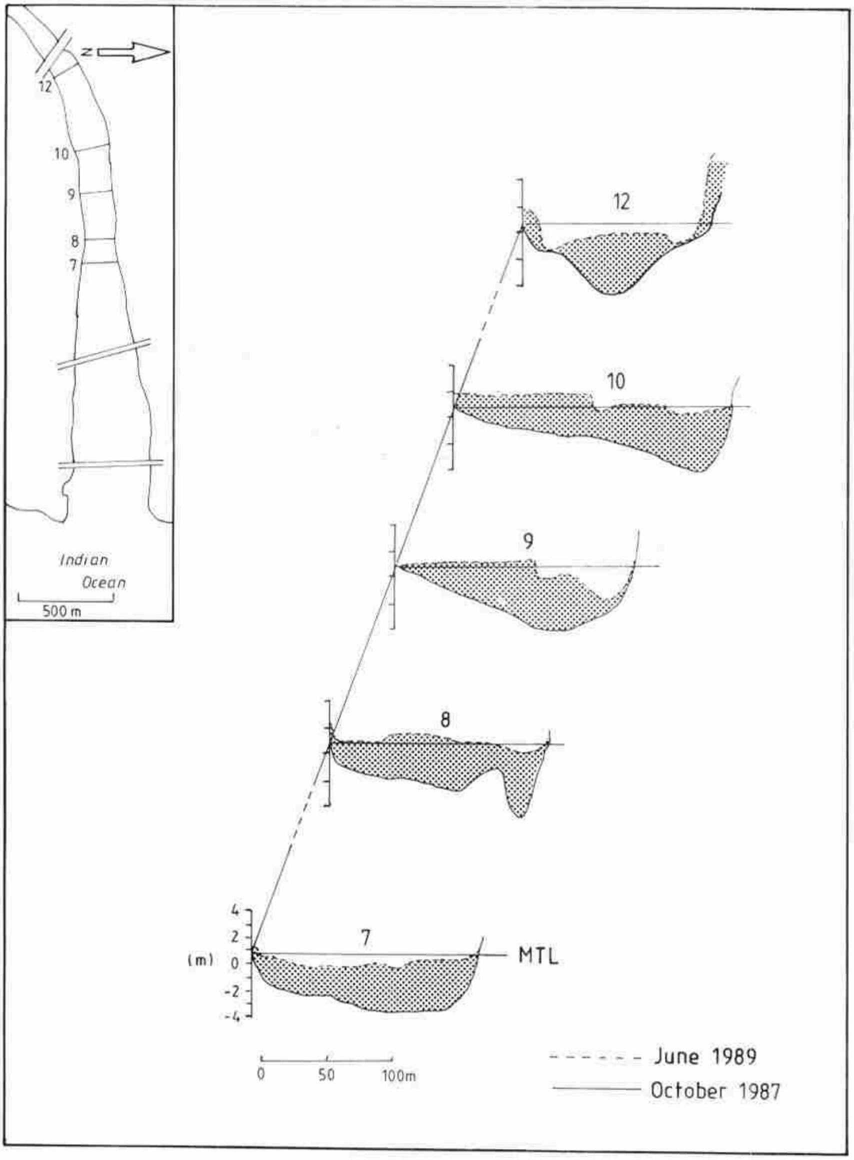

Fig. 12. *continued.*

River was in October 1917 when a discharge of 5700 m^3 s^{-1} was recorded.

The sedimentary succession studied in trenches and vibracores was in agreement with periodic surface sediment sampling. Vibracores revealed a sequence consisting of a poorly sorted layer of coarse grained sand followed by up to 2·5 m of organic-rich muds becoming thinly interbedded with very fine grained sand toward the top. This thin bedding is correlated with the observed period of low sedimentation. This was overlain by up to 2 m of planar cross bedded, fine grained sands in sets 0·7–0·8 m thick with small foresets defined by heavy mineral laminae.

Although the thickness of each unit varied laterally and in some cases the mud or fine sand was absent through subsequent channel formation, the same

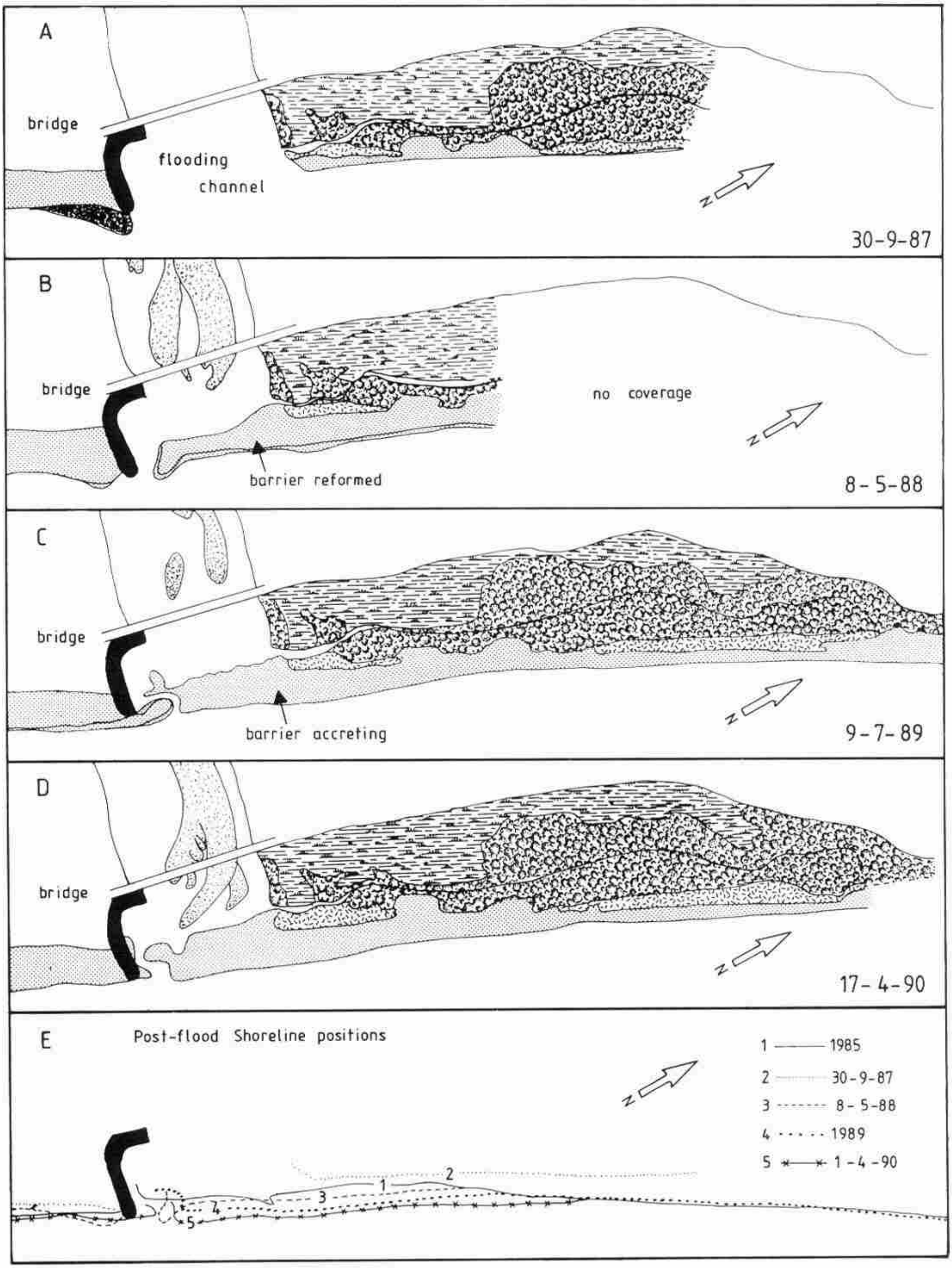

Fig. 13. Post-flood changes in the coast-parallel lagoon as interpreted from aerial photographs. The changes are mainly restricted to changes in the shoreline position shown in the composite diagram (E). The coastline prograded rapidly after the flood and assumed a position similar to that of the 1930s, as a result of the increased sediment supply in the nearshore. If the past is repeated it should take about 70 years to erode to the pre-flood position when overwash occurred. Ornament as in Fig. 6.

general sequence was produced throughout the estuary (Fig. 14). A similar sedimentation pattern of smaller extent is produced by minor floods; however, the erosion of existing sediments by bed scour during catastrophic floods indicates that facies associated with catastrophic flooding are like to dominate the sedimentary record in estuaries of this type. The thick horizons shown as sand in Fig. 4 may therefore consist of numerous successions of coarse grained sand overlain by thin mud beds and topped with fine grained sand, but the coarse resolution of available engineers' logs does not enable verification at this stage.

Within 21 months the scoured estuarine channel was infilled by rapid deposition, as the estuary regained a dynamically stable downstream profile. No supratidal deposition had begun by then but intertidal deposition of mud laminae had started the upward accretion of the braid bars. Calculations show that supratidal deposition of an additional 140×10^3 m^3 of sediment is required before the estuary approximates its pre-flood morphology. The smaller volume in the estuary at low tide reflects the presence of intertidal flats and it appears from the historical changes reported above that as these become emergent, downcutting of the flanking channels must occur to increase the subtidal volume.

LONG AND SHORT TERM SEDIMENTATION IN THE MGENI RIVER ESTUARY

The combined results of the historical aerial photographic interpretation and observations following the

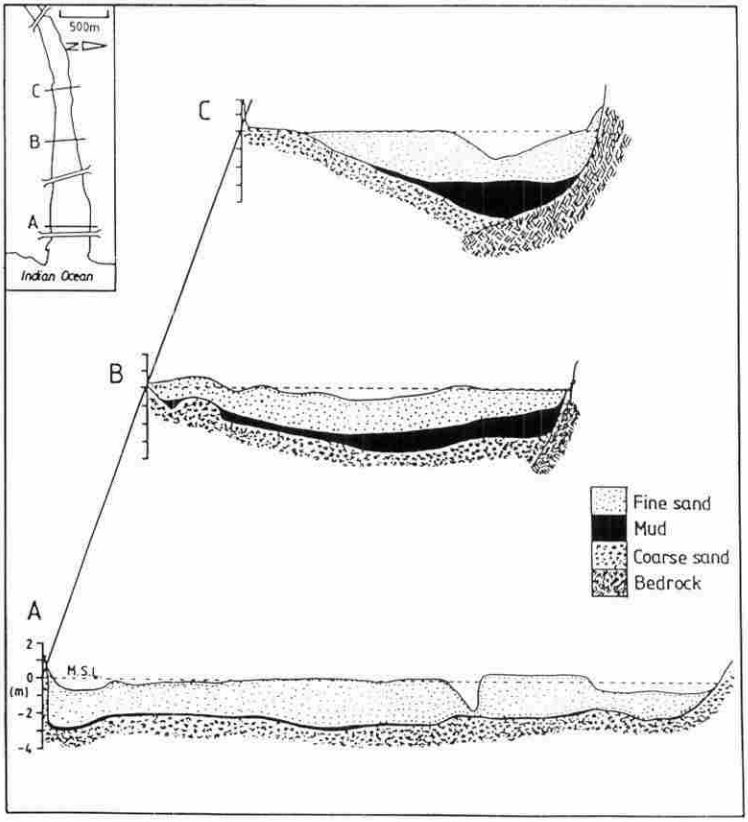

Fig. 14. Post-flood sedimentary succession in the river mouth, based on sequential sediment sampling, cross-sectional surveys and verified by vibrocoring. Note the downstream thinning of the mud horizon and the effect of fine grained sand in reducing gradients along the channel. Cross-section positions shown in inset.

1987 flood show several trends which relate to the long term sedimentology of the estuary. Aerial photographs from 1931 record a long period of slow geomorphological change from a shallow, braided river channel which, through bar emergence and vegetation growth and stabilization, eventually formed two comparatively deep marginal channels with a vegetated central island. This change may be related to increasing margin stability through mud deposition and vegetal colonization. Bank stability enabled downcutting and deepening of the channels. Under these conditions the estuary accommodated variation in discharge through temporary deposition (either in the channels or on the side-attached bars which characterized both anastomosing channels before the 1987 flood) or erosion. The deep channels around the island permitted an increased subtidal volume which was reduced by deposition of a flood tidal delta in the later stages of development of the estuary.

Events during the 1987 flood transformed this apparently stable morphology by exceeding normal energy thresholds. Over a few days more than $1{\cdot}8 \times 10^6$ m^3 of sediment was eroded from the estuary alone. Rapid post-flood sedimentation of $1{\cdot}3 \times 10^6$ m^3 filled the estuary to its earlier base level and its morphology reverted to that which it attained in the 1930s. Stabilization and vegetation of the intertidal bars and supratidal accretion in the 2 years following channel filling appears to follow the same pattern as that which, over a 50 year period, transformed the estuary to its stable (1986) morphology. It is therefore likely that a similar mature, pre-flood morphology will be attained in the future. Between major floods such as those of 1917 and 1987, minor floods partially eroded the bed and banks but this material was rapidly replaced from upstream as the river readjusted to equilibrium conditions.

Sediment deposited at the coast after the flood was sufficient to cause accretion of adjacent beaches to a position similar to that of the 1930s, but a slow retreat similar to that which occurred between 1931 and 1985 can be expected to occur again, ultimately terminating in overwash of the barrier.

Schumm (1968) noted that anastomosing rivers have typically low gradient, suspended load channels carrying only flood water which transports mainly a suspended load and little bedload. In view of the lack of progradation and progressive shoreline retreat between major floods, it is likely that, within the normal range of flow conditions, the Mgeni River carries mainly suspended load and only during major river floods is much bedload sediment deposited in the coastal zone for beach reconstruction. This implies further that the coast is in a state of swash aligned equilibrium.

Rejuvenation of the former coast-parallel lagoonal area cannot be achieved by a flood event and this area has gradually infilled. Fine grained deposition in the coast-parallel lagoon is a long term evolutionary trend, albeit enhanced by stabilization of the outlet by groyne construction and/or increased catchment sediment yield. It now acts only as a backwater and drains a small coastal catchment.

In terms of channel stability, increased catchment sediment yield would probably not impact on the estuary. Sedimentation is related not only to yield but also to the ability of the river to transport it. As the estuary is restored to its base level, increased sedimentation would be impossible without a rise in sea level. Instead, any increase in sediment load from the catchment would be transported through the estuary, after a possible temporary residence period, and deposited offshore.

Floods have periodically eroded accumulated sediment from the lower reaches of the Mgeni River estuary during the last century but little erosion of the rest of the estuary has occurred since the last major flood in 1917. Evidence for this is provided by two railway trucks which were lost during the 1917 flood. These trucks were exhumed by the 1987 event, having been buried for 70 years under the south bank of the estuary. The channel banks and central island have undergone intermittent accretion since 1917. It is therefore possible to estimate the net sediment accumulation rate in the estuary and, given the sediment yield from the catchment, to calculate the net proportion of sediment retained in the estuary annually. Marine derived sand of the barrier and flood tidal delta is excluded from the calculation as it is subject to rapid erosion and accumulation.

The total amount of sediment eroded from areas upstream of the flood tidal delta (Fig. 7) during the 1987 flood was approximately $1{\cdot}5 \times 10^6$ m^3 (Cooper *et al.*, 1990) which could be considered equal to the net amount of fluvial sediment accumulated since 1917. This yields a mean sediment accumulation rate of $21{\cdot}4 \times 10^3$ m^3 per year since 1917. Considering only the supratidal sediment upstream of section 2, the accumulation rate is $3{\cdot}4 \times 10^3$ m^3 per year. This may be considered equivalent to net suspended sediment accumulation as it is restricted largely to overbank deposition. The volume of bedload sediment deposited since 1917 is therefore $1{\cdot}24 \times 10^6$ m^3 [1 861 957 − (303 339 + 309 306)] or $17{\cdot}8 \times 10^3$ m^3 per year. This is approximately 46% of the predicted annual bedload sediment yield based on Rooseboom's (1975) data. Most of this probably accumulated soon after the 1917 floods in a similar way to that deposited since the 1987 flood. In view of the possible overestimation of sediment yield from Rooseboom's (1975) map, noted above, it is possible that all of the bedload sediment is retained in the estuary in interflood periods.

This study has shown that sediment accumulation and erosion in the Mgeni River estuary is strongly episodic and thus consideration of mean sedimentation rates is unrealistic. The erosion of $1{\cdot}8 \times 10^6$ m^3 of sediment from the estuary in a few days and its deposition in the sea clearly illustrates the importance of catastrophic floods not only in the estuary but also on the adjacent shelf and nearshore zone where large influxes of sediment influence sedimentation in the littoral zone and shelf.

CONCEPTUAL MODEL OF RIVER DOMINATED ESTUARIES IN NATAL

In river dominated estuaries of Natal, typified by the Mgeni, sedimentary processes follow a cyclical path, dominated by almost instantaneous flood impacts and long term, post-flood channel adjustment. A schematic diagram of sedimentary processes under stable sea level conditions is shown in Fig. 15.

In a mature or stable state (Fig. 15A) these estuaries have cohesive banks with moderately deep (1–3 m) channels in which tidal exchange produces semi-diurnal salinity and water level fluctuation. Tidal currents deposit a small flood tidal delta but ebb tidal deposition is inhibited by wave action. The seaward barrier face assumes a dynamically stable plan form and overwashed sediment is reworked by ebb currents. The channels are scoured to an erosion base of rock, compacted mud or gravel. Mud deposited during low flow periods is transported seaward in a turbid plume during increased river flow. Bedload supply to the coast is minimal. Flood tidal deltas are eroded during moderate floods but subsequently reform. Outlet dimensions vary with fluvial discharge and wave energy.

During major floods (Fig. 15B) the confined valleys restrict lateral expansion and promote downward erosion. Overbank deposition is limited in extent by narrow floodplains and mud is deposited in backwaters. River mouth barriers are completely eroded and submerged deltas are deposited offshore. When floods subside, salinity is re-established and suspension settling begins in the channel. At the same time, the barrier is reformed by emergence and landward translation of the submerged delta by overwashing in a typical rollover mode. Surplus sand in the nearshore may cause temporary progradation on the barrier face.

Post-flood bedload transport of fine grained sand into the estuarine channel from upstream causes shallowing and the uncohesive sandy banks, which are stripped of vegetation during floods, promote braiding (Fig. 15C). The shallow braided channel reduces the estuary volume and inhibits flood tidal deposition. Temporary increases in barrier width also cause outlets to close periodically.

In the long term, braid bars are stabilized with vegetation which, in turn, promote intertidal mud deposition (Fig. 15D). This stabilizes the banks and induces downward river scour and formation of deeper channels. Depending on morphology of the estuarine valley, deposition is concentrated either on a central island (Fig. 15E) or on the floodplain. In post-flood times, barriers narrow through wave and current dispersal of excess sediment to regain equilibrium plan forms. Larger water volumes are permitted by deeper estuarine channels and flood tidal deposition is ultimately renewed as the tidal circulation is re-established.

Facies arrangement in mature river dominated estuaries comprises one or two sand or gravel based channels with braid bars or side-attached bars. The channel lags during mature post-flood intervals contain few bedforms or bioturbation. Mud which accumulates in channels during low flows is removed by subsequent high flows. The channels are surrounded by elevated muddy areas produced by overbank deposition. These are typically vegetated by mangroves which support a dense burrowing infauna that produces characteristic bioturbation traces. Elevated areas behind the mangrove fringe support a saltmarsh flora and fauna. These areas are muddy and subject to infrequent inundation during unusual tides, increased river discharge or outlet closure. They are typified by desiccation features and the large burrows of sesarmid crabs (Cooper, 1986a). In backwater areas muddy lagoonal facies may accumulate, particularly if coast-parallel extension occurs. These deposits are typically intensely bioturbated.

Barrier associated facies include an outlet channel with evidence of reversing tidal currents provided by bedforms, although typically flood and ebb tidal currents dominate particular sections of outlet channels (Cooper, 1988). Small flood tidal deltas are present

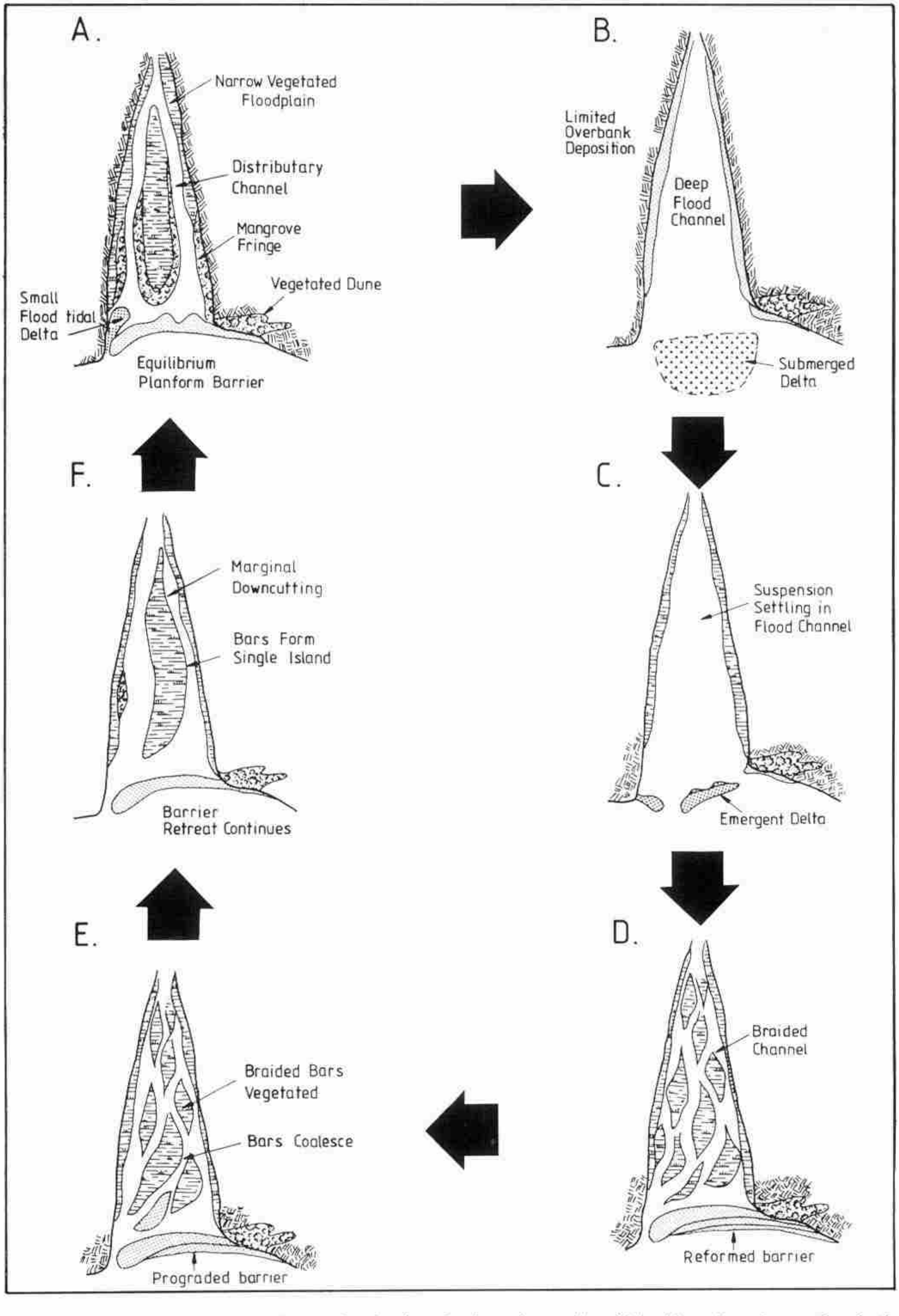

Fig. 15. Conceptual model of cyclical sedimentation in river dominated estuaries of Natal based on observations in the Mgeni River estuary.

and may extend upstream during mature stable periods. Small, ephemeral ebb tidal deltas form during periods of low wave energy.

Intertidal areas are limited in extent and are restricted mainly to the barrier and flood tidal delta. They are typified by structures characteristic of late stage emergence runoff. Barriers are dominated by overwash lamination and outlets do not migrate. Aeolian deposits may occur downwind of the barrier but are uncommon on the barriers themselves, due to periodic barrier erosion during floods. Floods accomplish more sediment erosion and deposition than many months or years of fairweather conditions in river dominated estuaries.

These cyclical changes in sedimentation and morphology indicate how a system like the Mgeni River estuary can undergo repeated, evolutionary flushing and resetting mediated by river floods (autocyclical controls) even in the absence of any fluctuation in relative sea level (allocyclical controls).

RIVER DOMINATED ESTUARIES AS TRANSITIONAL FLUVIO-MARINE ENVIRONMENTS

With regard to achievement of equilibrium in lagoons, Price (1947) and Phleger & Ewing (1962) presented the view that sedimentation and basin shape ultimately attain a balance with wave or tidal energy dissipation. If sedimentation and energy are not in balance, transport processes act to establish a balance by either trapping or bypassing the sediment supply (Nichols, 1989), or redistributing sediment within the lagoon (Cooper, 1986a). Extending this concept to river dominated estuaries, sedimentation and basin shape must strive for equilibrium by attaining a balance with fluvial discharge. Clearly, major flood events exceed normal hydrodynamics by several orders of magnitude and so morphological response to floods is only short lived. Channels and floodplains regain equilibrium through sedimentation and continue to adjust their channels through vegetation encroachment, bank stabilization and temporary erosion or deposition.

In one school of thought estuaries are ephemeral features which fill and become non-tidal river mouths, deltas or swamps (Friedman & Sanders, 1978; Schubel & Hirschberg, 1978; Roy, 1984; Begg, 1984a). Rusnak (1967), basing his argument on the concept that estuaries fill with sediment, defined positive, negative or neutral filled basins according to whether the principal sediment source was fluvial, marine or shoreline erosion, respectively. An alternative view is that an estuary can attain dynamic equilibrium with sediment supply and sea level changes and so retain its estuarine characteristics indefinitely. Stratigraphical sequences through some valley fills indicate this to have been the case in several Natal estuaries (Cooper, 1991a). It cannot simply be assumed that all estuaries are simply ephemeral features, although they may change from what King (1980) termed 'drowned river-valley estuaries' to, 'tidal river mouth estuaries'. The latter term implies that although the bedrock valley is full of sediment, estuarine characteristics still prevail in the remnant water body at the top of the sequence.

The Mgeni River estuary is one of a type of river dominated estuaries in which fluvial processes severely limit the extent of marine influences. Although variations on this sedimentary theme have been observed on the Natal coast (Cooper, 1991a), it may be considered broadly representative of a number of estuaries there. Peterson *et al.* (1984) decribed a 'small fluvially dominated estuary' on the tectonically uplifting, Oregon coast while similar features, termed 'estuarine deltas', were described from the Chilean coast (Araya-Vergara, 1985), one of the few coastal hinterlands with topographical steepness and seasonal rainfall comparable to that of Natal. A more detailed comparison of these river dominated estuaries with those of Natal is necessary to distil away local variability and so refine a generally applicable model for river dominated estuaries: the regional model presented here is intended to act as a starting point for such investigations.

When the correct combination of hinterland gradient, sediment availability and discharge characteristics exist, sedimentation may keep pace with, or even exceed, the rate of inundation of a drowned valley during transgression so that fluvial characteristics are maintained right to the coastal barrier. Thus while some estuaries, such as the Mgeni, may have gone through a period of fluvial delta progradation and lateral accretion into a deep basin during their evolution, such a condition may not necessarily exist in river dominated estuaries and a 'mature' stage may be maintained throughout transgression. Nichols & Biggs (1985) noted that estuaries on the US south-east coast, which have high sediment supply, were filled to capacity as fast as the advancing sea level rise drowned their valleys. Thus estuaries such as the Mgeni cannot be viewed simply as a more advanced variant of the typical microtidal estuary model. Maintenance of the stable sea level cycle described above results in a valley fill dominated by sandy sediments because periodic floods remove muddy sediments. To ascribe shallow, fluvially dominated conditions in estuaries to an advanced evolutionary stage and even blame such a condition on increased sedimentation through human interference is not always possible. In terms of Natal estuaries, however, this is the traditionally held view: increased sedimentation from agricultural malpractice has caused infilling and siltation, degrading the estuarine habitat (Heydorn, 1973a, b, 1979; Begg, 1978, 1984a, b). This misconception has driven attempts to restore estuaries to a state which they have not attained for several thousand years, if at all. Morphological changes such as those observed in the Mgeni River estuary instead represent estuarine responses to variations in discharge and morphological adjustment after major floods.

In conceptual terms, in a bedrock valley that is inundated during transgression, estuarine morphology can be viewed as a balance between sedimentation rates and the rate of volume increase of the drowned valley. The latter is influenced by the rate of relative sea level rise, but more particularly, in the case of bedrock valleys, by the valley topography. A fall in sea level will have the effect of reducing the total bedrock valley volume and so will appear to accelerate total sedimentation in the bedrock valley, even though it may cause channel incision into existing sediments.

In Fig. 16 a typical bedrock valley profile is shown in the lower part of the diagram. The graph above shows changes in the total bedrock valley (basin) volume against time. As sea level rises the total volume of the valley initially increases slowly as cross-sectional areas are comparatively small near the apex. When the shelf at SL_1 is reached at time t_1, the rate of volume increase is immediately accelerated (independently of any increase in the rate of sea level rise) by the larger valley cross-section. The volume of fluvial sediment supply required to keep pace with this accelerated volume increase becomes larger. SL_2 at time t_2 represents the entire volume of the basin at the maximum sea level attained, and SL_3 at time t_3 marks the entire volume of the bedrock valley after a minor regression.

In the upper diagram, the entire valley volume (solid line) is plotted against time, for the same intervals as those depicted in the lower diagram. A constant fluvial sediment supply (dotted line) is assumed for simplicity. While sediment supply exceeds the volume increase (light shading) a period of sediment surplus exists, during which fluvial influences would continue to the coast and a fluvially dominated estuary with characteristics similar to those of the Mgeni River would exist. A cyclical pattern of sedimentation driven by episodic floods, similar to that described above, would characterize this period of estuarine development. Excess sediment would be transported to the continental shelf. When the shelf in the valley profile was reached at time t_1 the rate of sedimentation initially kept pace but eventually lagged the increase in valley volume (dark shading) and at this stage conditions are suitable for formation of a typical microtidal estuary with a tripartite facies division. In the Mgeni River, this period is recorded in the deposition of muddy sediments in relatively deep water, which under shallow water conditions would not be preserved in the laterally confined valley. Under such conditions, progressive infilling by estuary head delta progradation and lateral swamp encroachment would operate following the model of Roy (1984). When the valley sides straighten the volume increase slows and

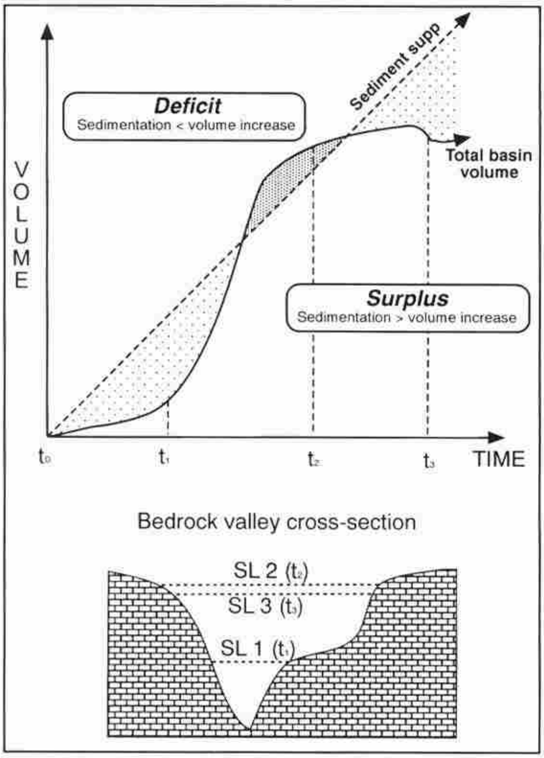

Fig. 16. Diagram to illustrate the relative control of sediment supply and basin volume during transgression on estuarine evolution (for explanation see text).

sedimentation again reaches a surplus stage with fluvially dominated cyclical sedimentation patterns. At time t_3 a minor regression causes channel incision into excisting sediments and leads to the present situation, where most fluvially derived sediment is deposited supratidally during increased discharge, or is transported directly into the sea after a temporary residence period in the estuary.

Peterson *et al.* (1984) noted an almost identical sequence of events in Alsea Bay, a river dominated estuary on the Oregon coast. There the nature of the Holocene fill changed from a lower fluvially dominated shallow water system to a deep water brackish estuary which gradually filled and was replaced by renewed shallow water estuarine conditions. Similarly to the situation in Natal, sediment trapping in Alsea Bay was minimal during shallow water periods during which fluvial sediment was transported directly into the sea and only during deep water periods was fluvial sediment retention high.

Most documented cases of estuarine sedimentation in microtidal settings are from broad alluvial valley or coastal plain settings where river gradients are comparatively low. In such cases fluvial sediment yields do not approach those of Natal, or if they do, deltaic progradation occurs. This is restricted in Natal by high wave energy and the steep nearshore gradient. In areas where estuaries form in narrow bedrock valleys, high sediment yield may cause an estuary to remain fluvially dominated throughout its evolution (Cooper, 1991a). Deltaic progradation and lateral and vertical sedimentation into a deep basin cannot therefore be accepted as a general model for estuarine sedimentation. As shown in Fig. 16 an estuary may change from one evolutionary mode to another during its development, and the major controls appear to be bedrock channel geometry and the rate of valley volume increase, coupled with sediment supply.

In terms of its global setting among transitional fluvio-marine depositional environments, the Mgeni is a river dominated estuary, which, although it receives abundant fluvial sediment, has not and is unlikely to become a delta. Deltaic progradation is prevented by high coastal wave energy (Cooper, 1991a), a deep, narrow continental shelf and dispersal of accumulated shelf sediment by the Agulhas Current (Flemming, 1981). The drowned valley in which the estuary originated has been filled with sediment and under such conditions it is driven by cycles of episodic flood scour followed by a long period of slow deposition and redistribution of sediment within the channel (Fig. 15).

In contrast to other areas where preserved estuary sequences rarely result from a single fill event (Demarest *et al.*, 1981; Clifton, 1982, 1983; Nichols & Biggs, 1985), the confined channels of Natal rivers, coupled with steep river gradients, have resulted in the complete erosion of pre-existing estuarine facies from earlier fill cycles. Only in marginal, coast-parallel lagoonal areas are pre-Holocene sediments preserved in this coastal setting.

The low water volume in river dominated estuaries minimizes tidal influences, even though an outlet may be maintained. Wave action limits coastal progradation and deltaic deposition. Such conditions contrast markedly with those associated with models of sedimentation proposed for other microtidal, wave dominated estuaries (Roy, 1984; Nichols, 1990; Zaitlin & Shultz, 1990). The Mgeni River estuary does not display a tripartite division of facies like microtidal estuaries, nor is it dominated by elongate sand bodies as form in tide dominated estuaries (Dalrymple *et al.*, 1992). In the threefold division of energy levels proposed by Dalrymple *et al.* (1992), the low energy central zone is defined as one where, in the long term, tidal and river energy balance out. In river dominated estuaries, fluvial energy dominates this zone in the long term as a result of the impact of periodic floods. River dominated conditions control estuary morphology both spatially and temporally. A river dominated estuary remains in a shallow, infilled state in which fluvial influences extend right to the mouth and flood tidal deposition occurs only ephemerally, as under the conditions described in 1986 (Cooper, 1988), if at all. Thus a river dominated estuary has only a bipartite division of facies. In the long term also, the estuarine valley fill is dominated by coarse grained, fluvial facies and does not act as a sediment sink. On these bases definition of a fluvially dominated estuary warrants recognition as a distinct class.

If estuaries are viewed conceptually as a function of the relative importance of tidal, wave and fluvial energy inputs (shown schematically in Fig. 17), the Mgeni River estuary represents one of a probable suite of river dominated estuaries. This conceptual diagram of estuarine morphology resembles the approach to deltas by Coleman & Wright (1975) and Galloway (1975) and extends the approach to estuaries taken by Zaitlin & Shultz (1990). Zaitlin & Shultz (1990) presented a conceptual ternary diagram for estuarine sedimentation on which they depicted the spatial arrangement of models for wave and tide dominated estuaries but omitted the river dominated apex. This was subsequently extended and it was

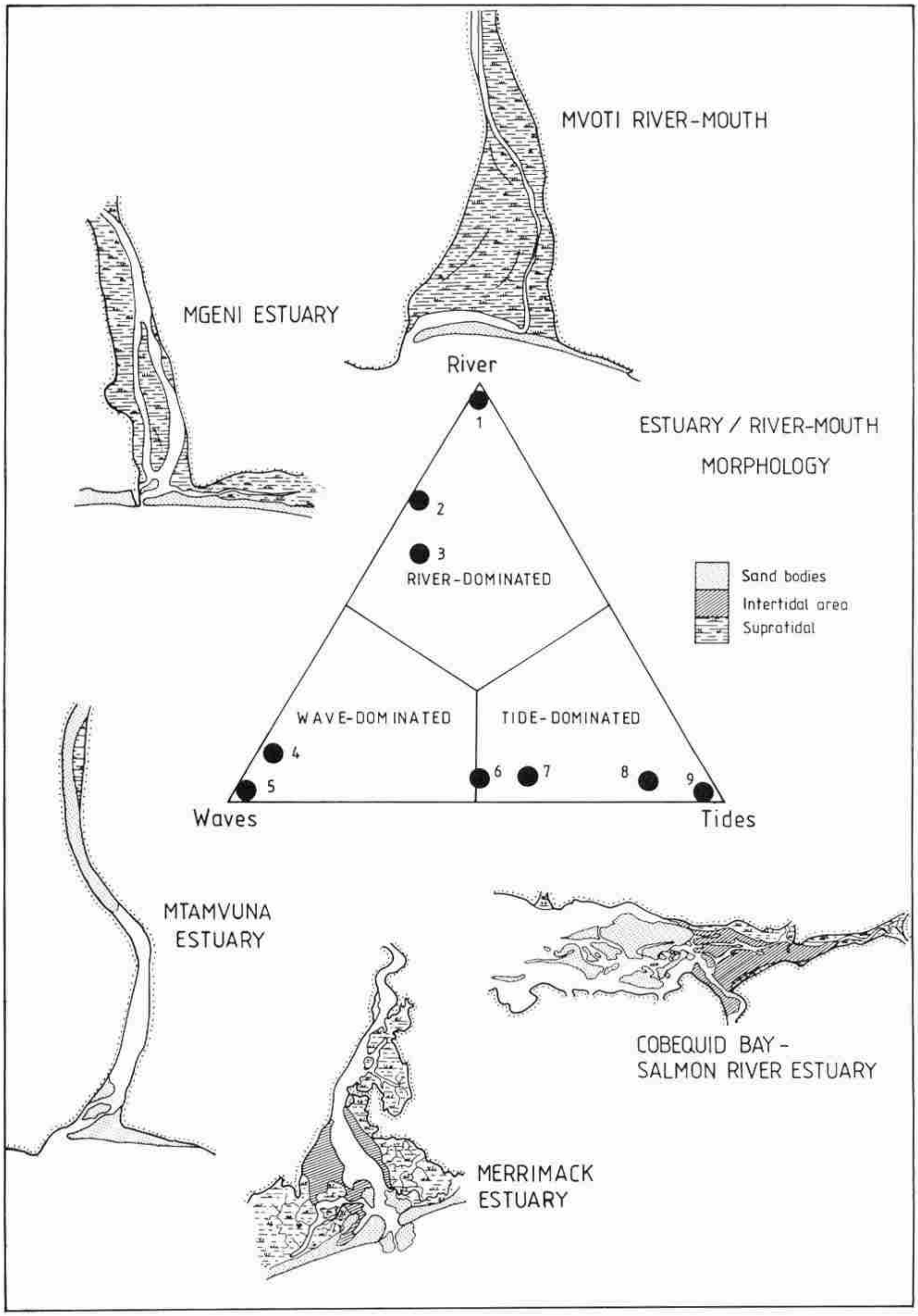

Fig. 17. Conceptual view of estuarine morphology as a function of the relative importance of wave, tidal and fluvial processes. Distinctive facies architecture exist in each category. 1, Mvoti River estuary, South Africa (Cooper, 1991a); 2, Mgeni River estuary (this paper); 3, Central Chilean coast estuaries (Araya-Vergara, 1985) and Orange River, South Africa/Namibia (van Heerden, 1986); 4, Mtamvuna River estuary, South Africa (Cooper, 1993); 5, New South Wales estuaries (Roy, 1984); 6, Merrimack River estuary, USA (Boothroyd, 1978); 7, mesotidal estuaries (Hayes, 1975); 8, Gironde River estuary, France (Allen, 1971); 9, Cobequid Bay, Bay of Fundy, Canada (Dalrymple *et al.*, 1990). Deltas may be classified similarly but they exhibit coastal progradation as a result of much greater fluvial dominance in all categories and so do not feature in this ternary diagram.

proposed (Dalrymple *et al.*, 1992) that deltas belong there. If, however, this scheme is limited to non-progradational landforms, channel confined, river dominated systems such as the Mgeni River estuary and many other environments may be accommodated. Such systems cannot be considered deltas as they do not exhibit coastal progradation.

To the lower right of the diagram lie tide dominated macrotidal estuaries while at the wave dominated apex lie the typical wave dominated estuaries with a tripartite facies arrangement (Roy, 1984). Hayes' (1975) mesotidal estuary model exhibits moderately strong tidal currents in the tidal inlet which promote more extensive tidal delta formation in comparison to wave dominated (generally microtidal) estuaries (Roy, 1984; Davies & Hayes, 1984). In a ternary diagram for estuaries (Fig. 17) the Hayes model could probably be placed between the wave and tide dominated extremes, such that the base of the triangle is roughly equated with tidal range.

The upper portion of the ternary diagram contains river dominated estuaries similar to the Mgeni in which fluvial facies extend right to the barrier and marine influences are minimized through steep gradients and high fluvial discharge. The Mvoti 'estuary' on the Natal coast (Cooper, 1991a) plots at the apex because it has no flood tidal delta due to an elevated rock outcrop which prevents tidal incursion through its permanent outlet.

Natal river mouths share common features with many transitional coastal environments but the nature and arrangement of facies in Natal river mouths is distinctive. For example, in contrast to wave and tide dominated estuaries, the river dominated estuaries of Natal are dominated by fluvial inputs. They do not, however, qualify for description as deltas as progradation is not possible. Neither do they display the characteristic downstream facies changes observed in wave dominated microtidal estuaries (Roy, 1984) and energy levels remain similar along the axis of the estuary valley. This differentiates Natal river dominated estuaries from the wave and tide dominated estuarine models of Zaitlin & Shultz (1990) in which fluvial influences were minimal.

The non-tidal river mouths of Natal such as the Mvoti (Cooper, 1991a), which are overwhelmingly dominated by fluvial inputs, can be located at the river dominated apex of the triangle. They show little downstream variation in energy levels as they are essentially river channels. Between these and the wave dominated extreme are the estuaries of Natal which, although fluvially dominated, experience minor marine inputs through their outlets. The Orange River estuary (van Heerden, 1986) would also plot in this position. Energy levels in these estuaries are similar through most of the back barrier but a slight increase may be noted in the immediate vicinity of the outlet through reversing tidal currents. The river dominated Alsea Bay in Oregon (Peterson *et al.*, 1984) displays several similarities to the Mgeni River estuary. However, the former has a wider valley which permits lateral channel migration and enabled the retention of pre-Holocene sediments in the bedrock valley fill. The sediment filled rias ('estuarine deltas') on the wave dominated coast of Chile in which coastal progradation is limited by high wave energy (Araya-Vergara, 1985) are also similar to the estuaries of Natal. This suggests that the Mgeni River estuary may be generally representative of river dominated estuaries which do not prograde seaward.

Zaitlin & Shultz (1990) placed the microtidal estuary model of Roy (1984) at the wave dominated apex. The similarity of this model to the Mtamvuna River estuary in southern Natal (Cooper, 1993) suggests that it too can be plotted there, as it exhibits the three divisions recognized by Roy (1984) of an upper, fluvially dominated zone, a middle reach dominated by low energy and a return to high energy conditions at the outlet. The St Lucia River estuary mouth in Zululand (Wright & Mason, 1990) also plots in this location.

The transition from an estuary to a delta is probably a function of both fluvial sediment supply and coastal environmental factors favourable to sediment deposition. It does not necessarily follow that an estuary will ultimately become a delta: it may only do so if coastal environmental conditions are favourable and a situation arises where excess sediment is retained immediately adjacent to the estuary mouth.

Following the approach of Nichols (1989) to lagoons, estuaries need not necessarily pass through a deep water period with deltaic progradation and swamp encroachment as proposed by general evolutionary models (Roy, 1984) of microtidal estuaries. If fluvial sediment supply constantly matches sea level rise and valley drowning, a shallow braided channel which experiences cyclical changes in morphology as depicted in the Mgeni River may be maintained throughout transgression and valley drowning. Only if drowning outstrips sedimentation for some period during transgression is there a deep water phase during which a generalized evolutionary model of deltaic progradation, swamp encroachment may prevail. This is particularly important to mud accumulation in laterally restricted and bedrock confined estuaries such as the Mgeni. It is possible for an estuary to change its characteristics during evolution from a wave to a fluvially dominated system, but this is not necessarily so and many other estuaries in Natal preserve no evidence for a deep water phase during their Holocene evolution.

Given the restricted size of Natal river mouths and the naturally high rates of sediment supply, the maintenance of form equilibrium with river discharge and tidal currents, where present, is the main geomorphological driving force. As Alexander (1976) noted, most Natal estuaries are full of sediment and any increase in catchment sediment yield is transported through the estuary and out to sea. Only basins which have not attained equilibrium will shallow through increased sedimentation. Consequently, measured changes in bed level in recent times in Natal estuaries must be viewed as morphological responses to short or medium term discharge variation. As many of these surveyed cross-sections do not extend across the floodplain which forms an integral part of Natal river mouths, they are of little value, because the channel form cannot be deciphered.

In river dominated estuaries equilibrium has been achieved and variation in sediment volume fluctuates with fine grained sediment buildup during low flows followed by erosion during minor floods. The equilibrium is punctuated by the effects of major floods which reduce the volume of accumulated sediment instantaneously, after which it rapidly regains equilibrium levels (Fig. 18A). This contrasts markedly with conditions in microtidal estuaries where a gradual accumulation of sediment occurs, perhaps accelerated by increased sediment loads or punctuated by events such as landslides or floods (Fig. 18B).

An estuary need not necessarily become a delta through continued fluvial deposition as suggested by Dalrymple *et al.* (1992), but it may persist, as may lagoons (Nichols, 1989). Estuaries only become deltas or prograding linear coasts if fluvial dominance is strong and nearshore conditions favour the retention of sediment in the vicinity. In areas such as the Natal coast where coastal wave energy is high, the shelf is steep and narrow and current driven shelf sediment dispersal is particularly vigorous (Flemming, 1981), no opportunity for delta formation exists. Under such conditions estuaries may persist on top of the valley fill sequence during sea level highstands where excess fluvial sediment passes through the estuary.

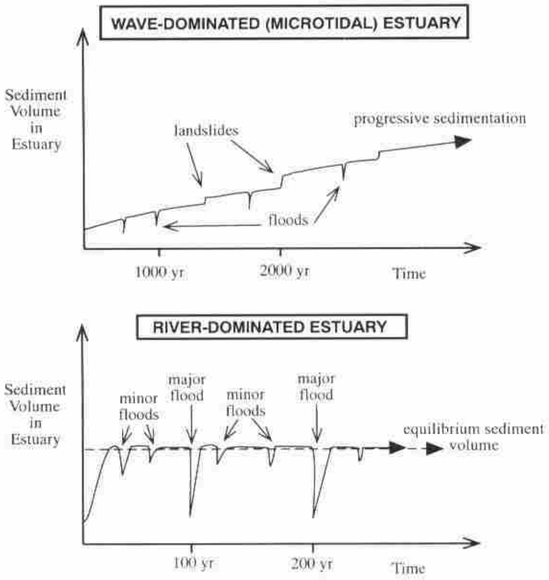

Fig. 18. Contrasting modes of sedimentation in river and wave dominated estuaries viewed as variation in sediment volume with time. River dominated estuaries exhibit an equilibrium volume of sediment which is punctuated by major floods but which rapidly regains its pre-flood volume. Under a stable relative sea level the volume is maintained in the long term. In wave dominated estuaries the water volume is gradually reduced. This may be accelerated by instantaneous events such as floods or landslides (in cliff bound estuaries), or long term increases in sediment yield from rivers.

The relative effects of sediment supply and sea level change determine the nature of estuarine fill at any particular time in its evolution. If sea level rise outstrips sediment supply estuaries become deeper, and conditions favourable to suspension settling occur. If sedimentation equals sea level rise the estuary will maintain its equilibrium morphology. If sedimentation exceeds sea level rise the estuary will infill and prograde if coastal conditions are suitable, or simply pass excess sediment onto the inner shelf. These three situations were assessed in coastal lagoons by Nichols (1989) who defined to end-members: a 'surplus' lagoon in which accretion exceeds relative sea level rise and a 'deficit' lagoon in which relative sea level rise exceeds the sediment accumulation rate. In this continuum he formed a conceptual model which enables lagoons to be viewed as a result of accretion and submergence. This type of approach is probably also applicable to the estuaries of Natal and elsewhere, in an evolutionary context. In Natal there is no evidence of differential rates of Holocene sea level rise (Cooper, 1991a) and so sediment supply might seem to be the only variable.

The conceptual scheme assists in placing Natal estuaries in evolutionary perspective and aids interpretation of what is otherwise a seemingly endless array of valley fills. It also provides a basis for further investigation of other river mouths and valley fills by assisting stratigraphical interpretation. The implication, which remains to be rigourously tested by drilling, is that estuaries with wide floodplains, in relation to catchment size, increase in volume rapidly when sea level rises. Thus they preferentially develop deep water muddy facies until sea level rise stops and deltas prograde across the lagoonal deposits covering them.

The impact of increased fluvial sediment yields on river mouth geomorphology in the study area is negligible. Excess sediment may accumulate temporarily but is transported seaward during floods in a dynamic equilibrium situation depicted in the models shown above. Increased soil erosion through farming and vegetation denudation will be reflected not in river dominated estuaries, but in the deep offshore areas where mud presently accumulates (Martin, 1987).

Changes in channel and floodplain morphology of river dominated estuaries arise through discharge fluctuations which range in scale from seasonal, to decade-long cycles of drought and non-drought, to daily and fortnightly tidal variation. The most dramatic impacts occur as a result of episodic floods which, in the latest stages of evolution, remove fine grained sediment from estuaries and lagoons and promote retention of channel lag deposits in the sedimentary record.

CONCLUSIONS

1. The Mgeni River estuary is a drowned river valley estuary on a wave dominated coast in which fluvial processes dominate over marine influences. It differs from typical models of microtidal estuaries in that it does not exhibit progressive evolutionary changes under stable sea level conditions and may maintain equilibrium of form through a series of cyclical morphological changes.
2. The laterally confined, coast-normal estuary fill sequence in the Mgeni River bedrock channel results from a single transgressive cycle fill as all previously accumulated sediment was eroded during the preceding incision.
3. Under constant sea level conditions, the Mgeni River estuary follows a cyclical pattern of development driven by episodic floods with an approximate 70–100 year cyclicity. This results in retention of mainly coarse grained sediments in the valley fill. This situation may be maintained during transgression if sediment supply keeps pace with the rate of valley inundation and so a coarse grained bedrock valley fill results.
4. If the rate of inundation (controlled by bedrock valley morphology and the rate of sea level rise) exceeds sediment supply, a situation may develop where a typical wave dominated morphology arises with deep water middle reaches. This situation persists until, as predicted by standard wave dominated estuary models (Roy, 1984; Dalrymple *et al.*, 1992), the estuary is infilled. The period during which such conditions may persist is controlled by fluvial sediment supply.
5. River dominated estuaries are a unique type of sedimentary environment which are associated with high fluvial sediment supply and nearshore conditions which do not favour coastal progradation. They may not be properly considered deltas as they do not exhibit coastal progradation; however, tidal influences may be so restricted that they do not meet typical descriptions of estuaries.
6. While the Mgeni River estuary may be representative of a number of river dominated estuaries on the Natal coast, variation does exist between the few documented examples in this and other areas (Peterson *et al.*, 1984; Araya-Vergara, 1985; Cooper, 1991a). These variations arise largely from different modes of sedimentation (lateral migration or vertical erosion and deposition) which may be mediated by valley dimensions, climatic variations, sediment supply rates and relative sea level changes. Further research is required to distil away such local variability and formulate a globally applicable model for river dominated estuaries.

ACKNOWLEDGMENTS

Initial research on the Mgeni River estuary was funded through the South African National Committee for Oceanographic research while the author was a research officer at the University of Natal. Subsequent aspects of this research were funded by the Department of Environment Affairs (South Africa) and the CSIR. I thank Arjoon Singh and Trevor Harrison for assistance in the field and Arjoon for drawing the figures. The referees, Brian Zaitlin and Maynard Nichols, provided valuable observations and constructive comments on the paper.

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(Manuscript received 19 August 1992; revision accepted 9 June 1993)